EVALUATING A NOVEL UV DEVICE FOR WASTEWATER DISINFECTION

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Abstract

UV disinfection is the most common method used in wastewater disinfection. However, some types of wastewater effluent have a low UV transmittance (UVT), which cannot be disinfected efficiently by a commercial UV reactor. A novel UV reactor (called the *project prototype*) was developed, which has a different type of reactor hydraulics than a typical commercial UV reactor. This change in hydraulics is believed to be an innovative method of improving the low UVT fluid disinfection. The main purpose of this project is to evaluate the feasibility the project prototype.

The settings of the project prototype were first refined, and then compared to a control reactor, which was used to mimic a commercial UV reactor (called the commercial unit) at a range of UV doses. The UV dose was manipulated by changing the number of operated UV lamps and operated flow rate of the reactors. The disinfection performance of the reactors was not only compared at conventional wastewater treatment plants, but also at stabilization ponds. Within the conventional wastewater treatment plants, the reactors were tested using the effluent from the primary, secondary and tertiary treatment stages. In total, the reactors were compared twelve times at seven different wastewater treatment sites.

The results show that the project prototype was, on average, 1.4 times worse than the commercial unit at treating tertiary wastewater, where the wastewater had a high UVT (55 to 65%). This high UVT value favours the use of the commercial unit, as it is designed for this UVT range. However, at a low UVT range, the project prototype performed, on average, 1.4 times better than the commercial unit, at treating secondary wastewater, where the wastewater had UVT of 22 to 55 %. In the stabilization pond tests, where the UVT was 11 to 25%, the project prototype performed 2.1 times better than the commercial unit on average, and up to 8 times better at one location. In the primary treatment test, where the UVT of the wastewater was extremely low (5%), the project prototype, on average, performed 4.5 times better than the commercial unit, and in one case up to 13 times better than the commercial unit.

The research found that the project prototype has an advantage when treating low UVT fluid and great potential in the commercial market. The project prototype performs better

than the commercial unit at stabilization ponds. This suggests that the project prototype would be a viable option for pond treated wastewater disinfection. In addition, the project prototype offers superior performance on primary treated wastewater. This indicates the potential application at marine outfalls (primary treated wastewater), and the possibility of primary wastewater disinfection for irrigation. Overall, this research confirms the feasibility of the novel reactor in wastewater disinfection.

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I would also like to thank Mr Aidan Crimp, who helped me a lot in the experiments and also gave me a lot of useful information and ideas. Also, I would like to acknowledge the many members of the technical staff from Massey University, who gave me a lot of help.

Last but not less, I would like to acknowledge my God. I believe that I would not be able to finish my master thesis without His help, as Proverbs 1:7 “The fear of the Lord is the beginning of knowledge, but fools despise wisdom and instruction”.

This thesis is dedicated to my father Zhaoguang Huang and mother Qiaosheng Lu who always support me.

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1. Introduction

1.1. Background

Wastewater disinfection is as important as wastewater organic and nutrient removal (Jamwal & Mittal, 2010), because it significantly reduces the risk that the local populations having contact with pathogenic wastewater (Das, 2001). For example, the treated wastewater of a wastewater treatment plant would normally be discharged into the nearby river or ocean. Therefore, wastewater disinfection could significantly reduce the pathogen level in the river or ocean, providing a better quality environment for the local populations.

Chlorination was the traditional method for disinfection, but it well known that some of the chlorination by-products are ecologically toxic to aquatic life (Monarca *et al.*, 2000). In contrast, ultraviolet (UV) disinfection has a lower life cycle cost, less carbon footprint and is more eco-friendly than the chlorination method (Guo *et al.*, 2009; Monarca *et al.*, 2000).

1.2. Research needs

Current commercial UV reactors are not energy efficient at disinfecting low UV transmittance wastewater, because a significant amount of the UV light is absorbed by the fluid. This means that little UV light can reach the microbial cells, and therefore less UV dose is delivered. UV dose is an important parameter that governs UV disinfection, and it is defined as the time integral of UV intensity. As a result, more UV lamps would be needed in a UV system to increase the delivered UV dose. This would result in higher capital and operating costs.

Using thin film hydraulics for UV disinfection is a method, which could increase the received UV dose of the microbial cells in low UVT fluid. This method is usually used for food and pharmaceutical product disinfection (Shama *et al.*, 1996). Thin film UV reactors generally are not able to handle large volumes of fluid in a short period; hence, not used for wastewater treatment. However, Professor Andy Shilton proposed that using a thin film hydraulics while maintaining a high operated flow rate (called supercritical flow hydraulics) would be applicable for wastewater treatment, especially for wastewater that has a low UVT (Shilton & Sykes, 2009). Thin film hydraulics reduces the traveling distance of the UV light, which preserves significant amount of UV light and therefore increases the received UV light of the microbial cells in the fluid. Although the UV exposure time of the fluid (and the microbial cells) will decreases due to the fast flow rate, the increase of the received UV light should be able to compensate this reduction, so resulting a better UV disinfection (greater received UV dose). Based on this, it is believed that a supercritical flow UV reactor could have better disinfection performance than a traditional wastewater UV reactor on a low UVT fluid.

1.3. The potential market

The global market of UV reactors was evaluated by WaterWorld (2010) and BccResearch (2011), individually. Both of the studies found that the market size is increasing and predicted that the size in 2016 would be $ 500 million US. If a supercritical flow UV reactor is developed and found to have an advantage at disinfecting low UVT fluid, the potential market of the reactor would expected to be a large portion of the total market size.

1.4. Project aim and objectives

The aim of this project is to assess the idea of applying supercritical flow hydraulics for wastewater disinfection, by evaluating the feasibility of using a supercritical flow UV reactor (called the *project prototype*) in wastewater treatment plants. In order to fulfil this aim, the objectives are:

- Comparing the disinfection performance of the project prototype with the previous generation prototype, which ensuring the progress of the prototype development.
- Refining the settings of the project prototype by
    - Testing the effect of the film thickness on the disinfection performance
    - Testing the effect of the reaction chamber slope on the disinfection performance
    - Testing the effect of the reflector shape on the disinfection performance
- Comparing the disinfection performance of the project prototype with a control reactor (called the *commercial unit*) over a range of UV doses, at different wastewater treatment sites.

2. Literature review

The literature review will first provide the background knowledge of UV light and UV disinfection mechanism. Next, the factors that can affect wastewater disinfection will be discussed, which could be the type of UV lamp used, the wastewater characteristics and the received UV dose. The received UV dose will be explored further in relate to hydraulic effect. An argument will be made on the question: '*Would application of supercritical flow to UV disinfection be a possible improvement.*' Finally, the prior art will be reviewed and discussed.

2.1. What UV light is

UV light is a type of electromagnetic radiation in the wavelength range of 100 to 400 nm. In this wavelength range, four types of UV light are classified. UVA (315-400 nm), which can cause mild damage on the skin. UVB (280 – 315 nm), which cannot only cause sunburn, but also skin cancer in an extreme case. UVC (200-280 nm) is the most hazardous type of UV light, which can be absorbed by RNA, DNA, and proteins; hence, causing lethal damage of the cell. UVC is also called the germicidal light, and is used in most of UV disinfection processes (Bolton & Cotton, 2008). Vacuum UV (100-200 nm) is only present under vacuum conditions, so it is not found in the natural environment. Figure 2-1 below illustrates the UV classification.

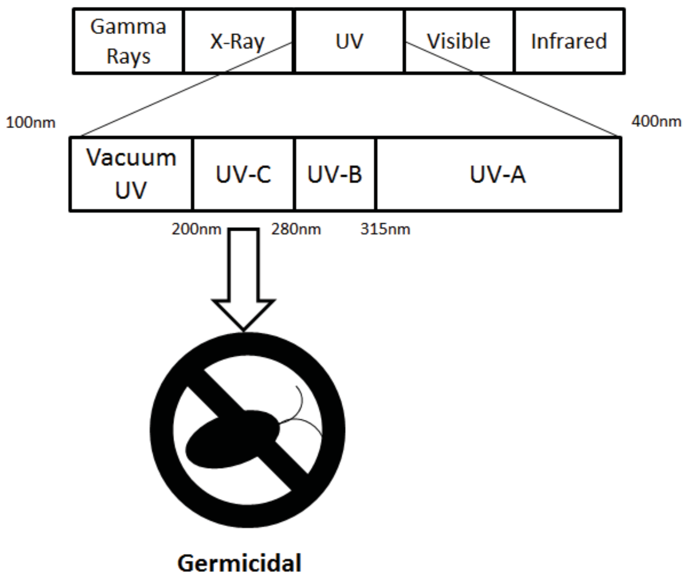


Figure 2-1, Range of electromagnetic waves

2.1.1. UV light propagation behaviours

The dynamic of UV light is similar to visible light except that UV light is extremely easy to be absorbed by materials. For example, only 25 to 30 % of UV light at 254 nm can be reflected by stainless steel, where the rest of the light is absorbed (Masschelein & Rice, 2002). Polished aluminium foil is currently one of the most UV reflective materials and can reflect up to 90 % of germicidal UV light (Masschelein & Rice, 2002). This means that using reflected UV light for disinfection is not energy efficient.

The incidence angle of UV light is important for the disinfection process. Similar to visible light, when the light has an incidence angle less than 60 degree on a surface of fluid, 95 % of the light can be delivered into the fluid. However, significant amount of UV light will be reflected if the incidence angle is greater than 60 degree (Masschelein & Rice, 2002). This means that when a UV lamp is placed on a type of fluid, only a portion of UV light from the lamp can be delivered into the fluid, as the light is emitted at different angle (hence different incident angle).

2.1.2. Beer Lambert's Law

When light travels through a fluid, significant amount of UV light is absorbed (see Figure 2-2). Beer Lambert's Law (see Equation 2-1) is often used to predict the UV intensity.

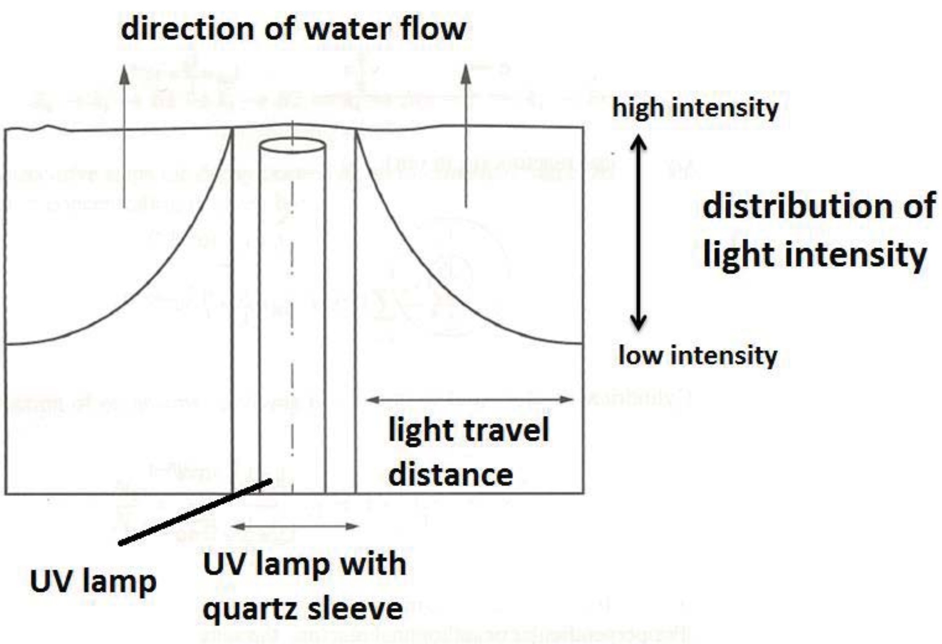


Figure 2-2, Irradiation profile of a single lamp in fluid (adapted from Masschelein & Rice, 2002, p. 86)

$$\frac{I_d}{I_0} = 10^{-\alpha d}$$

Equation 2-1, Beer Lambert's Law

Where:

I_d = Intensity after travelling a distance, d, through a given medium of absorbance, α (mW/cm^2)
I_o = Initial intensity (mW/cm^2)
d= Distance (or thickness) of the medium (cm)
α = Absorption coefficient of the medium (cm^{-1})

The intensity of UV light in fluid decays exponentially depending on the travelling distance and the absorption coefficient of the fluid. UV intensity decreases as travelling distance increases.

2.2. UV disinfection mechanisms

UV light is absorbed by various components of the cells, as the UV light penetrates through microorganism. Majority of the UV light is absorbed by protein, DNA, and RNA (Masschelein & Rice, 2002). Although the proteins in the cells absorb large amount of UV light, the inactivation of the cells is usually not due to protein disruption (Bolton & Cotton, 2008). Protein needs large amount of UV energy to be disrupted. Instead, DNA and RNA distortion are the major causation of the inactivation, as DNA and RNA require relatively small amount of UV energy to be distorted (Bolton & Cotton, 2008; Masschelein & Rice, 2002).

DNA and RNA are the fundamental templates of life. When DNA and RNA are damaged; the microorganisms will not able to reproduce, thus resulting in decline of the microorganism population (Masschelein & Rice, 2002). One of the well-known damages is thymine dimmer formation, as shown in Figure 2-3. If two thymines are closely collocated, the presence of sufficient UV light will initiate a photochemical reaction. As a result, thymine dimmer is formed and the shape of DNA (or RNA) is distorted, as shown in Figure 2-4. Likewise, the present of sufficient UV light can also initiate other photochemical reactions, distorting the shape of DNA chain, such as pyrimidine dimer, Cytosine dimer, protein –DNA cross links, etc. (USEPA *et al.*, 2006). If a DNA chain appears more than 100 dimmers, the DNA chain will no longer function (Oguma *et al.*, 2001).

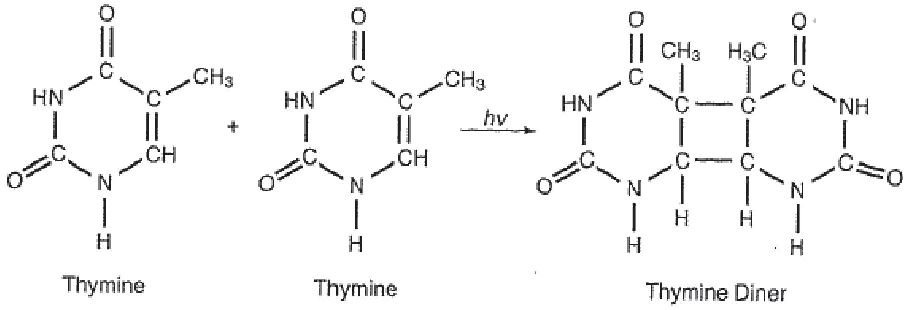


Figure 2-3, Chemical reaction of thymine dimer (Bolton & Cotton, 2008, p. page 28)

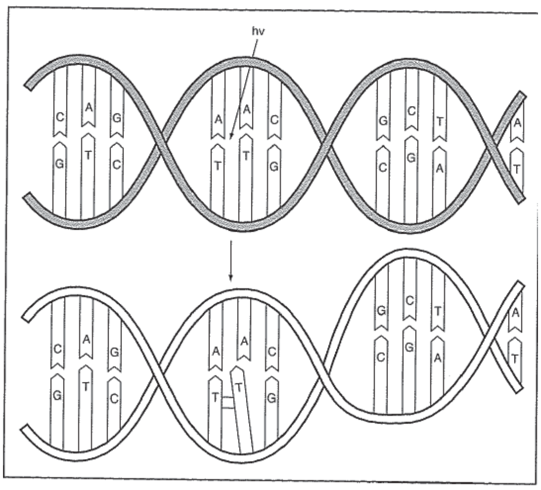


Figure 2-4, Disrupted DNA (Bolton & Cotton, 2008, p. 28)

Although protein disruption is not the major disinfection mechanism, researchers found that UVA and UVB (280 - 400 nm) can initiate photochemical reactions on proteins, which cause inactivation (Oguma *et al.*, 2002; Zimmer & Slawson, 2002). Zimmer and Slawson (2002) suggest that the proteins in a cell membrane can be affected by UVA, so disabling the function of the membrane. As a result, the reproduction process of the cell is stopped.

2.2.1. Wavelength and UV disinfection

UVC is known as the germicidal range for microorganisms. Figure 2-5 shows the relative absorbance response of DNA and RNA bases. The curves illustrates that the bases have an absorbance response peak at the wavelengths between 240 to 280 nm, which is within the germicidal region. Similar responses are also found in DNA absorbance and the absorbance of some microbial cells, as shown in Figure 2-6.

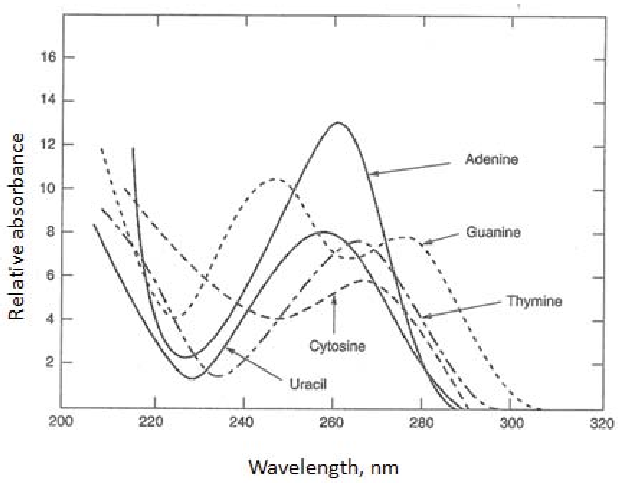


Figure 2-5, UV absorbance of DNA or RNA bases (Masschelein & Rice, 2002, p. 63)

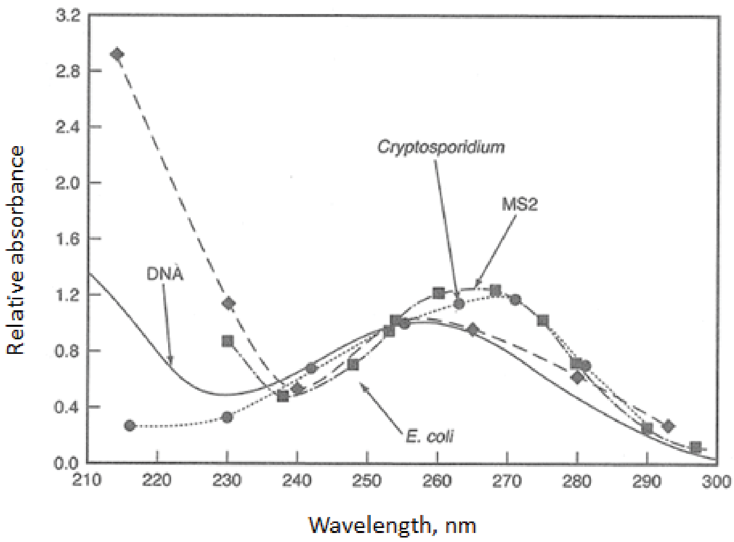


Figure 2-6, Relative UV absorbance of some microorganism and DNA (Bolton & Cotton, 2008, p. 29)

The effects of UVA and UVB on microorganism are complex and not well understood. As mentioned in section 2.2, UVA and UVB can cause disruption on the proteins of microorganisms. Furthermore, studies found that microorganisms can be better disinfected by irradiating with a broad wavelength range of UV light, which from UVA to UVC (Hallmich & Gehr, 2010; Oguma *et al.*, 2002; Zimmer & Slawson, 2002). Oguma *et al.* (2002) suggest that the better disinfection is due to the distortion of photolyase, by the UV light between 220 to 300 nm. Photolyase is an enzyme that can be found in certain microorganism. This enzyme can photo-repair UV damaged DNA chains (the details of photo-reactivation will be discussed in section 2.2.2.).   As a result photolyase distortion, fewer microorganisms can be photo-reactivated, which means better disinfection. Also, Oguma *et al.* (2002) suggest that 315 to 400 nm light (UVA) can excite certain molecules inside microorganisms, producing strong oxidant, such as, $O_2^{\cdot-}$, H_2O_2 and $^{\cdot}OH$, which damage the cells. In contradiction, USEPA *et al.* (2006) and Hallmich and Gehr (2010) suggest that 310 to 480 nm light (mainly UVA) has important roles in microorganism photoreactivation (details will be discussed in section 2.2.2).

2.2.2. Repair mechanism

Many microorganisms have the capability to repair damages from UV light (USEPA *et al.*, 2006). The repair mechanisms fall into two categories; photoreactivation or dark repair mechanism. This repairing of the microorganisms is one of the major disadvantages for UV disinfection (Hallmich & Gehr, 2010; Oguma *et al.*, 2001). Harris *et al.* (1987) shows 3 logs of *E. coli* in the UV treated samples can be reactivated by photoreactivation, where the log value can be calculated according to Equation 2-2.

$$\log inactivation = \log \frac{concentration\ of\ cells\ before\ UV\ treatment}{concentration\ of\ cells\ after\ UV\ treatment}$$

Equation 2-2, Log inactivation calculation

One of the major photoreactivation processes is carried out by an enzyme called photolyase, which is activated by 310 to 480 nm light (USEPA *et al.*, 2006). Once the enzyme is activated, it can break the covalent bond of pyrimidine dimers, repairing the distorted DNA or RNA (Jagger, 1967; Oguma *et al.*, 2001). Hallmich and Gehr (2010) show that the photolyase need as low as 0.065 mW/cm^2 of 310 to 480 nm light to be initiated.

Microorganisms can also undergo dark repair, although the dark repair mechanism is not the major recovery process (Zimmer & Slawson, 2002). Dark repair is defined as any repair mechanisms that do not require the presence of light, and it is often referred as excision repair (Oguma *et al.*, 2001; Zimmer & Slawson, 2002). Excision repair is a process of replacing the damaged DNA with the correct DNA sequence.

Since few cells are repaired by the dark repair mechanism and significant numbers of cells are recovered by photoreactivation, most literature assumes the effect of dark repair on UV disinfection performance is negligible (Oguma *et al.*, 2001; USEPA *et al.*, 2006; Zimmer & Slawson, 2002). As discussed above, photoreactivation could significantly affect the performance of UV disinfection. To reduce the photoreactivation, Hallmich and Gehr (2010) recommends three hours or more of dark treatment (where remain the UV treated effluent in dark). Also, studies have shown that fewer cells will be photoreactivated, after high dose of UV treatment or if the cells are irradiated by a wide range of UV light, as produced by medium pressure mercury lamps (Guo *et al.*, 2009; Lindenauer & Darby, 1994; Oguma *et al.*, 2002; Zimmer & Slawson, 2002). More discussions of medium pressure mercury lamps are in section 2.3.2.

2.3. UV emission & the technology

Mercury emission lamps are the most commonly used technology in UV disinfection systems (Masschelein & Rice, 2002; Oguma *et al.*, 2002). The mercury emission lamps fall into two categories; low pressure mercury lamps and medium pressure mercury lamps.

It is known that light is a form of energy, and the mechanism of mercury emission lamps is conversion of electrical energy into light energy. While a mercury emission lamp is operating, electrons are penetrating through the mercury plasma, from the cathode to anode of the lamp. As shown in Figure 2-7, when an electron hits a ground state (lowest energy state) mercury atom, the mercury atom gains energy and enters an excited state. As an excited state atom is not stable, the mercury atom spontaneously releases the energy (in the form of light) to become ground state again, where ground state is the most stable energy state. Different wavelengths of light are produced, as electrons hit mercury atoms in at different angles. Moreover, the emitted light (photon/energy) can be reabsorbed by another mercury atom to release electrons (Masschelein & Rice, 2002). Therefore, the diameter and gas pressure of mercury lamps need to be carefully designed, in order to, maximize the emission of light within the germicidal range.

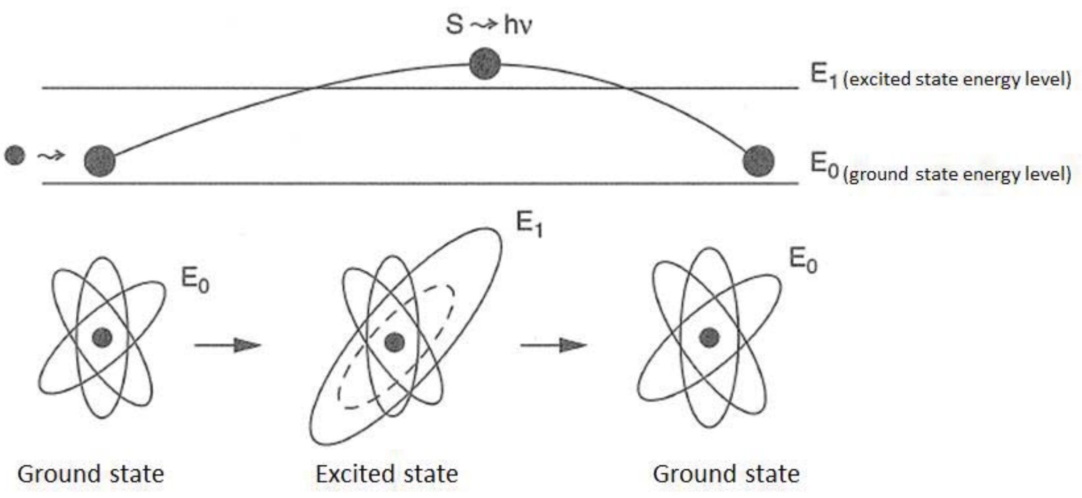


Figure 2-7, Spontaneous emission illustration (Masschelein & Rice, 2002, p. 10)

2.3.1. Low pressure mercury lamp

Low pressure mercury lamps are the most conventional UV lamps used in UV reactors (Oguma *et al.*, 2002). The lamps emit monochromatic (single wavelength) light at 254 nm, which is effectively absorbed by DNA (see Figure 2-8), and therefore cause microorganism inactivation. A low pressure mercury lamp usually has partial pressure 0.1 to 10 Pa, preferred operational temperature 20 to 40 ^{o}C and lifetime of 8,000 to 12,000 hours (Bolton & Cotton, 2008; Masschelein & Rice, 2002). Low pressure mercury lamps can only convert 25 to 45 % of the electricity they received into UV light, and the rest of the electricity is lost to heat and visible light (Masschelein & Rice, 2002).

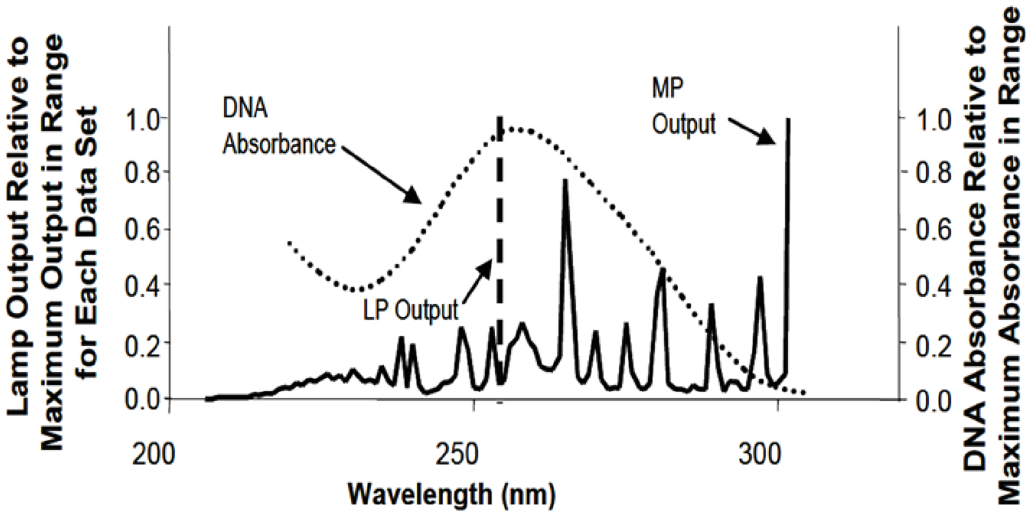


Figure 2-8, Comparison of low pressure mercury lamp (LP) and medium pressure mercury lamp (MP) emission spectrum with DNA absorptivity (USEPA *et al.*, 2006, pp. 2-21)

Figure 2-9 is the performance data of a Low pressure mercury lamp used in this project, which is has similar behaviour to a typical low pressure mercury lamp. At the first 100 hours, the lamp has 100 % relative efficiency. Between 100 to 1000 hours, the relative efficiency of the lamp starts to drop dramatically. After 1000 hours, the relative efficiency of the lamp has less decrease and become the decrease rate is constant. The decrease of the relative efficiency is due to oxidation which darkening the surface of the lamp (USEPA *et al.*, 2006).

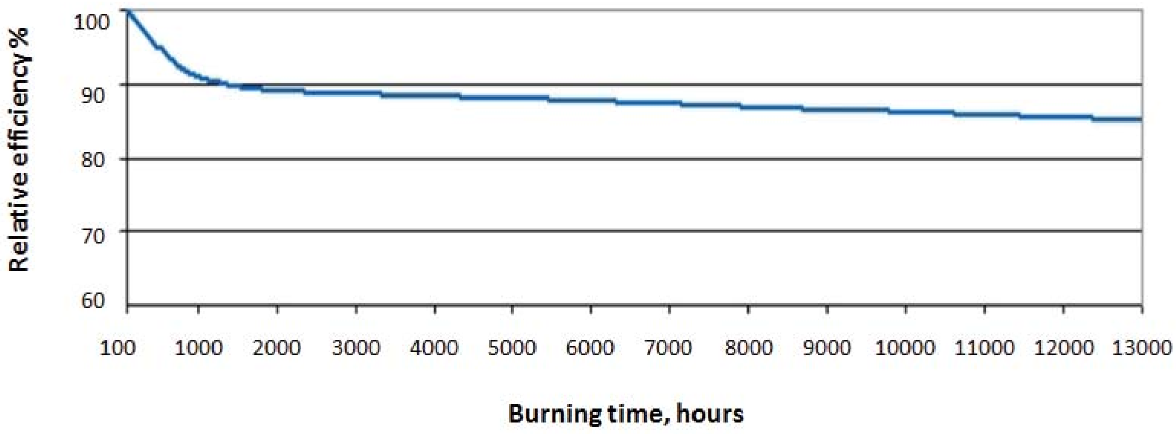


Figure 2-9, Lifetime of low pressure mercury lamp (LightTech)

2.3.2. Medium pressure mercury lamp

Medium pressure mercury lamps emit more than one specific wavelength of light (polychromatic; see Figure 2-8). A typical medium pressure mercury lamp usually has gas pressures of 10^4 to 10^6 Pa, operational temperature 600 to 900 °C and 4,000 to 8,000 hours of lifetime (Bolton & Cotton, 2008; Masschelein & Rice, 2002). When a medium pressure mercury lamp ages; not only the relative efficiency of the lamp will decrease, but also the emission spectrum will change (Masschelein & Rice, 2002).

Compared to low pressure mercury lamps; the UV light intensity of medium pressure mercury lamps is adjustable by altering supply voltage, which is one of their major advantages (USEPA *et al.*, 2006). Also, as discussed in section 2.2.1, medium pressure mercury lamps emit polychromatic light, which can reduce the occurrence of photoreactivation and increase disinfection effect. On the other hand, medium pressure mercury lamps have lower emission efficacy of germicidal light than low pressure mercury lamps, as a lot of non-germicidal light is produced (Schalk *et al.*, 2005). Furthermore, this type of lamps might need an additional cooling system in some cases (e.g. when the lamp is not submerged in fluid), as the operational temperature of the lamp can be as high as 900 °C (USEPA *et al.*, 2006). This would lead to extra capital and operational costs.

2.3.3. Other light technologies

UV light can be produced by other light technologies other than the mercury pressure lamps, such as flash lamps, excilamps, and UV LED (Bolton & Cotton, 2008; Masschelein & Rice, 2002). However, these technologies are not ready to be used in a UV reactor.

Flash lamps is a type of lamps continuously flash (within several microseconds) to produce light by a large amount of electrical energy supply (Bolton & Cotton, 2008). The UV flash lamp requires high voltage (10-30 kV) to emit polychromatic light (185-600 nm). It can flash about 30 times within a second. According to Bolton and Cotton (2008) and Masschelein and Rice (2002) this type of lamp has low germicidal efficiency and lifetime. Thus, very few commercial systems use this lamp.

The light emission mechanism of an excilamp is similar to a mercury lamp. The gases inside the excilamp is excited electrically, and then releasing photon (light). An excilamps can produce 185-600 nm wavelengths. These lamps have germicidal efficacy 12% to 16%, which is low, and the lifetime (3,000- 6,000) is relatively short (Bolton & Cotton, 2008; Schalk *et al.*, 2005).

UV LED technology is the most promising technology, because UV LEDs require less energy and have longer lifetime than other technologies (Vilhunen *et al.*, 2009). However, UV LEDs generally emit low intensity UV light, so long exposure time of fluid will be required in a UV reactor (Li *et al.*, 2010; Vilhunen *et al.*, 2009). This is one of the major drawbacks for UV LEDs disinfection in water/wastewater.

2.4. Effect of wastewater characteristics on UV disinfection

Table 2-1 shows the effect of wastewater characteristics on UV disinfection. Despite the effects of oil, grease and hardness, where the UV transmittances of the quartz sleeve is reduced. The effects of the other factors can be categorized into two mechanisms, the UV absorption and the UV shielding (for microorganisms). UVT_{254} is a measurement to characterized the UV absorption of the fluid and total suspended solid (TSS) is a measurement to acts as a proxy of shielding effect. These two measurements are usually used, which are already well acknowledged in literature (Scheible *et al.*, 1986; USEPA *et al.*, 2006).

Table 2-1, Wastewater characteristic that effect on UV disinfection (Metcalf & Eddy, 2003, p. 1309)

Constituent	Effect
BOD, COD, TOC, etc.	No or minor effect, unless humic materials comprise a large portion of the BOD
Humic materials	Strong adsorbers of UV radiation
Oil and grease	Can accumulate on quartz sleeves of UV lamps, can absorb UV radiation
TSS	Absorption of UV radiation, can shield embedded bacteria
Alkalinity	Can impact scaling potential. Also affects solubility of metals that may absorb UV light
Hardness	Calcium, magnesium, and other salts can form mineral deposits on quartz tubes, especially at elevated temperatures
Ammonia	No or minor effect
Nitrite	No or minor effect
Nitrate	No or minor effect
Iron	Strong adsorber of UV radiation, can precipitate on quartz tubes, can adsorb on suspended solids and shield bacteria by adsorption
Manganese	Strong adsorber of UV radiation
pH	Can affect solubility of metals and carbonates
TDS	Can impact scaling potential and the formation of mineral deposits

2.4.1. UV transmittance (UVT)

UV transmittance (UVT; see Equation 2-3) measures how much UV light can pass through the fluid. A high UVT fluid allows more UV light to penetrate; resulting in better UV disinfection. A low UVT fluid is harder to disinfect with UV. The effect of humic materials, iron, TSS, etc. is accounted in on the measurement of UVT. Interestingly, the UVT will decrease as the TSS concentration increase, due to the shielding and absorption effect of the solids (Loge *et al.*, 1996; Scheible *et al.*, 1986).

$$100 \times \frac{I_d}{I_0} = UVT$$

Equation 2-3, UV transmittance calculation

Where:

I_d = Intensity after travelling a distance, d, through a given medium of absorbance, α (mW/cm^2)

I_o = Initial intensity (mW/cm^2)
UVT= UV transmittance (%)

The UVT of fluid is standardized as UVT_{254}, where is the transmittance of 254 nm light through 1 cm thick of the fluid. This value can be obtained by a spectrophotometer, and USEPA *et al.* (2006) gives a full detail of the procedure. In a wastewater treatment plant, long term UVT monitoring is usually required before a UV reactor is designed and installed in the plant (Trojan Ltd, 2009; USEPA *et al.*, 2006).

2.4.2. Total suspended solid (TSS)

The effect of TSS on UV disinfection is complicated. Some studies have found that an ingresses concentration of TSS has a negative relationship with the UV disinfection (Johnson & Qualls, 1985; Loge *et al.*, 1996; Scheible *et al.*, 1986). Lindenauer and Darby (1994) suggest that increased TSS levels would lead to increased cell photoreactivation; because less UV light is delivered into the cells. Both Loge *et al.* (1996) and Scheible *et al.* (1986) suggest the presence of suspended solid will cause scatter effect and provides shielding for microorganism, reducing the delivered UV light. However, Whitby and Scheible (2004) found the propagation of UV light is not affected if the TSS is lower than 50 mg/L. Furthermore, some studies suggest the effect of TSS on UV disinfection not only depends on TSS concentration, but also the particle size and how the bacteria are embedded in particles (Emerick *et al.*, 1999; Madge & Jensen, 2006; Nelson, 2000). Madge and Jensen (2006) found that suspended solids less than 5 micron have no effect on UV light propagation. Emerick *et al.* (1999) found that UV disinfection is unexpectedly better in stabilization pond effluent than ordinary secondary wastewater effluent (aerated lagoon); even though the stabilization pond effluent contains higher TSS concentration and lower UVT. Later, Nelson (2000) suggested that the degree to which coliform are embedded in stabilization pond effluent is different from the secondary treated wastewater effluent; hence, the difference in UV disinfection. The suspended solids in stabilization ponds are mainly algae (Nelson, 2000), which provide bacteria with no refuge from the UV light. In contrast, the solids in treated secondary wastewater can be soil or organic/inorganic matters, which can contain the bacteria, providing shielding protection. This suggests that the concentration, particle size and types of TSS play important roles in affecting UV disinfection.

2.4.3. Microorganism concentration

The microorganism concentration in wastewater can affect the UV disinfection. The concentration of the microorganism could affect the UVT of the fluid (Irvine *et al.*, 2002), and therefore the UV disinfection. In addition, it is believed that greater microorganism concentration would result in more microbial inactivation (greater log reduction). The reaction rate of a first order reaction will be elevated as the reactant concentration is raised, because of the increases of molecule collision probability. Similarly, high concentration of microorganism provides a better chance for UV light to reach the microbial cells, and therefore allows more inactivation. This is partially confirmed by Emerick *et al.* (1999) study. The results of the study showed that the microorganism in the tested wastewater would be harder to disinfect after the concentration is lower than certain level. This is commonly known as the tailing region (which will be discussed in section 2.5) and is attributed to the shielding effect from suspended solids (Emerick *et al.*, 1999). However, the results also hint the effect of the microorganism concentration, as the microorganism can be easily disinfected initially.

2.5. UV dose

The UV dose delivered by a reactor is the key parameter that governs the disinfection performance (Trojan Ltd, 2009). UV dose is the time integral of UV intensity (energy flux) of the target object (see Equation 2-4).

$$D = \int I \, dt$$

Equation 2-4, UV dose calculation

Where:

D = Applied ultraviolet dose (mW s/cm^2)
I = Intensity (mW/cm^2)
t = Retention time (s)

At a given UV dose, UV reactors should have the same performance, regardless of whether the dose is obtained by high UV intensity with short exposure time or low UV intensity with long exposure time (Oliver & Cosgrove, 1975). However, Sommer *et al.* (1998) suggest that at a given UV dose, if the UV intensity is too low, the damaged cells would have more chances to be repaired than in high UV intensity; hence less microorganism disinfection.

The relationships between UV dose and the inactivation of the microorganism are usually presented as microbial UV dose response curves, and the procedure of construing the microbial UV dose response curves is given by USEPA *et al.* (2006). Figure 2-10 shows the UV dose response of some microorganism.

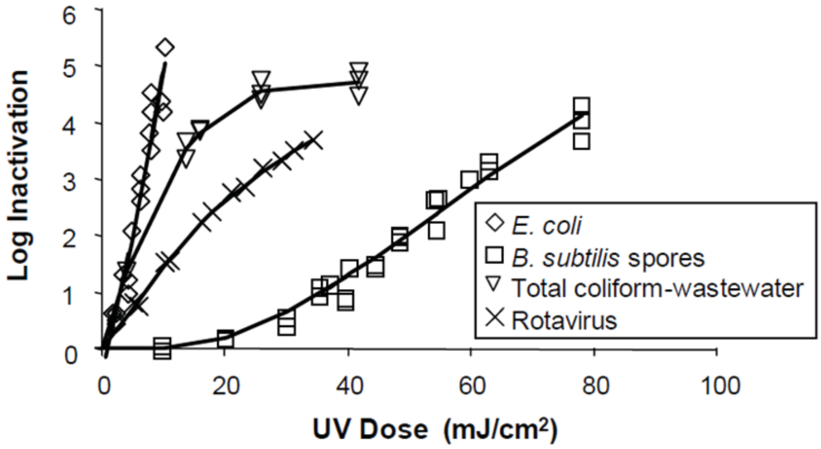


Figure 2-10, Dose response curve of microorganisms (Chang *et al.*, 1985)

The shape of a microbial UV dose response is affected by the characteristics of the microorganism and growth medium (USEPA *et al.*, 2006).Generally, three regions can be identified in a microbial UV dose response curve: the shoulder, linear and tailing regions.

In the shoulder region (at low UV dose), little inactivation occurs (e.g. *B.subtilis* spores in Figure 2-10), a result which is attributed to dark and photo repair mechanisms (Morton & Haynes, 1969). In many cases, microorganisms have no shoulder region in their microbial UV dose response curve (e.g. *E. coli, Total coliform and Rotavirus* in Figure 2-10).

In the linear region (after the shoulder region), the inactivation of microorganisms increase linearly as UV dose increases. This is the region that the log inactivation of microorganisms can be approximated based on the classical first order kinetic expression model (Scheible *et al.*, 1986), as shown in Equation 2-5

$$\log inactivation = \log \frac{N_0}{N} = kIt$$

Equation 2-5, First order kinetic expression model for UV disinfection

Where:

N = bacteria concentration after disinfection

N_o = the initial bacteria concentration
k = the first order decay constant
I = the light intensity
t = the exposure time

This first order kinetic expression model is only satisfactory for the microorganism that does not have shoulder and tailing region (Iranpour *et al.*, 1999). Above a certain UV dose, the microbial UV dose response is in the tailing region, in which there is little improvement of inactivation as UV dose increases (e.g. *Total coliform* in Figure 2-10). Many studies agree that the tailing region is attributed to the suspended solid in the fluid medium (Emerick *et al.*, 1999; Loge *et al.*, 1996; Scheible, 1987). The microbial cells can be embedded in a solid, which provides refuges to the cells from UV light; therefore the cells are more resilient to the UV light (Nelson, 2000). This indicates that as the log inactivation increases, of which the remaining bacteria in the fluid decreases, the remaining bacteria will become more difficult to be inactivated than the initial bacteria.

2.6. The effect of hydraulics on UV disinfection

The hydraulics of UV reactors plays an important role in UV disinfection. A good hydraulics design reactor can significantly reduce short-circuiting and dead spaces; hence allowing higher level of disinfection (Jolis *et al.*, 1999). The following sub-sections will discuss how the UV dose is affected by the reactor hydraulics.

2.6.1. Plug flow hydraulics vs. complete mix hydraulics

Qualls and Johnson (1985) found that a UV reactor with a small dispersion coefficient has better disinfection performance than a UV reactor with larger dispersion coefficient, even though the HRT of the reactors are the same. An ideal plug flow reactor has a dispersion coefficient of zero and a complete mix reactor has a dispersion coefficient of infinity, and will perform better than a complete mix reactor, at a given HRT (Forney *et al.*, 2003).

Plug flow reactors are preferred for UV disinfection, because of the UV dose distribution (USEPA *et al.*, 2006). Two types of UV dose distribution could be obtained from UV reactors, as shown in Figure 2-11 .

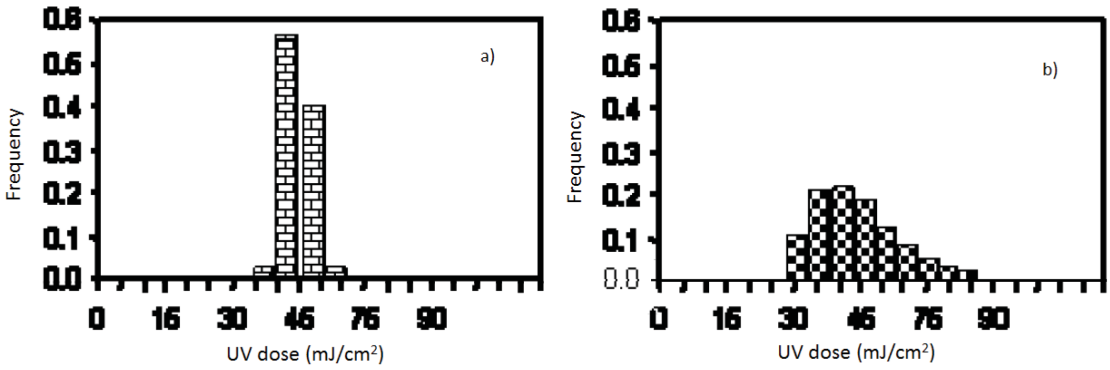


Figure 2-11, Two types of hypothetical dose distribution, adapted from USEPA *et al.* (2006, pp. 2-10)

As reactors have different dispersion coefficient, hence different resident time distribution, the UV dose distribution will vary depending on the resident time distribution. In CFD (computational fluid dynamics) modelling, the UV dose of each mesh point can be calculated; thus, the UV dose distribution of the reactor can be predicted. Figure 2-11 shows that UV reactors could have a high frequency and narrow range of UV dose (referred as type a reactor) or a low frequency and board range of UV dose (referred as type b reactor). USEPA *et al.* (2006) suggests that type a reactor is preferred for UV disinfection, and generally is a plug flow reactor. For example, a type of bacteria needed a UV dose of 40 mJ/cm^2 or greater to be inactivated. Although a portion of the fluid in the type b reactor receives UV dose up to 85 mJ/cm^2, of which the microorganisms will be surely inactivated; there is a portion of fluid that only receives 30 mJ/cm^2, of which the microorganisms will not be disinfected. This means that type b reactors are energy inefficient. In comparison, most of the fluid in the reactor a receives 40 to 70 mJ/cm^2 of UV dose, which is sufficient to inactivate the microorganisms. Therefore, the type a reactor is more energy efficient than the type b reactor, in this case.

Even within the same reactor, hydraulics could have an impact on the UV disinfection. Both Wols *et al.* (2011) and Koutchma *et al.* (2004) found that certain degree of lateral mixing within the fluid (turbulent flow) can further improve the UV disinfection performance. Koutchma *et al.* (2004) believe that the turbulent flow enhance the lateral mixing of the fluid, increasing the chance of microorganisms expose to UV light; so, elevating the received UV dose of microorganisms. Overall, it is found that turbulent plug flow hydraulics is desirable for UV disinfection.

2.6.2. The effect of lamp spacing on UV disinfection

Lamp spacing (the distance between lamps) is an important factor for the reactor hydraulics. The lamp spacing does not only affect the distance that the UV light needs to travel in a UV reactor, but also the hydraulic flow. Iranpour *et al.* (1999) suggest that the lamp spacing is important for hydraulic behaviour, while the stage of scaling up a UV reactor, the size of the reactor, and number of lamps are less important. Lamp spacing of 7.5 cm (centre to centre; fluid layer of 2.5 cm) is usually used in UV reactor (Loge *et al.*, 1996; Trojan Ltd, 2013). Two studies have been found examining the effect of the lamp spacing on UV disinfection.

Scheible *et al.* (1986) compared two UV reactors, which had the same reactor size but different lamp spacing, as demonstrate in Figure 2-12. One of the reactors had a lamp spacing of 7.3 cm (Reactor A) and the other reactor had a lamp spacing of 3.55 cm (Reactor B). The result of the experiment showed that the lamp spacing had no effect on UV disinfection. However, the authors failed to account for the variation in treatment throughout the volume of Reactor B. While the overall treatment achieved by Reactor B was the same as Reactor A, there would have been sections of the Reactor B near or within the lamp array where treatment would have been better, due to the closer proximity of the lamps. This fact was not considered in the authors overall conclusions.

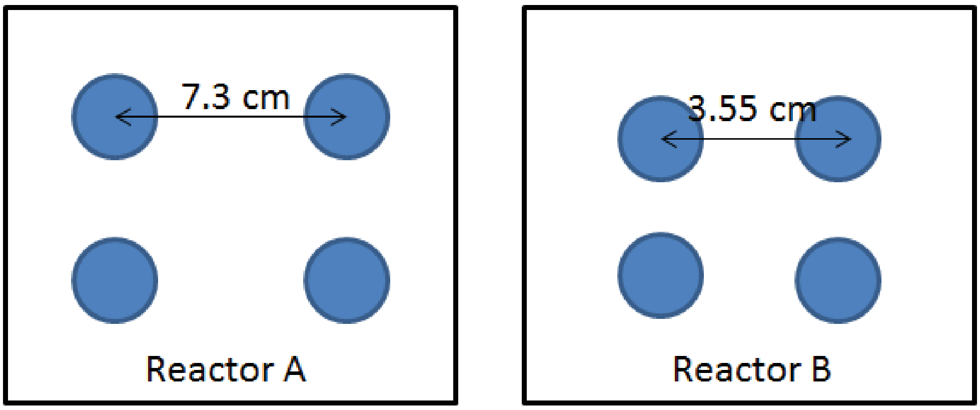


Figure 2-12, Hypothetical Reactor A and Reactor B

Qualls and Johnson (1985) also compared UV reactors to evaluate the effect of lamp spacing. In contrast to Scheible *et al.* (1986), the lamp spacing was reduced by compressing the reactor size. This meant the HRT of the reactor was also reduced. The results suggest that UV reactors will have poor performance when the UV lamps are spaced less than 5 cm apart. Qualls and Johnson (1985) believed that this decrease in performance is a result of HRT reduction (smaller volume). However, the authors disregarded the fact that the reduction of the lamp spacing decreases the UV light travelling distance, hence increasing the received UV light.

In a later study, Iranpour *et al.* (1999) proposed that the hydraulic boundary has a significant effect on UV disinfection. This can explain the observations from Qualls and Johnson (1985). When the spaces between lamps are compressed, the fluid velocity will increase in order to maintain the flow rate. Conversely, the layer of fluid on the surface of quartz sleeve flows at a decreased velocity due to the hydraulic boundary effect, which creates a velocity gradient across the fluid, as shown in Figure 2-13. This gradient means that fluid near the surface of the quartz sleeve receives a far greater UV dose (e.g. point B; high UV intensity and long exposure time) than the fluid flowing further from the quartz sleeve (e.g. point A; low UV intensity and short exposure time). This introduces variations in UV disinfection performance across the fluid, and therefore a poor treatment overall.

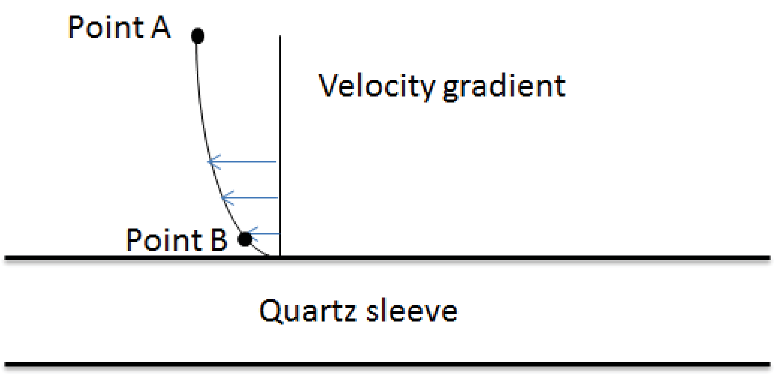


Figure 2-13, illustration of hydraulic boundary layer

Overall, the studies suggest that lamp spacing has a significant effect on UV disinfection, with lamp spacing greater than 5 cm recommended.

2.6.3. The effect of reactor configuration on UV disinfection

The UV dose distribution of a UV reactor is affected by the reactor configurations. Wols *et al.* (2011) modelled 17 different UV reactors (see Figure 2-14) and found that the reactor configuration of the reactor has significant effect on UV dose distribution. Based on the model, Wols *et al.* (2011) concluded that the VRD8 reactor (see section A in Figure 2-14; an L-shape reactor) has better disinfection performance than the helical reactor (see section B in Figure 2-14; an S-shape reactor). This agrees with Sozzi (2005) study, which the author modelled an L-shape and S-shape annular UV reactor and found that the L-shape reactor has less hydraulic short-circuit and dead space than the S-shape rector, therefore, better in UV disinfection. Overall, this demonstrate the importance of reactor configuration.

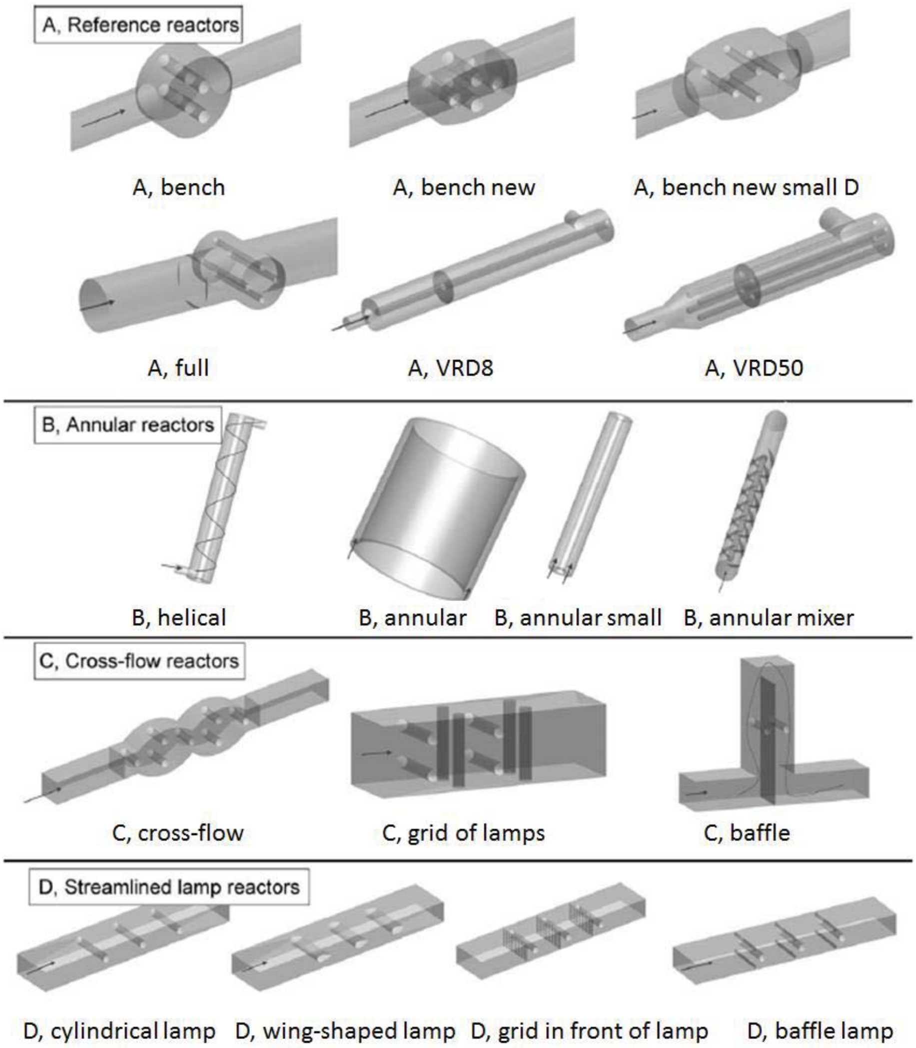


Figure 2-14, Different UV reactors that were assessed in Wols *et al.* (2011) study

2.6.4. A concept of supercritical flow UV disinfection

Thin film disinfection is one of the hydraulic configurations used for low UVT fluid, such as food and pharmaceutical products. In this method, a thin film of fluid is generated, and then disinfected by UV light irradiation. According to the Beer Lambert's law, UV light is significantly absorbed by the fluid as the light travels through the fluid, but UV light is effective for disinfection only when it is absorbed by microbial cells. Due to the thin film hydraulics, the light only needs to travel a short distance, and therefore avoids the lost due to the fluid absorption.

Some types of wastewater have a low UVT value (e.g. secondary treated wastewater), which does not favours the use of typical commercial UV reactors (commercial UV reactors see section 2.7.1). Although thin film UV reactors are good at treating low UVT fluid, this type of reactors are not used in wastewater treatment as they are not designed to handle a large volume of fluid in a short period. However, Professor Andy Shilton proposed that using thin film hydraulics while maintaining a high operated flow rate, known as supercritical flow hydraulics, would be applicable for wastewater disinfection, especially for wastewaters that has low UVT (Shilton & Sykes, 2009).

Supercritical flow is a type of hydraulic behaviour, where the fluid is 'stretched' (becoming a fast flow thin film of fluid), as a result of greater inertial force than viscous force on the fluid (Mott, 2006, p. 447). Any flow that has Froude number (see Equation 2-6) greater than one is classified as supercritical flow.

$$N_F = \frac{v}{\sqrt{g y_h}}$$

Equation 2-6, Froude number calculaiton for supercritical flow

Where:

N_F = the Froude number
V = the velocity of the flow
g= the acceleration of gravity, 9.81 m^2s^{-1}
y_h = the hydraulic depth

The UV light travels a much shorter distance in a supercritical flow reactor (2 mm, as used in the project prototype; see section 3.1.2) than in a typical commercial UV reactor (generally 2.5 cm, see section 2.6.2). In theory, a large amount of UV light could be preserved by using the supercritical flow hydraulics when the UVT of the fluid is low, because of the short travelling distance. This means that the microbial cells in the fluid would receive a much higher UV intensity in the supercritical flow UV reactor than in a typical commercial UV reactor. However, the supercritical flow UV reactor would have a much shorter HRT than a typical commercial UV reactor, due to the hydraulic configuration, and therefore provides a shorter UV exposure time. Despite this shorter HRT, it is believed that the high UV intensity could compensate the short UV exposure time (according to Equation 2-4). Therefore, the supercritical flow UV reactor would provide a higher UV dose than a typical commercial UV reactor when treating a low UVT wastewater.

In order to test the hypothesis that proposed by Professor Shilton, Shilton and Sykes (2009) developed a supercritical flow UV reactor as shown in Figure 2-15. This supercritical flow UV reactor was then compared against two commercial UV reactors (see Figure 2-16 and Figure 2-17) in the laboratory and at a wastewater treatment plant.

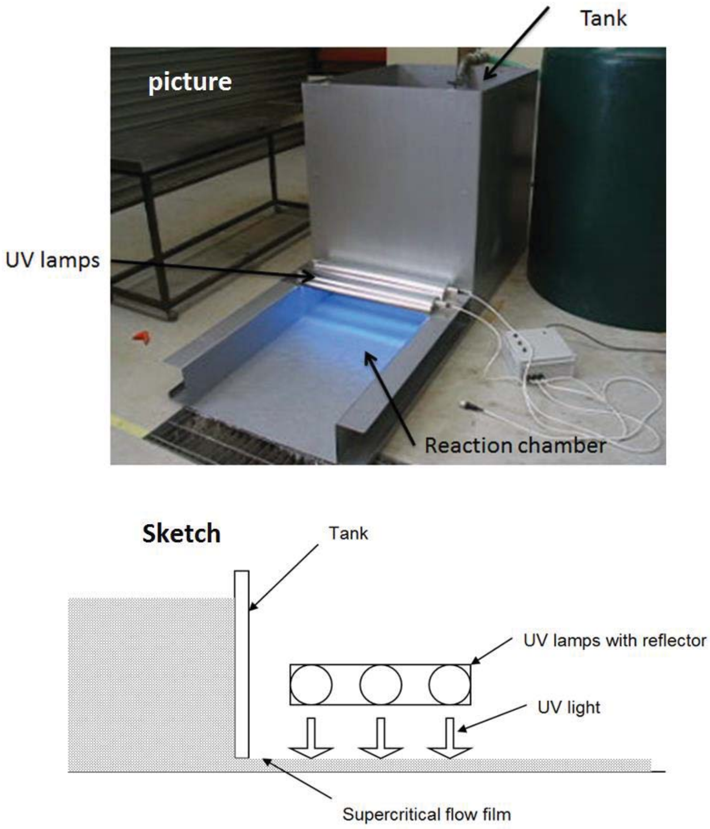


Figure 2-15, The supercritical flow UV reactor (Shilton & Sykes, 2009)

Figure 2-15 shows the picture and sketch of the supercritical flow UV reactor. A thin film of supercritical flow fluid can be generated, on a reaction chamber, by pushing the fluid through a thin gap between a sluice gate and the reaction chamber. The thin film is then disinfected by UV light irradiation. The reaction chamber of the reactor is 1.2 m long and 0.8 m wide, and the reactor tank is 1 m long, 1 m wide and 1.2 m high (Shilton & Sykes, 2009). Low-pressure mercury lamps are used in the reactor (no quartz sleeve) and the lamps are partially covered by parabolic reflectors.

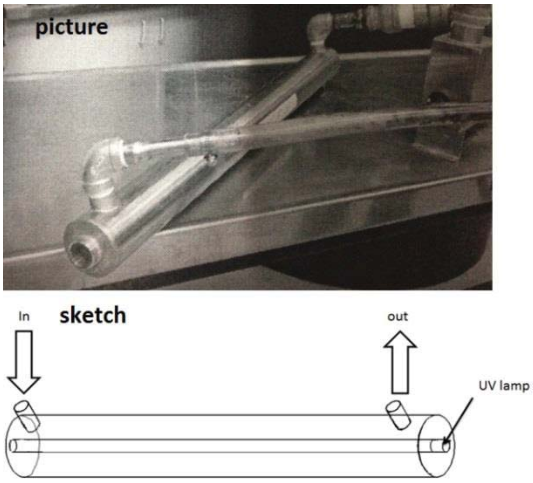


Figure 2-16, Steriflo 900 (Shilton & Sykes, 2009)

Figure 2-16 shows the picture and sketch of one of the commercialized UV reactor, Steriflo 900, which was used for comparison with the supercritical flow reactor. The reactor is a product from Contamination Control Ltd, of which is 0.85 meters long and 0.12 meters in diameter. A low-pressure mercury lamp is contained in a quartz sleeve in the centre of the reactor. The fluid is disinfected by UV light, as it flows through the empty space between outer surface of the quartz sleeve and inner surface of reactor wall. It is designed for treating farm wastewater. The reactor has a treatment capacity of 2.5 to 3.5 m^3 per hour (Shilton & Sykes, 2009).

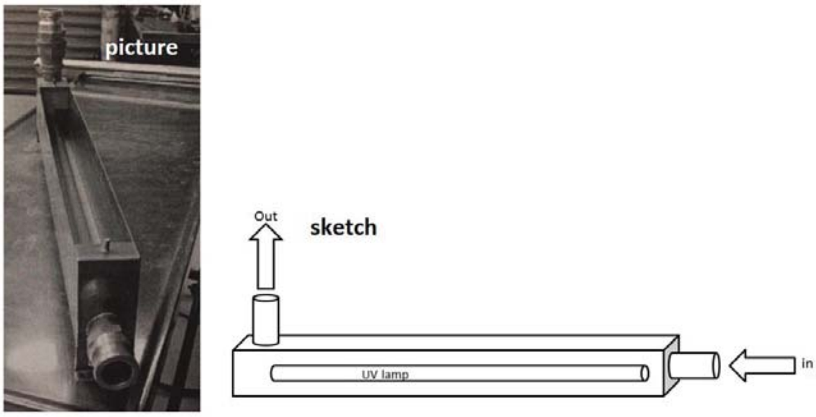


Figure 2-17, Steriflo Channel reactor (Shilton & Sykes, 2009)

Figure 2-17 shows the picture and sketch of the other commercialized UV reactor, Steriflo Channel, which is manufactured by the same company as Steriflo 900. The reactor is 0.85 m long, 0.4 m wide and 0.4 m height. Again, a low-pressure mercury lamp is used and the lamp is contained inside a quartz sleeve.

The supercritical flow UV reactor and the commercial UV reactors were compared on the basis of watt per flow ratio, which Shilton and Sykes (2009) believed could be a proxy for UV dose. The supercritical flow reactor performed better than the commercial UV reactors in the laboratory tests with the low UVT synthetic wastewater. However, two out of three trials at the wastewater treatment plant, the supercritical flow reactor did not perform as well as the commercial reactors. The UVT of the wastewater and the variation in the experimental results was not reported, so it is difficult to know why this occurred. Overall, some promising results were found, but a further investigation will be needed to confirm the feasibility of a supercritical flow UV reactor for wastewater disinfection.

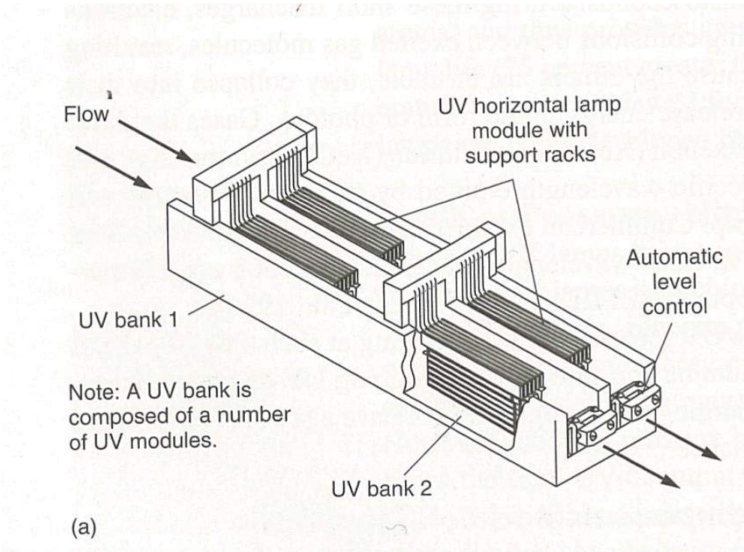
It is necessary to acknowledge that the supercritical flow UV reactor has a non-submergible UV lamp configuration (UV lamps are not submerged in the fluid). A significant amount of UV light can be lost in this configuration due to the reflection off the surface of the fluid (see section 2.1.1). In addition, most of the UV light is not directly delivered into the fluid, but reflected and then delivered into the fluid via the reflectors placed above the lamps (see Figure 2-15). As mentioned in section 2.1.1, portion of UV light will be absorbed by the reflective material, every time the light is reflected. Based on this, Bolton and Cotton (2008) believed that a submergible UV lamp configuration (e.g. typical commercial UV reactors; see section 2.7.1) has higher efficiency in delivering UV light into the fluid than the non-submergible UV lamp configuration. However, with low UVT fluid disinfection, the loss of UV light as it passes through the fluid will be significant. This means that the loss due to reflection in the supercritical flow reactor might be lower than the loss due to the low UVT fluid in a typical commercial UV reactor.

2.7. Prior art

Previous sections have discussed the factors that could affect UV disinfection and propose the idea of supercritical flow UV disinfection. This section will review some of the prior art of UV reactor. The section will first introduce the common commercial UV reactor designs, and then the relevant UV reactors from literature and patent documents. The point of reviewing the prior art is to indicate the potential patentability and the novelty the method. It is not possible to review the entire patent in this project. The comprehensive patent review would need to be conducted by a professional patent consultant, if it is required in the future.

2.7.1. Common design in wastewater treatment

Two types of UV reactors can be commonly found in commercial markets and wastewater treatment plants; open channel UV reactors and close channel UV reactors (see and Figure 2-19). As the name implies, fluid is not enclosed in an open-channel UV reactor and is enclosed in a closed-channel UV reactor. An opened-channel UV reactor can have horizontal UV lamp configuration or vertical UV lamp configuration, as shown in Figure 2-18. Similarly, a closed-channel UV reactor can have perpendicular (relative to the flow direction) UV lamp configuration and parallel UV lamp configuration.



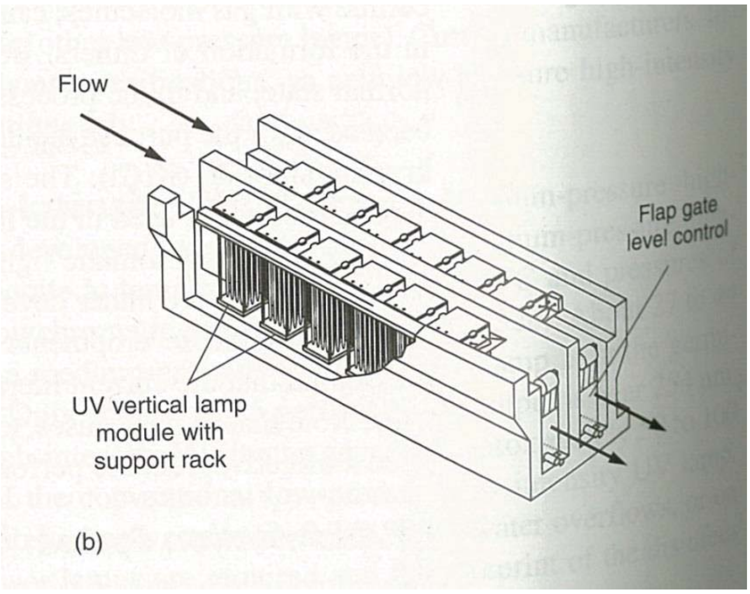
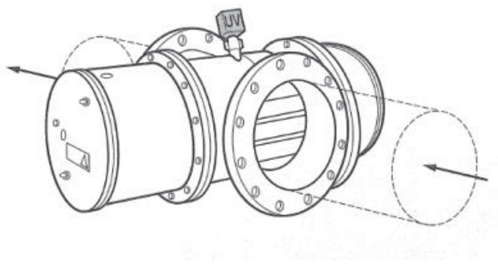
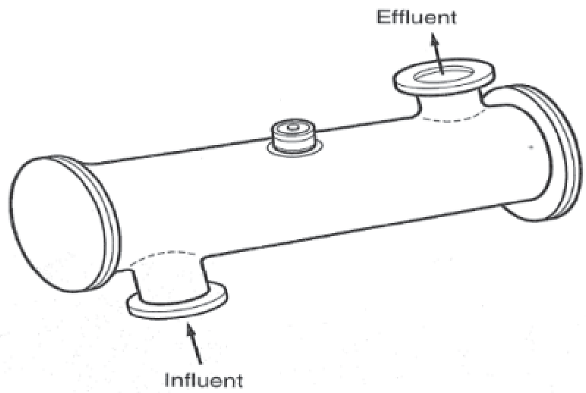


Figure 2-18, Typical open channel system, (a) horizontal lamps position; (b) vertical lamp position (Metcalf & Eddy, 2003, p. 1302)



a) UV lamps perpendicular to the flow



b) UV lamp parallel to the flow

Figure 2-19, Typical close channel system, (a) perpendicular lamp position; (b) parallel lamp position (Metcalf & Eddy, 2003, pp. 1304-1305)

Inside these UV reactors, low-pressure mercury lamps or medium-pressure lamps can be used. The lamps are contained in quartz sleeves, preventing the lamps being wet. Fouling is a common problem found on UV disinfection, where a layer of material accumulates on the surface of quartz sleeves (USEPA *et al.*, 2006). As a result, the efficiency of UV lamp decreases. Therefore, most of UV reactors have automatic quartz sleeves cleaning mechanism installed.

2.7.2. Review of thin film UV reactors

Since no design has been found on claiming supercritical flow UV disinfection, thin film UV reactors are reviewed, as thin film is one of the key characteristics of supercritical flow. In addition, reactors that have non-submergible UV lamp configuration are reviewed, as this configuration is a consequent of supercritical flow. The reviewed reactors are found from literature and patent documents, and Appendix 2 shows all the reviewed patents (only relevant designs are discussed in this section).

2.7.2.1. *A thin film beer disinfection device*

Lu *et al.* (2010) studied a thin film UV reactor for beer sanitization. Figure 2-20 shows the design of the thin film reactor. Thin film is generated by allowing fluid flow through a thin gap between two reactor sidewalls, of which the sidewalls distance is adjustable by a regulating valve. UV light is supplied by medium-pressure mercury lamps and evenly distributed on the inner surface of the sidewalls via the fibre cluster. Electric fans are used in order to prevent overheating of the lamps.

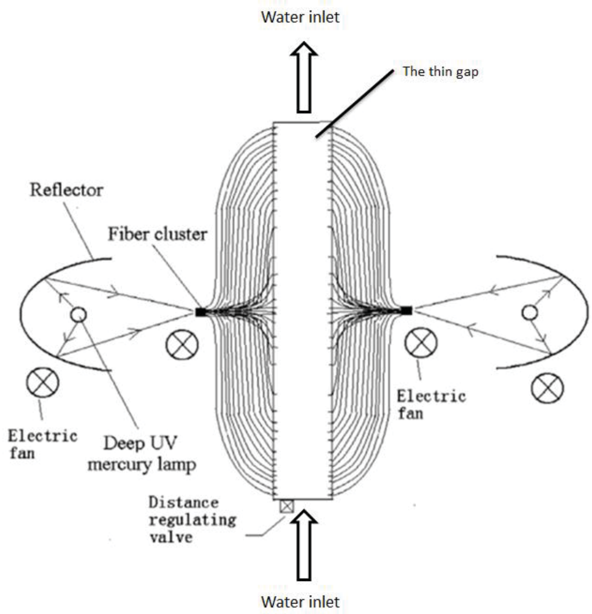


Figure 2-20, UV reactor in Lu *et al.* (2010) study

The reactor would be expected have better performance as the film thickness or the flow rate decrease. The received UV intensity of the beer would increase as the film thickness decrease (according to Beer Lambert's Law), and the UV exposure time would increase as the flow rate decrease. Therefore, the beer would receive a higher UV dose as these two factors decrease, and this is what was found, indeed. The results of Lu *et al.* (2010) shows that the reactor at a higher flow rate setting could achieve a better performance than at a lower flow rate setting; if the higher flow rate setting has a thinner film thickness than the lower flow rate setting, as indicated in Table 2-2. For example (the yellow cells), the reactor at a flow rate of 5 l/h and film thickness of 2.5 mm has better performance (less *E. coli*) than the reactor at a flow rate of 3 l/h and film thickness of 5 mm. likewise, the green and blue cells have similar observations. The reduction in film thickness increase UV intensity in the beer; therefore, offsetting the decrease of the UV exposure time due to the increase flow rate. As a result, the beer receives a higher UV dose; hence, the reactor has better performance. While these results confirm the concept of using thin film flow with UV disinfection, the design of the reactor was not such that it could accommodate significant flow rate relative to the supercritical flow reactor, proposed in this thesis.

Table 2-2, Lu *et al.* (2010) experimental data

flow rate l/h	*E. coli* present (CFU/ml) at the thin-film thickness of			
	2.5 mm	3.0 mm	3.5 mm	5.0 mm
3	0.78 ±0.24	0.87±0.15	0.98±0.24	1.22±0.13
5	0.82 ±0.21	1.18±0.16	1.92±0.10	2.45±0.18
7	1.53 ±0.11	1.80±0.1	2.01±0.11	2.34±0.16
10	1.98 ±0.10	2.13±0.24	2.20±0.12	2.68±0.34

2.7.2.2. Juice thin film disinfection devices

Koutchma (2008) studied two main types of laminar thin film juice/cider UV disinfection reactors (see Figure 2-21), which were the CiderSure (reactor A) and Taylor-Couette flow UV reactor (Reactor B)

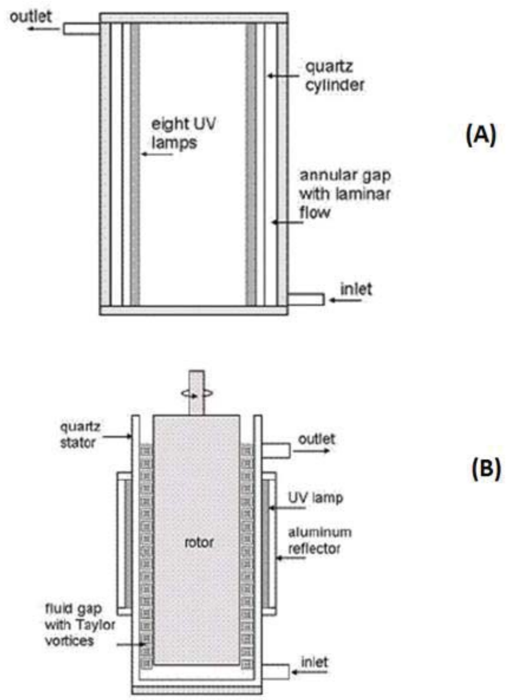


Figure 2-21, Typical thin film UV reactor for juice/cider (Koutchma, 2008)

The CiderSure reactor is a product from FPE Inc., Macedon, NY. In the reactor, eight low-pressure mercury lamps are contained by one big quartz cylinder. Thin film is generated by pumping juice through a thin annular gap of 0.8 mm, between the inner surface of the reactor wall and outer surface of the quartz sleeve, as shown in Figure 2-21 A. CiderSure is a common reactor used in food industries (Koutchma *et al.*, 2004).

The Taylor-Couette flow UV reactor was invented by Forney and Pierson (2011). Thin film is generated by pumping fluid through the annular gap between the surface of rotor and inner surface of the stator (see Figure 2-21 B), which the gap can be as thin as 8 mm (Forney *et al.*, 2003). The UV light is supplied from the low-pressure mercury lamps, which are covered by aluminium reflectors and mounted on the outer wall of the reactor. The rotor will rotate during the disinfection, reducing the thickness of hydraulic boundary layer. As a result, the residence time distribution is improved; hence the UV dose distribution. Taylor-Couette flow UV reactors were proven to be more effective than a conventional single lamp UV reactor in wastewater treatment (Forney *et al.*, 2003). Originally, Taylor-Couette flow UV reactors were designed for wastewater treatment application; however, Forney *et al.* (2003) later pointed out that the fouling effect which is a major drawback of the reactor for wastewater treatment. Ye *et al.* (2005) found that using the Taylor-Couette flow reactor for juice disinfection had a 3 to 5 log improvement in activation, compared to a commercial fruit juice UV reactor (a simple channel flow between concentric cylinders). Therefore, Taylor-Couette flow reactor is now one of the most common juice disinfector in food industries (Koutchma, 2008).

Both the CiderSure and Taylor-Couette flow reactor have non-submergible UV lamp configuration, but the reactors are not supercritical flow UV reactor. The flow rate of the fluid in a CiderSure is too slow to be a supercritical flow. The fluid in the Taylor-Couette flow reactor is technically classified as a closed channel flow, where a close channel flow cannot be classified as supercritical flow.

2.7.2.3. Centrifugal thin film disinfection reactor

Oppenheimer *et al.* (1959) designed a centrifugal thin film UV disinfection reactor (see Figure 2-22), for pharmaceutical fluid treatment. The fluid is ejected onto the internal wall of a cylindrical tube, generating centrifugal forces to spread the fluid on the wall as a thin film. UV lamps are placed in the centre of the reactor (not shown in Figure 2-22) to provide UV light for disinfection. The reactor was further studied by Milzer *et al.* (1954), who found that the reactor could effectively inactivate viruses from tissue culture. Nevertheless, Oppenheimer *et al.* (1959) suggest that the reactor can only operate at relatively low flow rate, in order to generate a thin film.

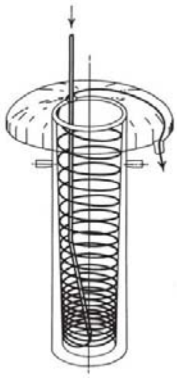


Figure 2-22, UV reactor configuration in Oppenheimer *et al.* (1959)

The design could classify as a non-submergible UV lamp reactor, as the lamps are place in the middle of the reactor and not submergible. The fluid of the reactor is driven by the centrifugal force. However, the flow of the reactor is not what would naturally be considered supercritical flow hydraulics, as according to Mott (2006, p. 460) this term is only applies to fluid on an open channel.

2.7.2.4. Bell shape thin film disinfection

A bell shape thin film UV reactor (see Figure 2-24) was designed by Shama *et al.* (1996). A falling thin film is generated by the specially designed valve. As shown in Figure 2-23, fluid enters the valve through the inlet tube, flows down in the annular space between nozzle casing and central barrel, impacts on the disc and flows laterally outward, forming a bell shaped thin film. UV light for disinfection is provided by low-pressure mercury lamps (as shown in Figure 2-24), of which one is positioned inside the bell shaped fluid (contained by the quartz sleeve) and others are optionally allocated outside of the bell shaped fluid. In the study, Shama *et al.* (1996) found that the treatment capacity of the reactor is small, so more than one reactors would be needed, in parallel, to handle large volume fluid disinfection.

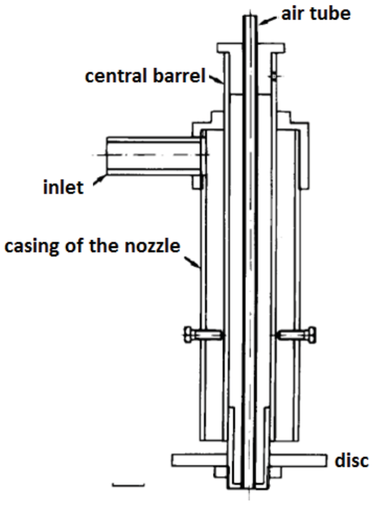


Figure 2-23, Special valve design for the reactor (Shama *et al.*, 1996)

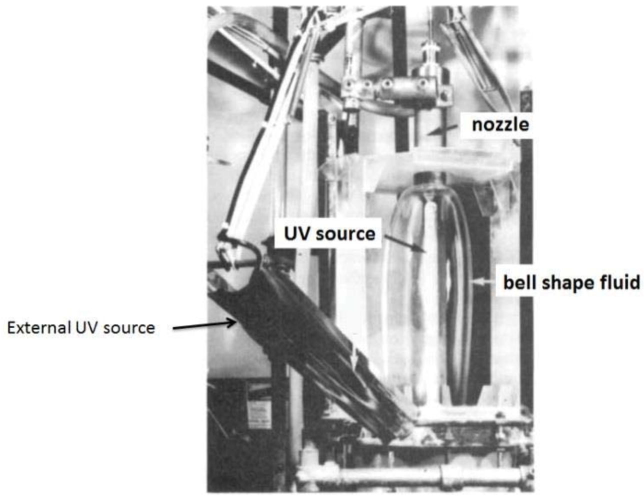


Figure 2-24, UV reactor designed by Shama *et al.* (1996)

The reactor could arguably classify as a non-submergible UV lamp reactor, as the lamp are placed in the middle of the bell and not submerged. The reactor is not a supercritical flow UV reactor, as a falling type of thin film cannot be classified as a supercritical flow.

2.7.2.5. Open channel low head UV reactor

The open channel, low head UV reactor (see Figure 2-25) was invented by Kora Ltd. (Israel) for aqua-cultural water disinfection and reclamation (Mamane *et al.*, 2010). The reactor cannot be classified as a thin film disinfection reactor, as the fluid in the open chamber is 10 to 15 cm thick. However, this reactor is discussed, because the reactor has the non-submergible UV lamp configuration.

The reactor consists of two parts, a rectangular chamber, which allows fluid to enter and exit and a UV source component (see Figure 2-26), which made up of UV lamps are UV reflectors. The fluid is disinfected by UV light, as it flows through the rectangular chamber, as shown in Figure 2-26.

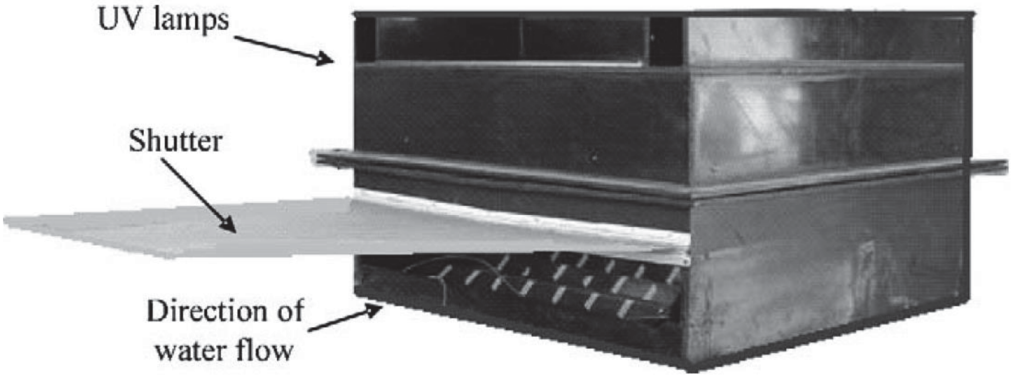


Figure 2-25, Open channel, low head UV reactor (Mamane *et al.*, 2010)

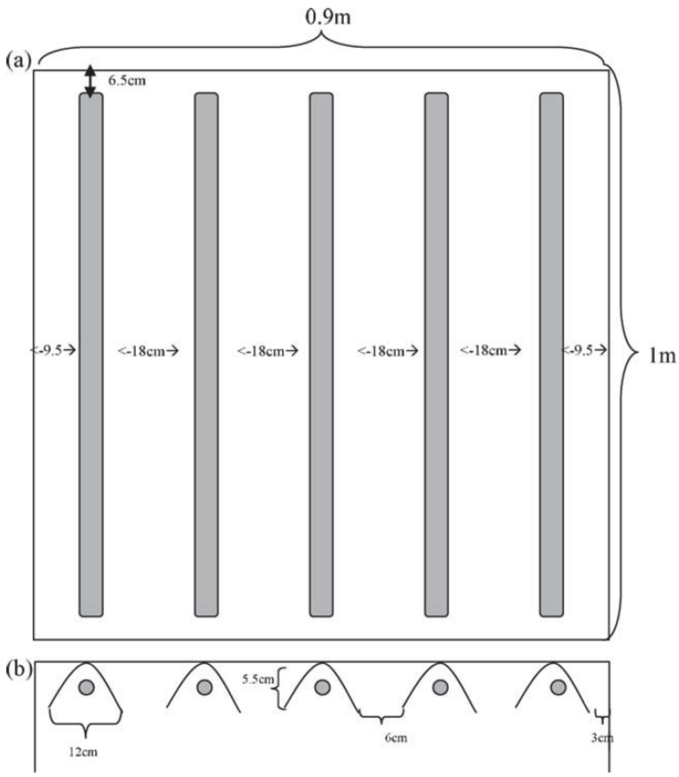


Figure 2-26, UV source component, (a) Top view of the reactor UV source; (b) Side view of reactor UV source (Mamane *et al.*, 2010)

Mamane *et al.* (2010) found that the reactor is not effective at delivering UV light into the fluid, as shown in Figure 2-27 (remember the water layer is 10 to 15 cm). Thus, the reactor would need a long retention time, in order to achieve high level of disinfection.

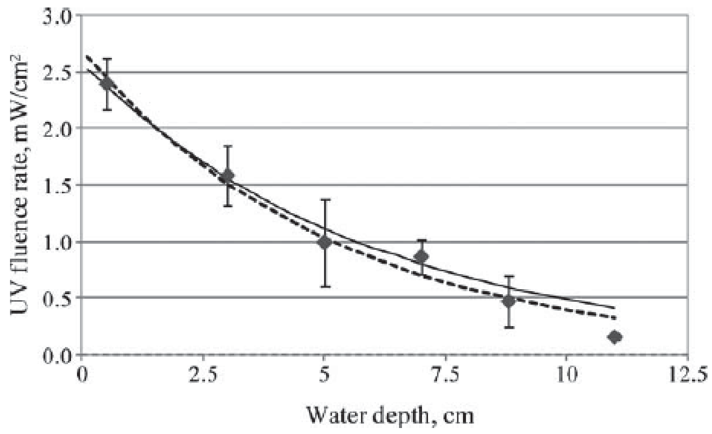


Figure 2-27, UV dose measurement of the open channel, low head UV reactor (Mamane *et al.*, 2010)

2.7.2.6. UV liquid steriliser (US 20120097862 A1)

The UV liquid steriliser (see Figure 2-28) is a thin film UV Reactor for drinking water treatment. Thin film is created by the fluid passing through an annular gap between the outer surface of the quartz sleeve and the inner surface of the reaction chamber. The gap can be 5 to 10 mm thick. The UV lamp and quartz sleeve in the reactor is elongated, extending the hydraulic retention time of the fluid. Specially designed mixing baffles are installed around the UV lamp. The baffles can enhance the mixing of the fluid in lateral direction, while minimizing the increase of dispersion coefficient.

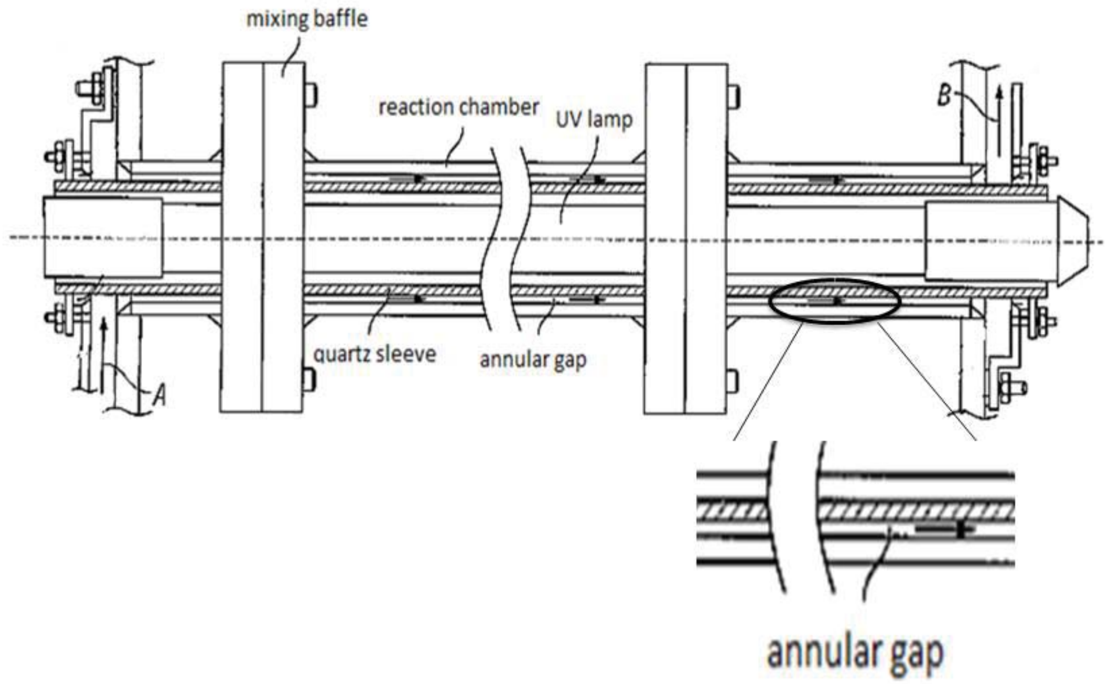


Figure 2-28, UV liquid steriliser (Snowball, 2012)

This reactor is not a supercritical flow UV reactor, as supercritical flow hydraulics is only applied to an opened channel. Also, the UV lamps in this reactor are submerged in fluid. Therefore, this reactor is not a supercritical flow UV reactor and does not have the non-submergible UV lamp configuration.

2.7.2.7. Fluid disinfection apparatus and method (US 20090004050 A1)

The fluid disinfection apparatus (see Figure 2-29) is a thin film UV reactor for low UV transmittance fluid disinfection, such as juice and soup. The thin film is created by passing the fluid through a thin channel between two UV transparent discs. The discs rotate in opposite directions to produce a uniform thin film, which is then disinfected by UV light from UV lamps. Snowball (2009) suggests that the UV transparent discs can be made of quartz. The UV lamps are allocated above and below the discs.

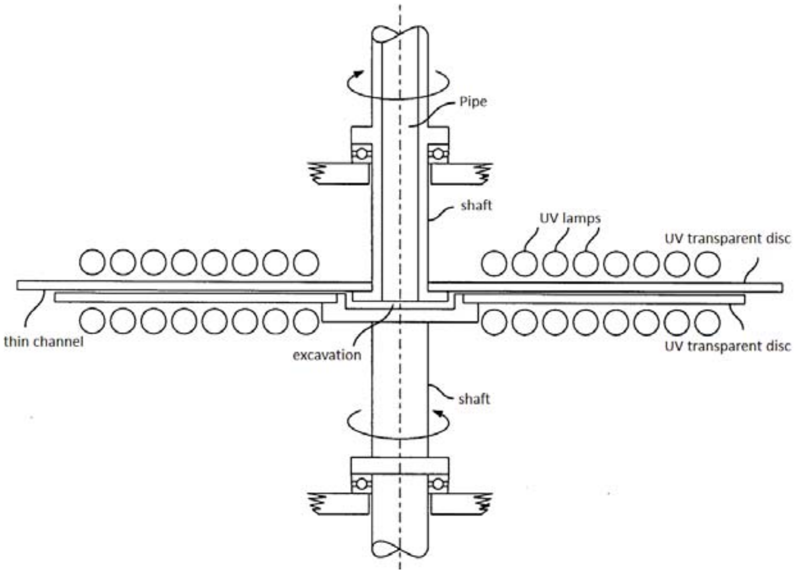


Figure 2-29, Fluid disinfection apparatus from Snowball (2009)

The reactor has the non-submergible UV lamp configuration. However, it is not a supercritical flow UV reactor, as the fluid is flow in a closed channel.

2.7.2.8. Fluid disinfection apparatus and system (EP 1865997 A2)

Similar to the design of US 20090004050 A1, the fluid disinfection apparatus (see Figure 2-30) is also a thin film UV reactor for low UV transmittance fluid disinfection, such as fruit juice and beverage syrups. Differently, the thin film is created by coating fluid on the surface of a roller. The thin film is then disinfected by UV light from the UV lamps, which are contained within quartz sleeves. The treated fluid is separated from the roller by an air knife, and discharged. Inside the reactor, the UV light is concentrated by using parabola shaped reflectors.

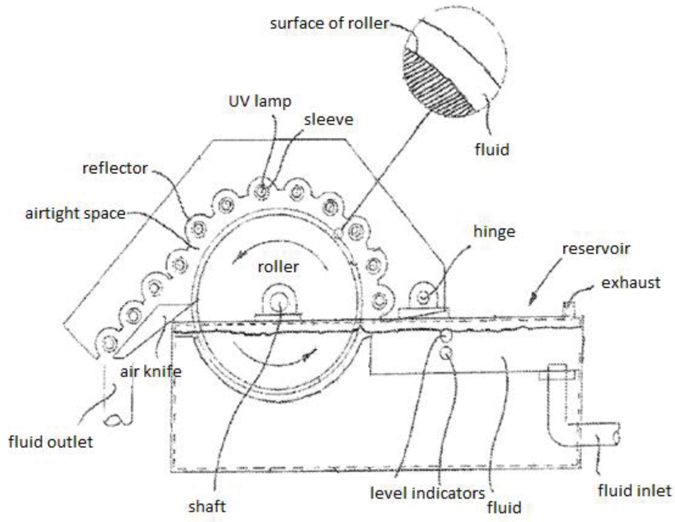


Figure 2-30, Fluid disinfection apparatus and system from Snowball (2007)

The reactor has a non-submergible UV lamp configuration. The UV lamps are covered by parabolic reflectors, which is similar to the supercritical flow UV reactor in Shilton and Sykes (2009) study(see section 2.6.4). Nevertheless, this reactor is not a supercritical flow UV reactor as the fluid is carried by the roller.

2.7.2.9. *Ultraviolet fluid disinfection system and method (US 6447720 B1)*

The ultraviolet fluid disinfection system in Figure 2-31 is designed for drinking water and wastewater treatment. Inside the reactor, fluid is forced to flow up by a vertical riser, which creates a thin layer of fluid at the surface of the vertical riser. The thin layer is then disinfected by UV light, which could be provided from UV lamps or UV LEDs. The treated fluid then flows over the vertical riser and is discharged. The reactor is debatably a thin film UV reactor; if only consider the thin layer of fluid at the surface of the vertical riser.

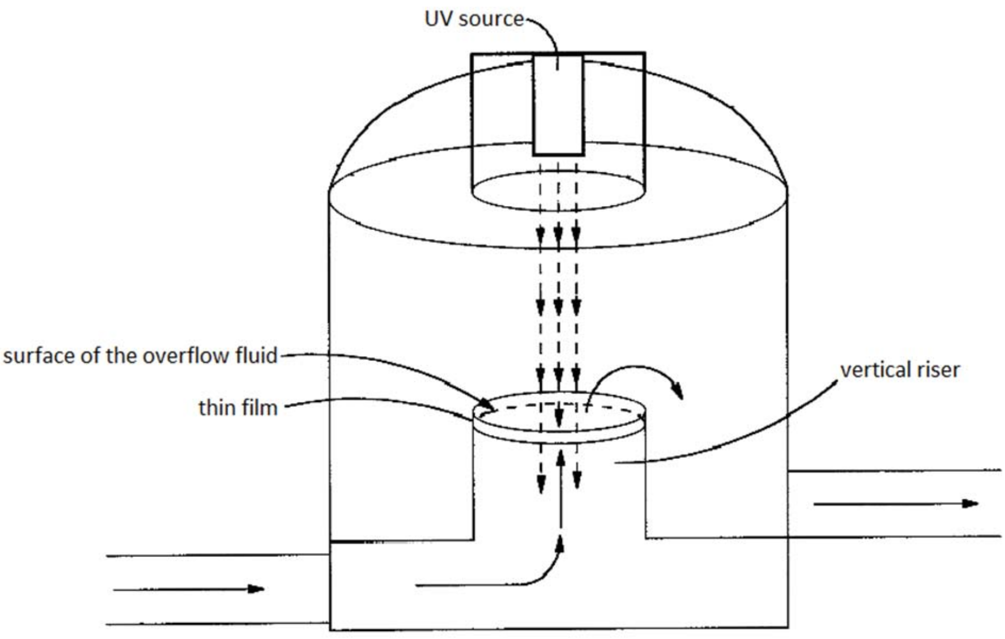


Figure 2-31, Ultraviolet fluid disinfection system from Horton *et al.* (2002)

The reactor has the non-submergible UV lamp configuration. However, the reactor is not a thin film reactor. The thin film here is not generated by the reactor, but by defining the boundary, where the thin film is defined as the fluid layer above the vertical riser. Therefore, this reactor is not a supercritical flow UV reactor.

2.7.2.10. Ultraviolet wastewater disinfection system and method (US 6403030 B1)

The ultraviolet wastewater disinfection system (see Figure 2-32) is a thin film UV reactor. It is an improved version of the design of US 6447720 B1. Fluid enters the reactor, flows up through the interior pipe, and then overflows on the surface of a plate via hole/holes, creating a thin film. The thin film is then disinfected, and discharged by UV light. The UV light in the reactor could be provided by UV lamps or UV LEDs.

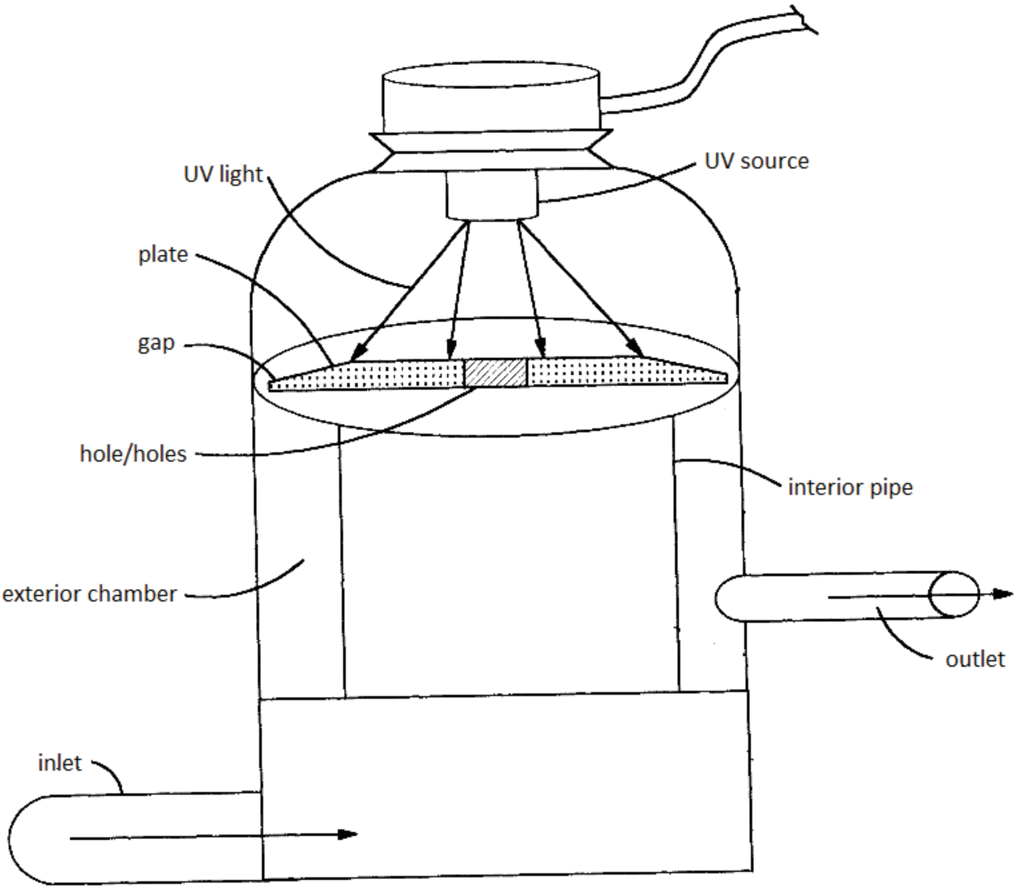


Figure 2-32, Ultraviolet wastewater disinfection system and method from Horton (2002)

The reactor has the non-submergible UV lamp configuration. However, the thin film of the reactor is not a supercritical flow. This is because supercritical flow only occurs when the inertial force is greater than the viscous force (Mott, 2006, p. 447), where the flow of the thin film is driven by gravitational force, which is unlikely to have greater inertial force than viscous force. Therefore, the reactor is not a supercritical flow UV reactor.

2.7.3. Reactors comparisons

The UV reactor studied in this thesis has the unique feature of applying supercritical flow hydraulics on UV disinfection. The UV lamps of the reactor are not submerged due to this hydraulics. Base on this, the supercritical flow UV reactor and the reviewed devices are compared in Table 2-3, and no supercritical flow UV reactor is found.

Table 2-3, comparison of prior art with project prototype

Patent / literature device	Supercritical flow	Discussion	Section	Non-submergible UV lamp	Reference
Supercritical flow reactor	**Yes**	**See section 3.1.1**		**Yes**	**N/A**
Beer UV reactor	No	Thin film UV reactor, but the flow rate is too slow to be supercritical flow.	2.7.2.1	Yes	Lu et al. (2010)
CiderSure reactor	No	Thin film UV reactor with closed channel flow and slow flow rate; therefore not a supercritical flow reactor.	2.7.2.2	Yes	Koutchma (2008)
Tayloer-Couette flow UV reactor	No	Thin film UV reactor with closed channel flow; therefore not a supercritical flow reactor.	2.7.2.2	Yes	Forney and Pierson (2011)
Centrifugal thin film disinfection reactor	No	Thin film UV reactor, but lack of information to determine whether is supercritical flow or not. The reactor is design for disinfecting pharmaceutical products and has slow flow rate. Therefore, it is unlikely to be used for wastewater treatment and it would not be a concern for future patent application.	2.7.2.3	Yes	Oppenheimer *et al.* (1959)
Bell shape thin film UV reactor	No	Thin film UV reactor, but uses falling film flow, so is not categorized as supercritical flow reactor.	2.7.2.4	Yes	Shama *et al.* (1996)
Open channel low head UV reactor	No	Not a thin film reactor and ineffective disinfection	2.7.2.5	Yes	Mamane *et al.* (2010)

US 20120097862 A1	No	Thin film UV reactor with closed channel flow, therefore, not supercritical flow reactor.	2.7.2.6	No	Snowball (2012)
US 20090004050 A1	No	Thin film UV reactor with closed channel flow, therefore, not a supercritical flow reactor.	2.7.2.7	Yes	Snowball (2009)
EP 1865997 A2	No	Thin film UV reactor, but the fluid is carried by the roller; therefore, not a supercritical flow reactor.	2.7.2.8	Yes	Snowball (2007)
US 6447720	No	Not a thin film UV reactor	2.7.2.9	Yes	Horton *et al.* (2002)
US 6403030 B1	No	Thin film UV reactor, but the flow rate of the fluid is too low to be supercritical flow.	2.7.2.10	Yes	Horton (2002)

2.8. Literature review summary

UV disinfection has been studied for many years. It is often used in water and wastewater treatment. One of the well-known disinfection mechanisms is DNA and RNA distortion due to the photoreaction. Nevertheless, the effect of wavelength on disinfection mechanism is still not fully understood. The major drawback of using UV disinfection is lack of disinfection residual, of which a UV damaged microorganism can be repaired by undergoes photoreactivation or dark repair. This reduces the disinfection efficiency.

UV light can be generated by different technologies; however, mercury lamp technology is currently the best technology. It was found that medium-pressure mercury lamps provide better disinfection than low-pressure mercury lamps. Nevertheless, Low-pressure mercury lamps are more often used, because of the long lifetime and high UVC efficiency.

UV disinfection can be affected the wastewater characteristics. UV transmittance (UVT) and total suspended solid (TSS) are the two major factors affect the wastewater disinfection. However, it is believed that the concentration of microorganisms has effect on UV disinfection. TSS is an interesting factor, as studies suggest that the concentration, particles size and types of solid can have effects on the UV disinfection.

UV dose is the key parameter to govern microorganism inactivation, which can be affected by the hydraulics of reactors. It is found that turbulent plug flow hydraulics is preferred in UV reactors. The lamp spacing in a traditional UV reactor is important, as it can affect the hydraulics and therefore the UV disinfection. Generally, a lamp spacing of 7.5 (centreline spacing) is preferred. The configuration of the reactor can also affect the hydraulics of the fluid. Thin film hydraulics has been used for low UVT fluid disinfection, but the hydraulics configuration often result a low flow treatment capacity.

Professor Shilton proposed that fast flow thin film hydraulics (supercritical flow) can be applied for wastewater disinfection, and promising results were found. Currently, no supercritical flow UV reactor for wastewater treatment has been found on any published documents. This indicates the patentability of the reactor. Therefore, a project to continuous the study of Shilton and Sykes (2009) – evaluating the feasibility of a supercritical flow UV rector was conducted

3. Method and materials

The experiments of the project are a continuous development process of Shilton and Sykes (2009). Two supercritical flow UV reactors and a control reactor were fabricated and tested on wastewater treatment sites. This section will provide the details of the reactors, instruments, wastewater sites, experimental procedures and methods of analysis.

3.1. Reactors

Three Reactors were tested in the project. The supercritical flow UV reactors used in the project (reactor A and B) are improved versions of the supercritical flow UV reactor as described in Shilton and Sykes (2009). Reactor A in Figure 3-1 is the second-generation supercritical flow prototype (referred as 2nd generation). Reactor B in Figure 3-1 is the third generation supercritical flow prototype, which is referred to as the 'project prototype' because this reactor was mainly studied throughout the project. Finally, the reactor C in Figure 3-1 is the control reactor, which is used to mimic a standard submersible UV lamp reactor from the commercial market. This reactor will be referred to as the 'commercial unit' in the project.

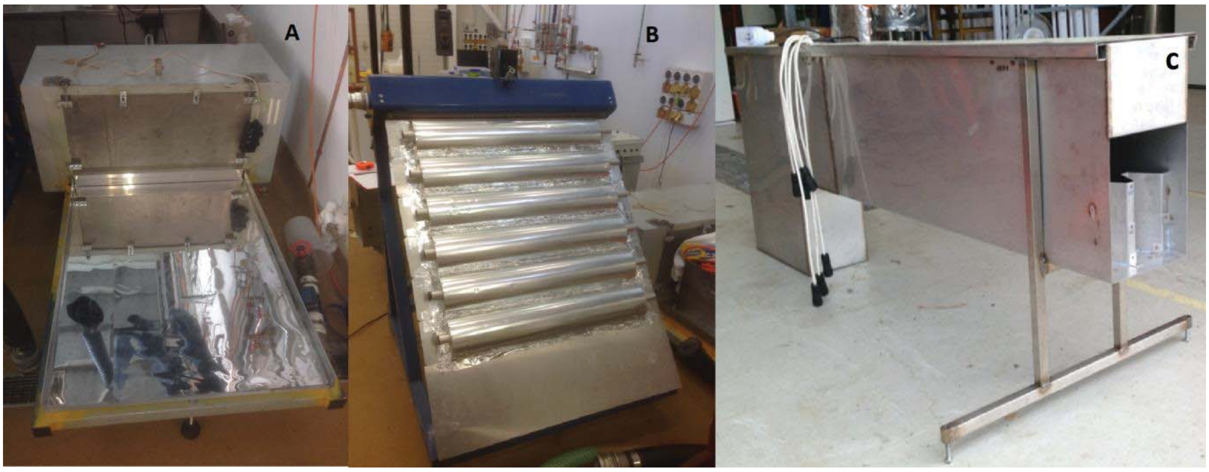


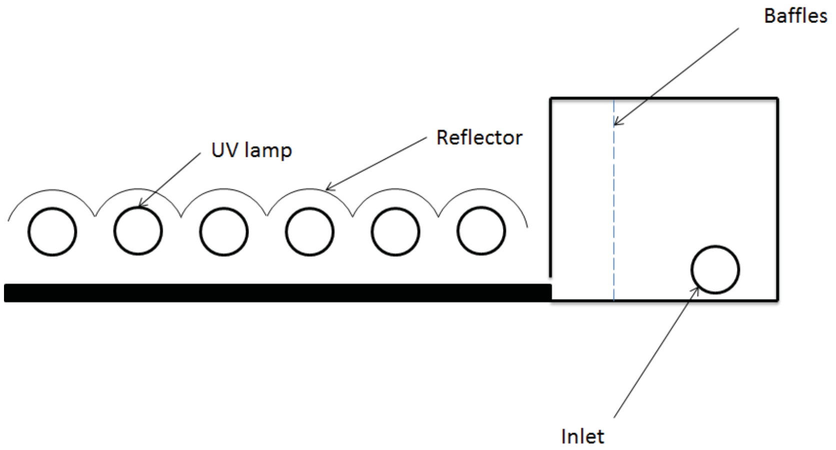
Figure 3-1, Pictures of the reactors in the project (A: the 2nd generation; B: the project prototype; C: the commercial unit)

3.1.1. The 2nd generation

The 2nd generation is a supercritical flow UV reactor. Supercritical flow is defined by calculation of the Froude number (see calculations in Appendix 3). It is an improved version of the supercritical flow UV reactor in Shilton and Sykes (2009). Similar to the reactor, the 2nd generation consists of two components, which are the reaction chamber (1100 long and

800 mm wide) and the UV source with the reflector. The base of the reaction chamber is overlaid a layer of polish aluminium material, which has UV reflectance 88% (according to the manufacture specification). Differently, the 2nd generation has a smaller closed tank (500 mm wide, 1100 long and 500 mm high), which is more convenient for transportation.

Figure 3-2 shows the sketch of the 2nd generation. A supercritical flow thin film can be generated by pushing fluid through an adjustable gap between a sluice gate and the base of the reaction chamber (see Figure 3-3). This thin film can be disinfected by UV light from the UV sources. There is a baffle inside the reactor tank, which is used to reduce the kinetic energy of the fluid inside the tank; hence producing a smooth thin film.



Note: not to be scale

Figure 3-2, Sketch of the 2nd generation

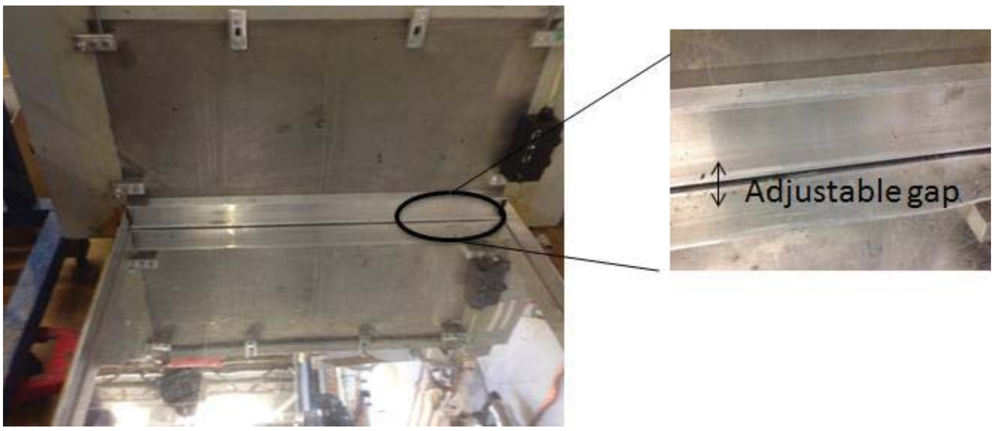
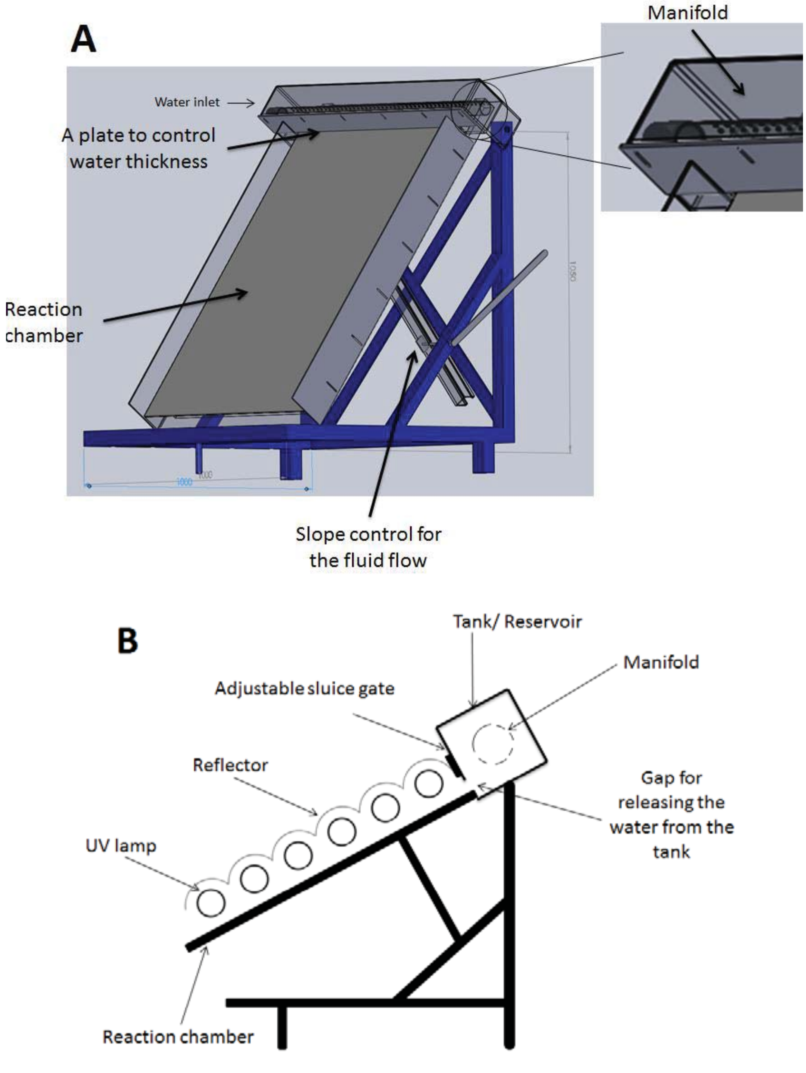


Figure 3-3, Adjustable gap of the 2nd generation

3.1.2. The project prototype

The project prototype is a supercritical flow UV reactor (calculation see Appendix 3) and an improved version of the 2nd generation. Similar to the 2nd generation, the reactor consists of two components, which are a slope adjustable reaction chamber (see Figure 3-4) and the UV source with the reflector. The size of the reaction chamber is the same as the 2nd generation, of which the dimensions are 1100 mm long and 800 mm wide. The mechanism of generating the supercritical flow thin film is also the similar to the 2nd generation. Differently, the project prototype has a smaller closed tank than the previous version (145 mm wide, 1000 mm long and 140 mm high). Inside the tank, a manifold is used instead of a baffle, where the manifold is a pipe which full of holes for fluid distribution (see Figure 3-4, A).



Note: not to be scale

Figure 3-4, Sketch of the project prototype; A: 3D sketch, B: 2 D sketch

3.1.2.1. Adjustable gap

At a given flow rate, the reduction of film thickness will decreases the HRT of the fluid; hence reduce the UV exposure time. However, the reduction of film thickness will decreases the travelling distance of the UV light, and therefore significantly increase the received UV intensity of the microbial cells in fluid. It is believed that the increases of UV intensity could compensate the decreases of UV exposure time, so that a thinner film would result a better UV disinfection. In order to confirm this hypothesis, a sluice gate was used in the project prototype to control the film thickness (see Figure 3-5).

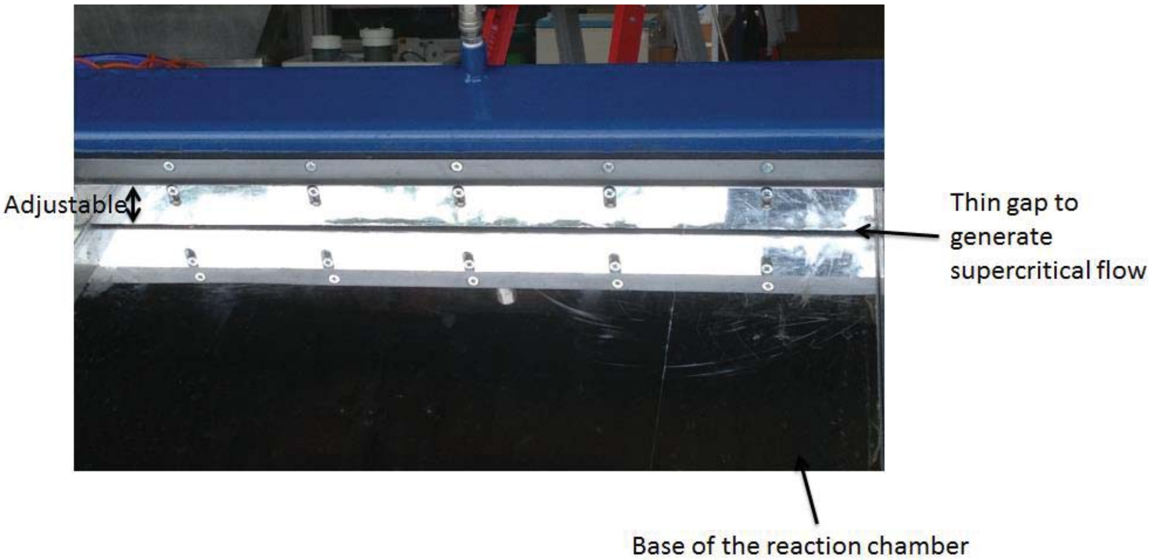


Figure 3-5, The adjustable sluice gate of the project prototype

As shown in Figure 3-5, the thickness of the film can be controlled by manipulating the gap between the sluice gate and the base of the reaction chamber. The surface of the sluice gate is coated with a layer of aluminium material to maximize the UV reflection. The minimum sluice gap of the project prototype is 2 mm. If the gap is smaller than 2 mm, leaking will occurred.

3.1.2.2. *Adjustable slope*

The fluid velocity in an open channel is a function of the channel slope. At a given flow rate, fluid velocity would increase as the slope increase; hence, the thickness of the fluid would decrease. In the case of the project prototype, the increase of the reaction chamber slope would increase the fluid velocity and reduce the film thickness. Given this, it was uncertain if the change of reaction chamber slope would have noticeable impact on the disinfection performance. Therefore, the slope of the reaction chamber is designed to be adjustable, as shown in Figure 3-6, in order to assess the effect of flow slope on UV disinfection. The range of the slope adjustment is from 0 (flat) to 60 degree.

Figure 3-6, Demonstration of flow slope adjustable of the project prototype

3.1.2.3. *Reflectors*

Two types of reflectors were tested in on the project prototype, which were the parabola (see Figure 3-7) and square (see Figure 3-7) shaped reflectors (specifications see Appendix 4). The parabola shaped reflector is carefully designed to focus the UV light, in which the lamps are posited at the focal point of the parabola. Thus, it reduces the UV lost due to the unnecessary reflection. In contrast, the square shaped reflector is designed to be compressed, low cost (use less aluminium material) and easy to be manufacture. Since light is not focused in the square shaped reflector, the UV light would be reflected in a less effective manner. The reflectors were tested to assess if the dynamic of UV light reflection would make a substantive impact.

Figure 3-7, Parabola reflector (A: top of reflector; B: underside of the reflector; C: reflector on the project prototype)

Figure 3-8, Square reflector (A: top of reflector; B: underside of the reflector; C: reflector on the project prototype)

3.1.3. The Commercial unit

The commercial unit is used to mimic a typical opene channel commercial product. Figure 3-9 shows the sketch of the commercial unit. The device is a submergible UV lamp reactor and has an array of two by three low-pressure mercury lamps. The lamps spacing is 75 mm and lamp to wall spacing is 35 mm (see Figure 3-9) as it would be used in most of UV reactor (see discussion in section 2.6.2). Inside the reactor, an adjustable weir is used at the outlet to control the fluid level inside the reactor. A baffle is used at the inlet to reduce the kinetic energy of the fluid, producing a smooth flow. The full details of the commercial unit design see Appendix 5. The commercial unit is reasonably similar to the reactor used in the study of Loge *et al.* (1996). Overall, the commercial unit is can be classified as a standard UV reactor from the commercial market.

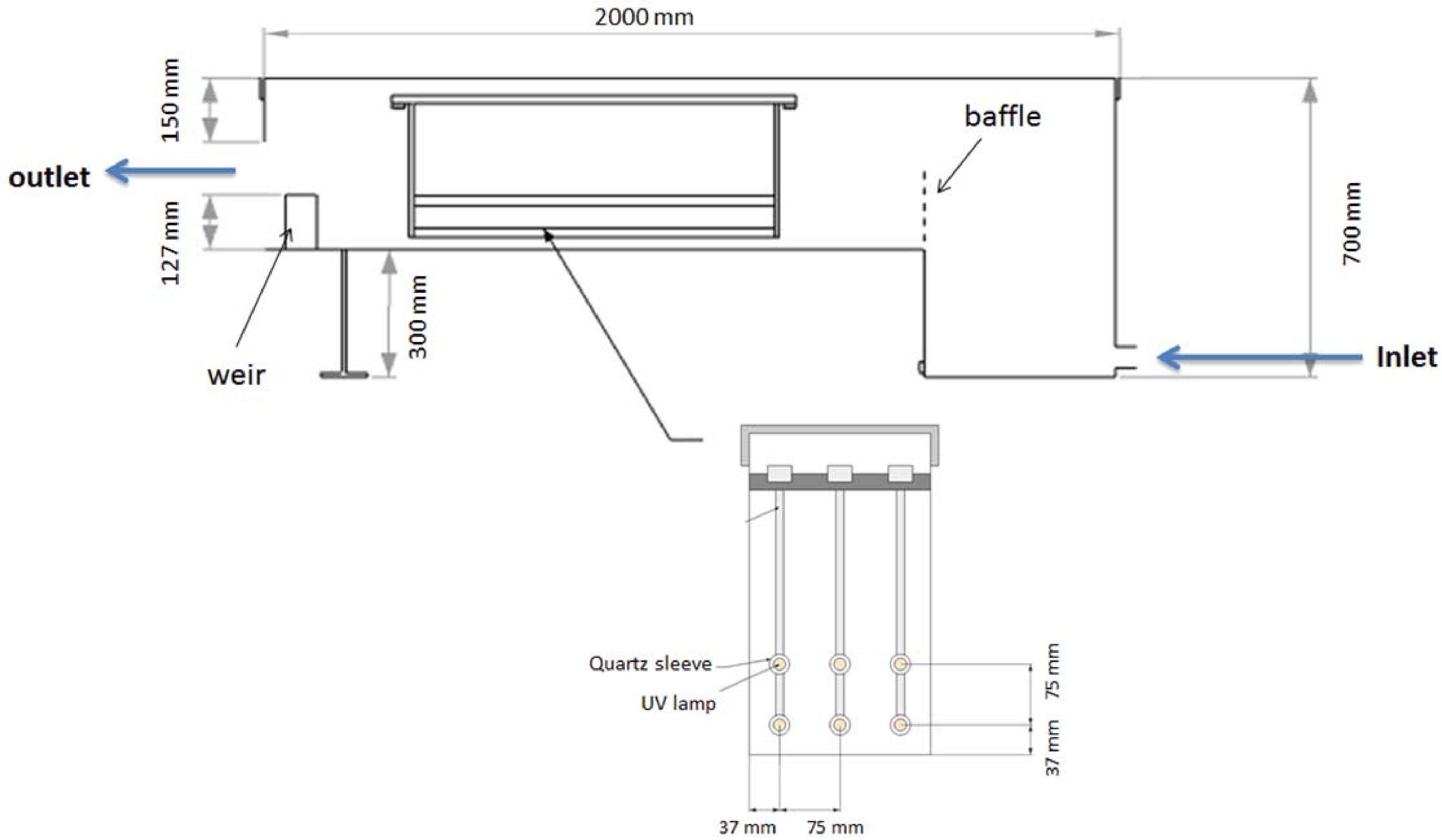


Figure 3-9, Sketch of the commercial unit

3.2. Reactor components and instrument

In this section, the important components in the reactors are described. These include the UV lamp, ballast, UV intensity meter, and flow rate control device.

3.2.1. UV lamps

Throughout the project, 87 watt high output low-pressure mercury lamps were used (Davey Water Product Ltd, series number GPH840N2/S; specifications see Appendix 6.) The lamps were used less than 100 hours in the entire project. Thus, the relative efficiency of the lamp should be 100%, according to the manufacture specification.

3.2.2. Ballast

Ballasts are an electrical component, which protecting UV lamps from electrical damage. Theoretically, 87 watt of ballasts should be used, as the UV lamps are 87 Watt. However, 80 watt ballasts (TRIDONIC Ltd, OMB 80, Art No. 89001030) were used in the project, due to the high cost of a 87 watt ballast. This is practically acceptable. This is confirmed by the UV lamp manufacture, and their products do not use 87 Watt ballast as well (Davey Water Product Ltd). Moreover, the reactors were compared on a relative base. Thus the type of ballast is not critical, but the consistency of the comparison.

3.2.3. UV intensity meter

UV intensity meter (ILT 1400 with detector SEL 2407150) was used in each experiment to ensure the UV lamps were operating. The detector was placed inside the reactors, and then the UV lamps were turned on in an order. Thus, the reading of the meter could indicate whether the lamps function or not. The meter and detector were calibrated according to ISO 17023:2005, which is traceable to National Institute of Standards and Technology.

3.2.4. Flow rate control device

The flow-rate control device used in the project consists of a gate valve to control the flow, a flow meter (TM 200, GPI) to provide an instantaneous flow rate reading and a ball valve to turn on and off the flow. The flow meter has flow rate measurement capacity from 76 to 790 L/min with accuracy of ± 3 % (specifications see Appendix 8).

3.3. Experimental procedure

The project prototype (the third generation) was first compared with the 2nd generation to assess the progress of the development process. The settings of the project prototype were then refined by testing the variables of the reactor. Finally, the project prototype was benchmarked against with the commercial unit to evaluate the feasibility and determine the potential application of the reactor.

In each experiment, the UV lamps were always given 15 minutes to warm up before use. The wastewater samples and reactor effluents were collected by using a two litres bottle on a pole. The bottle had been rinsed by the sampling fluid each time before it is used. The collected sample was then stored in a sterile container. Separate replicates were taken each time, and a two-minute time interval was used between the replicate collections. The collected samples were always analysed within 6 hours.

3.3.1. Comparison of the project prototype and the 2nd generation

The project prototype was believed to be a better version of the 2nd generation; therefore, the project prototype was compared with the 2nd generation in order to confirm this improvement. The reactors were first compared at a low UVT wastewater condition with film thickness of 2, 4 and 6 mm (as regulated by the sluice gate). Based on the results, the reactors were compared again at a film thickness of 2 mm at a high UVT wastewater condition.

The experiment was conducted in Palmerston North Wastewater treatment Plant (the process of the plant see section 3.3.3.1). The influent of the installed UV system was used (the testing point B in Figure 3-11, section 3.3.3.1). The low UVT wastewater was provided by the secondary treated wastewater and the high UVT wastewater was provided by the tertiary treated wastewater (alum dosed).

In the experiment, six UV lamps and the parabola shaped reflector was used. The reaction chamber was set at a flat slope and the flow rate was fixed at 500 L/min. Three replicates of influents and five of effluents of the reactors were collected at each operated condition (e.g. the gap thickness changed or the wastewater condition changed).

3.3.2. Project prototype variable test

As discussed in section 3.1.2, it was believed that the thickness of the sluice gate gap (film thickness), the slope of the reaction chamber and the shape of the reflector would affect the performance of the project prototype, and therefore these variables were tested. The project prototype was evaluated under different UVT conditions, which was similar to the test mention previously (section 3.3.1). The detail of each variable test is shown in the following.

3.3.2.1. Thicknesses sluice gate gap

The project prototype has an adjustable sluice gate (see section 3.1.2.1), which is to regulate the film thickness. The sluice gate gap thickness of 2, 4 and 6 mm were tested, where 2 mm is the minimum gap thickness of the project prototype. During this test, while only the gap of the sluice gate was changed, the slope of the reaction chamber was fixed at zero degree and the parabola shaped reflector was used.

3.3.2.2. Slopes of the reaction channel

The slope of the reaction chamber is adjustable from 0 to 60 degrees and three levels of slope were tested, which were 0, 30 and 60 degree. During the test, while only the slope of the reaction chamber was changed; the sluice gate gap was fixed at 2 mm and parabola shaped reflector was used.

3.3.2.3. Shapes of Reflector

Two different shapes of reflector were tested on the project prototype, which were the parabola and square shaped reflector. During the test, while only the type of reflector was changed; the sluice gate gap and slope of the reaction chamber were fixed at 2 mm and 0 degree, respectively.

3.3.3. Comparison of the project prototype and the commercial unit

After the desirable settings of the project prototype had been determined, the project prototype and commercial unit were compared. During the experiments, the sluice gate gap and reaction chamber slope of the project prototype were fixed at 2 mm and 0 degree, respectively. The parabola shaped reflector was used.

The reactors were tested at a range of watt per flow, which is a ratio of UV lamp wattage per reactor flow rate, as shown in Equation 3-1.

$$watt\ per\ flow = \frac{numbers\ of\ UV\ lamps \times wattage\ of\ the\ UV\ lamp}{process\ flow\ rate\ of\ the\ reactor}$$

Equation 3-1, Watt per flow calculation

Shilton and Sykes (2009) believes that this ratio is a proxy for UV dose, because the UV intensity of a lamp is relative to the lamp wattage, and the exposure time of the fluid is relative to the reactor flow rate. The data of Nieuwstad *et al.* (1991) confirmed this idea, where the watt per flow of the reactor has strong positive linear relationship with the measured UV dose, as shown in Figure 3-10.

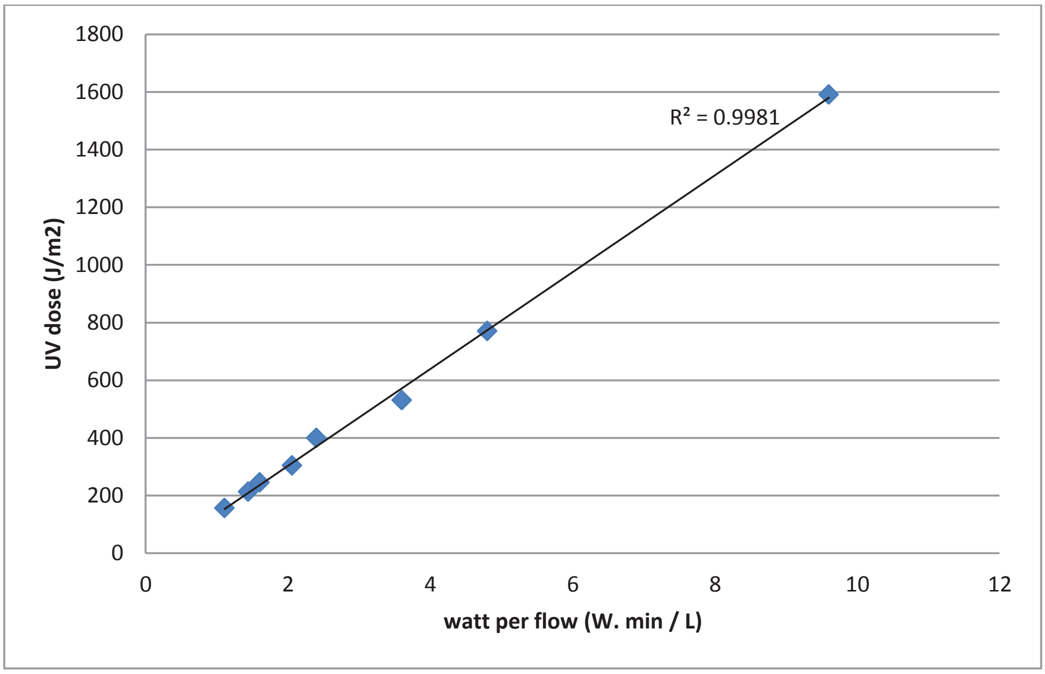


Figure 3-10, Relationship between watt per flow and UV dose in a reactor, data from Nieuwstad *et al.* (1991)

The wattage per flow ratio of the project prototype was regulated via the operated flow rate and number of UV lamps, but the watt per flow of the commercial unit was only regulated by the flow rate. This is because of the geometry of the commercial unit. If a UV lamp in the commercial unit was turned off, part of wastewater would short circuit, resulting ineffective disinfection. The reactors were at first tested at wattage per flow ratio range of 0 to 2 W. min/ L (settings of the reactors see Table 3-1). After examining the initial results, it was decided to expand the range up to 4 W. min/ L (setting of the reactors see Table 3-2).

Table 3-1, Reactors operational conditions in the early stage

Commercial unit	Flow rate: 750, 500, 350, and 250 L/min UV lamps used: 6 lamps in all flow rate conditions
Project prototype	Flow rate: 500 L/min UV lamps used: 1, 2, 3, 4, 5, and 6 lamps Flow rate: 250 L/min UV lamps used 1, 2, 3, 4, 5, and 6 lamps

Table 3-2, Modified reactors operational conditions

Commercial unit	Flow rate: 750, 500, 350, 250 and 130 L/min UV lamps used: 6 lamps in all flow rate conditions
Project prototype	Flow rate: 500 L/min UV lamps used: 1, 2, 4 and 6 lamps Flow rate: 250 L/min UV lamps used 1, 2, 3, 4, and 6 lamps Flow rate: 130 L/min UV lamps used 1, 2, 4, and 6 lamps

In each experiment, three replicates of the influents were collected every 30 minutes, and five replicates of the effluents were collected each time after the watt per flow setting is changed. The influent samples were collected every 30 minutes.

Before the experiments had been conducted, a pre-experiment was conducted. The influent of the installed UV system in PNWWTP (secondary treated) was collected and analysed every 15 minutes until 45 minute. The results show that the concentration of microorganism is reasonably consistent within period (results see Appendix 9). Based on these results, the influent samples in the experiments were collected every 30 minutes.

The reactors were compared at primary, secondary and tertiary treatment stages of conventional wastewater treatment plants. Additionally, the reactors were tested in stabilization pond systems, which have very different wastewater characteristics. The summary of wastewater treatment sites and setting of the reactors are reported in Table 3-3.

Table 3-3, Summary of the UV trials

Site	Primary treatment		Secondary treatment		Tertiary treatment		Pond treatment	
	√/x	Setting as	√/x	Setting as	√/x	Setting as	√/x	Setting as
PNWWTP	√	Table 3-2	√	Table 3-1	√	Table 3-1	x	
Levin WWTP	√	Table 3-2	√	Table 3-1	x		x	
Paraparaumu WWTP	x		√	Table 3-1	x		x	
Fielding WWTP	x		x		√	Table 3-2	x	
1st trial Rongotea	x		x		x		√	Table 3-1
2nd trial Rongotea	x		x		x		√	Table 3-2
1st Shannon	x		x		x		√	Table 3-2
2nd Shannon	x		x		x		√	Table 3-2
Foxton Beach	x		x		x		√	Table 3-2

Since the reactors were tested in a variety of wastewater system, the results are believed to be representative. Nevertheless, the trade-off of an on-site experiment is time consuming and expensive. On average, one on-site experiment requires three full days works and cost approximately $1000 for the associated material and travelling cost.

3.3.3.1. Palmerston North Wastewater Treatment Plant

The Palmerston North Wastewater Treatment Plant (PNWWTP) receives both domestic and industrial waste. The wastewater treatment consists of screening, grit removal, sedimentation, aerated lagoon, clarification, and finally UV disinfection, as shown in Figure 3-11. In certain times of the year, alum is optionally dosed depending on the level of the river that receives the effluent. In the treatment system, the sedimentation is the primary treatment, the aeration lagoon and clarifier is the secondary treatment, and alum dosing is the tertiary treatment.

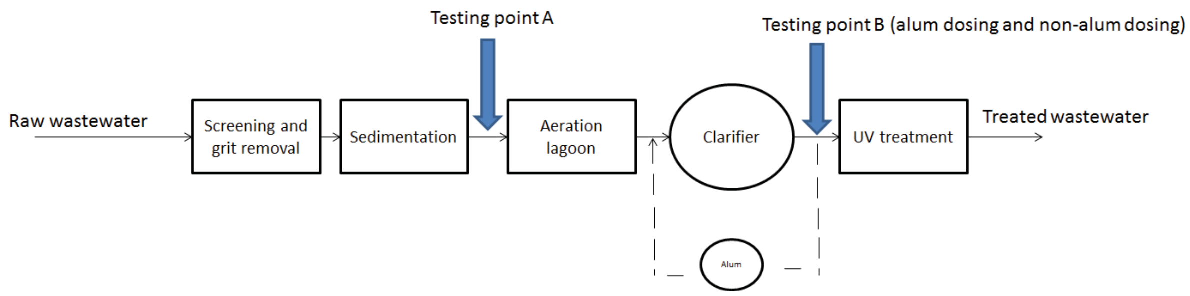


Figure 3-11, PNWWTP process

The reactors were tested after the primary, secondary and tertiary treatment of the plant. The primary treated wastewater test was conducted at the testing point A (after the sedimentation; as shown in Figure 3-11). The wastewater in an ocean outfall is normally primary treated and then discharged into the ocean, without having any disinfection. Given that, the project prototype should theoretically good at disinfecting low UVT fluid (i.e. primary treated wastewater); therefore, this is to assess the applicability of the reactor for primary treated wastewater disinfection applications. The secondary and tertiary treated wastewater tests were conducted at the testing point B (prior to the UV treatment; as shown in Figure 3-11). When alum is not dosed, the wastewater from the testing point B is secondary treated; when alum is dosed, the wastewater is tertiary treated.

3.3.3.2. Levin Wastewater Treatment Plant

The Levin WWTP receives both domestic and industrial wastewater. The industrial wastewater is mainly the effluent from meatworks. This plant is the simplest wastewater treatment plant used in the study, where the series of the process are screening and grit removal, sedimentation, trickling filter, clarification and aerated lagoon, as shown in Figure 3-12. In the treatment system, the sedimentation is the primary treatment, and the process from trickling filter to aeration lagoon is the secondary treatment.

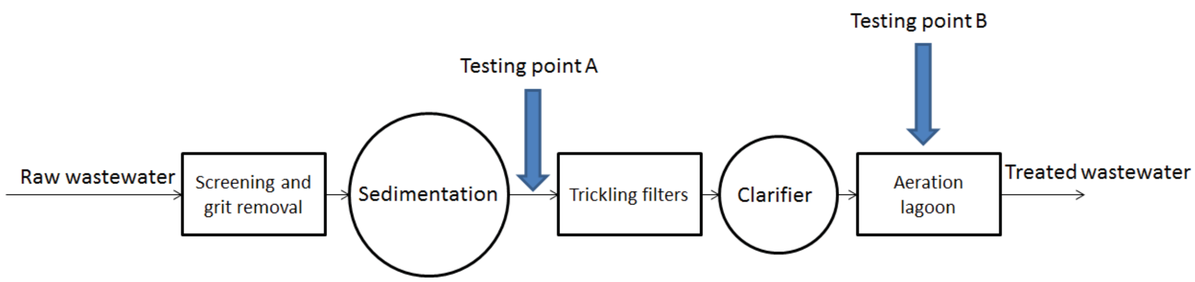


Figure 3-12, Levin WWTP treatment process

Primary and secondary treated wastewater tests were conducted in this plant. The primary treated wastewater test was carried out at the testing point A (after the sedimentation; as shown in Figure 3-12). Again, this test is to assess applicability of the reactor for primary treated wastewater. The secondary treatment test was carried out at the testing point B (as shown in Figure 3-12). Due to the limitation of accessing the outlet of the lagoon, the reactors were tested at the lagoon. When the reactors were tested at the aerated lagoon, the wastewater was drawn from the upstream of the aerated lagoon, treated, and then discharged two meters downstream into the lagoon, as shown in Figure 3-13.

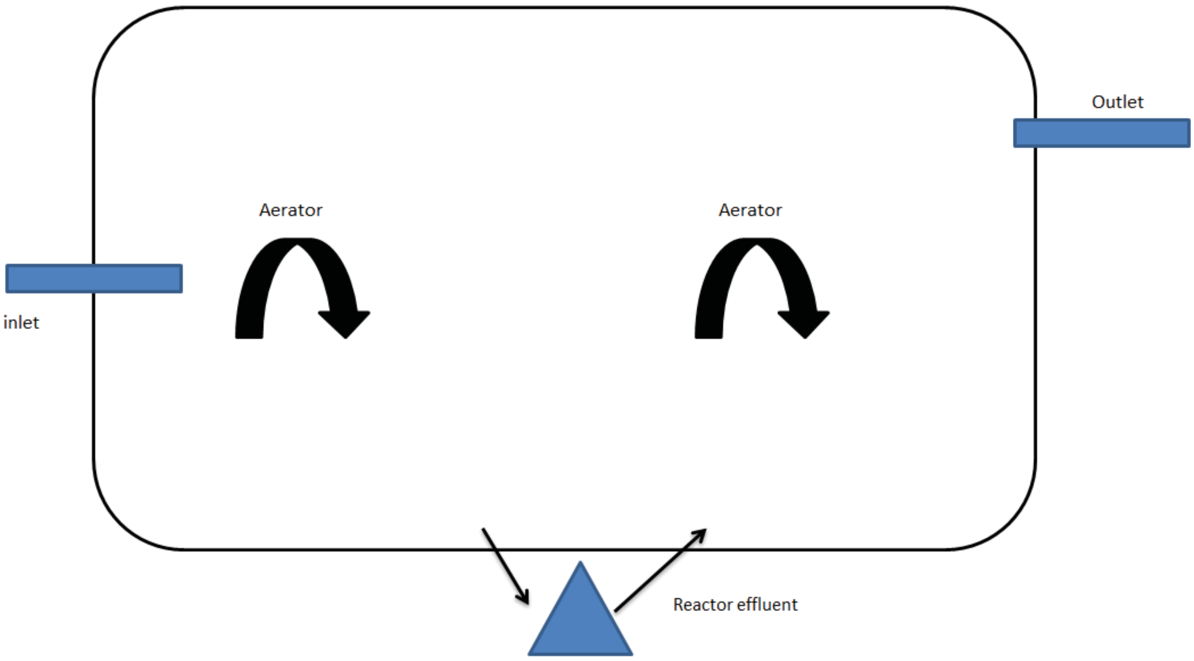


Figure 3-13, Experimental set in the aerated lagoon pond

3.3.3.3. Paraparaumu Wastewater Treatment Plant

The Paraparaumu WWTP is the most modern WWTP used in this study. The plant uses a biological nutrient removal process to treat the wastewater. The plant has a complex process, which has anoxic treatments, anaerobic treatment, aerated treatment and disinfection treatment, as shown in Figure 3-14. In the treatment system, the wastewater is secondary treated, skipping the primary treatment.

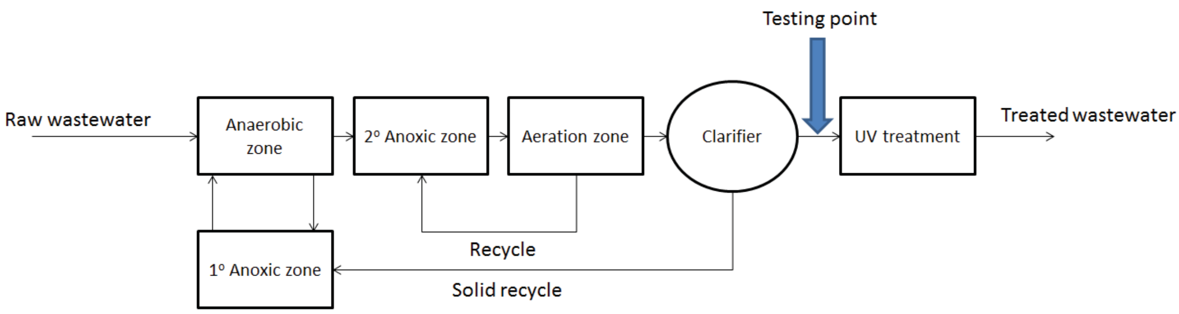


Figure 3-14, Paraparaumu WWTP process

The secondary treated wastewater test was conducted in the plant. The reactors were tested after the clarifier but prior to the UV system, as the blue arrow shown (in Figure 3-14).

3.3.3.4. Fielding Wastewater Treatment Plant

The Fielding wastewater treatment plant (WWTP) receives both domestic and industrial wastewater. The wastewater treatment in Fielding WWTP is different from an ordinary WWTP. The series of process are screening, grit removal, anaerobic pond treatment, aerated lagoon treatment, sedimentation, trickling filter, chemical addition (polymer and alum), membrane filtration, and finally UV disinfection, as shown in Figure 3-15. In the treatment system, the process from the anaerobic pond to the sedimentation is a hybrid treatment of primary and secondary treatment, the trickling filter is the secondary treatment and the membrane filtration is the tertiary treatment.

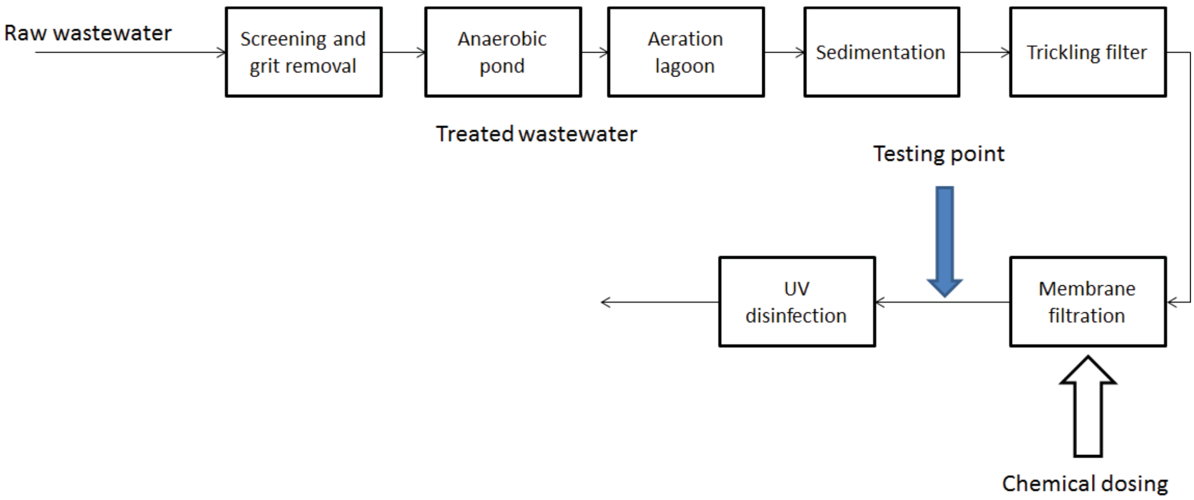


Figure 3-15, Fielding WWTP process

Tertiary treated wastewater test was conducted in this plant. The reactors were tested after the membrane filtration process but before the UV system, as the blue arrow shown (in

Figure 3-15). After the chemical dosing and the membrane filtration process, the wastewater should be reasonably clean.

3.3.3.5. Rongotea stabilization pond system

The wastewater treatment system in Rongotea is a series of ponds, as shown in Figure 3-16. The wastewater is treated by passing through a primary pond, secondary pond, maturation pond and then wetland, as shown in Figure 3-16. An aerator is used in the first pond to improve the oxygen diffusion and enhance the mixing of the pond.

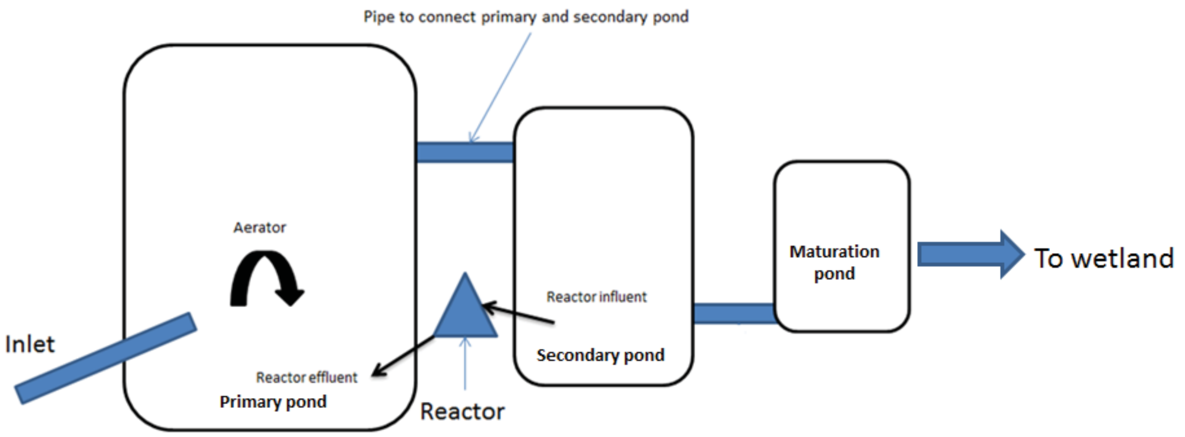


Figure 3-16, Experimental set up in Rongotea stabilization pond

As shown in Figure 3-16, the secondary pond wastewater was used for the test. The treated wastewater was discharged into the primary pond. The retention time of the primary pond is very long; therefore, it is confident to assume that no recycling treatment occurred during the UV trials.

3.3.3.6. Shannon stabilization pond system

The wastewater in Shannon is treated by a stabilization pond system, which baffles are used to divide a big pond into a primary pond, a secondary pond and a series of wetlands, as shown in Figure 3-17. Two aerators are used in the first pond to improve the oxygen diffusion and enhance the mixing of the pond.

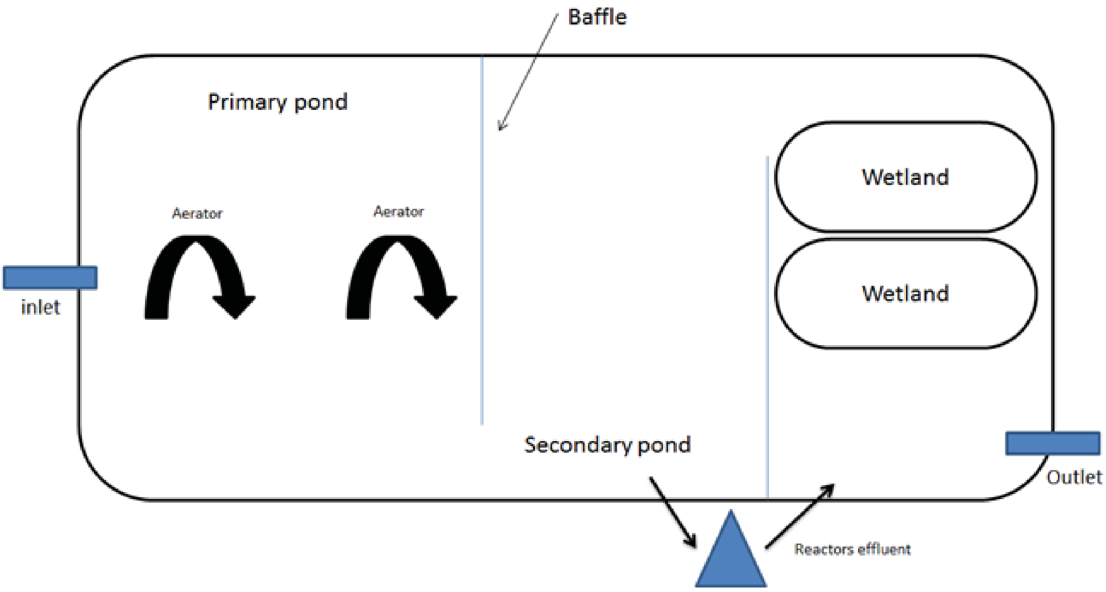


Figure 3-17, Shannon pond system and the experimental set up

As Figure 3-17 shown, the wastewater from the secondary pond was used in the tests, and the treated wastewater is discharged into the wetland pond.

3.3.3.7. Foxton Beach stabilization pond system

The wastewater in Foxton beach is treated by stabilization ponds, which are constructed from one big pond using a baffle as a divider, as shown in Figure 3-18. An aerator is used in the first pond to improve the oxygen diffusion and ensure the mixing.

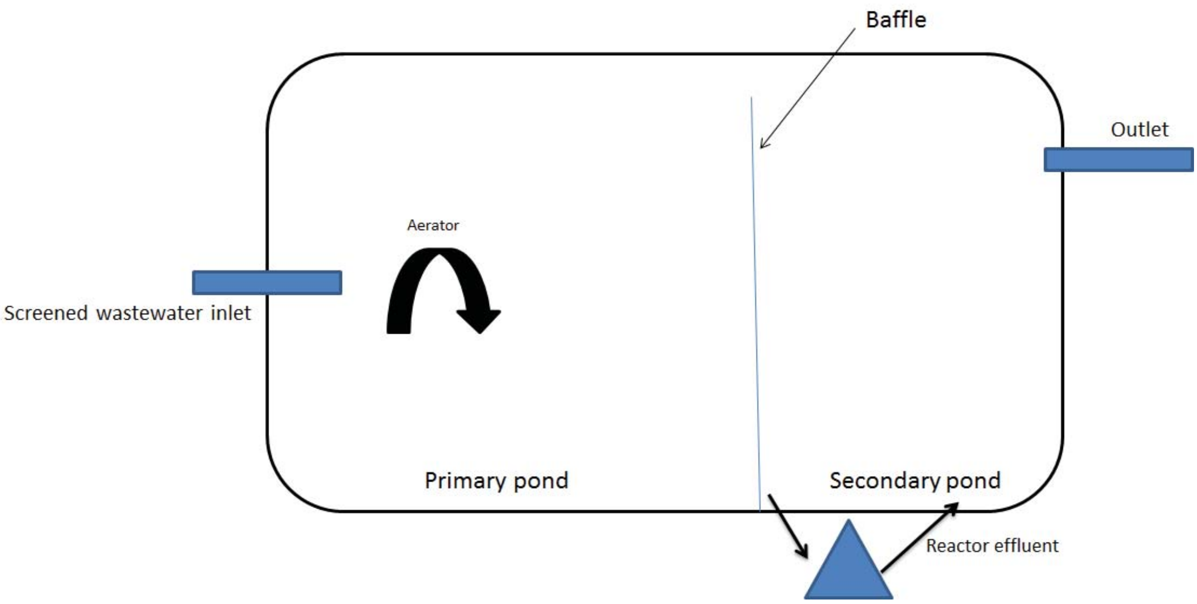


Figure 3-18, Foxton beach pond system and the experimental set up

Due to the limitation of the outlet accessibility, the reactors were tested at the secondary pond. The wastewater was drawn from the upstream of the secondary pond, disinfected and then discharged two meters downstream into the pond. This is to avoid the recycling of the disinfection treatment.

3.4. Methods of analysis

This section will discuss how the samples were analysed. Three main analyses were conducted throughout the project, which were the bacteria enumeration, UVT measurement and TSS measurement.

3.4.1. Pathogen indicator for wastewater test

Wastewater contains different types of microorganisms and it is impossible to identify and quantified all of them. A pathogen indicator is used in wastewater disinfection, which serve as a proxy to show the presence and quantity of pathogens (Toze, 1997).

E. coli was used as the pathogen indicator in the project, as it is commonly used in wastewater guidelines (Beca Ltd, 2008; USEPA, 2013), and also believed to be a good indicator for presence of faecal contamination (Trojan Ltd, 2009) and public health risk (Elmund *et al.*, 1999). *E. coli* is easily detected by using the MUG technology (4-methylumbelliferyl-ß-D-glucuronide). MUG is a chemical that can bind on the enzyme, β-glucuronidase, which specifically produced by *E. coli*, forming a fluorescent blue colour under the 356 nm UV light.

3.4.2. Bacteria enumeration

Multiple tube fermentation, membrane filtration and enzymatic substrate test are three of the most commonly used methods for bacteria enumeration of wastewater sample (APHA *et al.*, 2012). Multiple tubes fermentation is a labour intensive and material consuming method (APHA *et al.*, 2012), which is difficult to use for analysing a large amount of samples, such as in this project. Membrane filtration is known as the most reproducible method; however, it has limitation in analysing high turbidity, toxic, or non-coliform bacteria rich samples (APHA *et al.*, 2012). Enzymatic substrate test is a relatively new method. It is suggested that this method is as reproducible as membrane filtration (Noble *et al.*, 2003; Yakub *et al.*, 2002), but has less limitation in wastewater characteristics. Furthermore, the procedure of the analysis is simple. Therefore, enzymatic substrate test was used throughout the project.

Colilert ® is one of the commercialized package that utilize the enzymatic substrate test method (APHA *et al.*, 2012). The procedure can be as simple as adding the package chemicals into the sample, sealing the sample in a special tray and then incubated for 24 hours to show the result as shown in Figure 3-19.

Figure 3-19, Colilert test procedure (adapted from IDEXX Laboratories, 2013)

Dilution might be necessary, depending on the concentration of the sample, where the colilert® product can only measure the samples that contain *E. coli* less than 2419 MPN/100 mL. The dilution was conducted according to the dilution method (1010 D) given by (APHA *et al.*, 2012). The tested wastewater was normally collected and analysed a few days (one or two days) prior each experiment to estimate the correct dilution factor.

3.4.3. UV Transmittance

UVT_{254} is the UV transmittance of the fluid at 254 nm light. The UVT_{254} of the influent samples were measured in each experiment, as it is recommended by USEPA *et al.* (2006).

The UVT_{254} of the sample can be obtained by measuring the absorbent of the sample at 254 nm in a 1 cm wide quartz cuvette, and then calculated based on Equation 3-2. Details of the measurement procedure is given by USEPA *et al.* (2006, pp. 3-15).

$$UVT_{254} = 100 \times 10^{-absorbance}$$

Equation 3-2, UVT calculation

3.4.4. Total suspended solid

Total suspended solid (TSS) is the undissolved solids in fluid. TSS concentration can affect the UV disinfection (as discussed in section 2.4.2). Therefore, the TSS concentration of the influent was measured in each experiment. The TSS concentration is determined by filtering the sample through a 0.45-micron filter, and then conducting the calculation as shown in Equation 3-3. Details of the procedure is given by section 2540 D of APHA *et al.* (2012).

$$\text{TSS} = \frac{g\ of\ dry\ weight\ filter\ after\ filtration - g\ of\ dry\ weight\ \ filter\ before\ filtration}{L\ of\ \text{sample filtered}}$$

Equation 3-3, TSS calculation

3.4.5. Quality control

Since the measurement of *E. coli* concentration is critical, quality control was carried out. Additional samples were collected and sent to a third part for analysis. The results from the third party were then compared with the experimental results. Overall, no statistical differences were found between the results from the experiments and the third party. This suggests that the collected data are reliable and reproducible result (full details see Appendix 10.)

4. Results and discussion

The performance of the project prototype and the 2nd generation (previous prototype) were first compared, and then the refine settings of the project prototype were determined, by testing the three variables. Finally, the project prototype and the commercial unit (which is the control reactor) were compared twelves times at seven wastewater systems sites. This section will report the experimental results and also discuss the implication. The experimental data were compared in a statistical manner, and the statistical analyses are shown in Appendix 11.

4.1. Comparison of the project prototype and the 2nd generation

The performance of the project prototype (the 3rd generation) and the 2nd generation was first compared at the sluice gate gaps of 2, 4 and 6 mm, treating a low UVT wastewater. The wastewater from the inlet of the PNWWTP installed UV system was used, which was secondary treated and had a UVT of 18%, TSS of 78 mg/L and an average *E. coli* concentration of 198,216 MPN/100 mL. Both of the reactors were evaluated, using six UV lamps and the parabola shaped reflector. Since the reaction chamber slope of the 2nd generation is not adjustable and fixed at zero degree, the reaction chamber slope of the project prototype was also set at zero degree. The reactors were operated at flow rate of 500 L/min. Figure 4-1 shows the box plot of the reactor performances at 2, 4 and 6 mm sluice gaps.

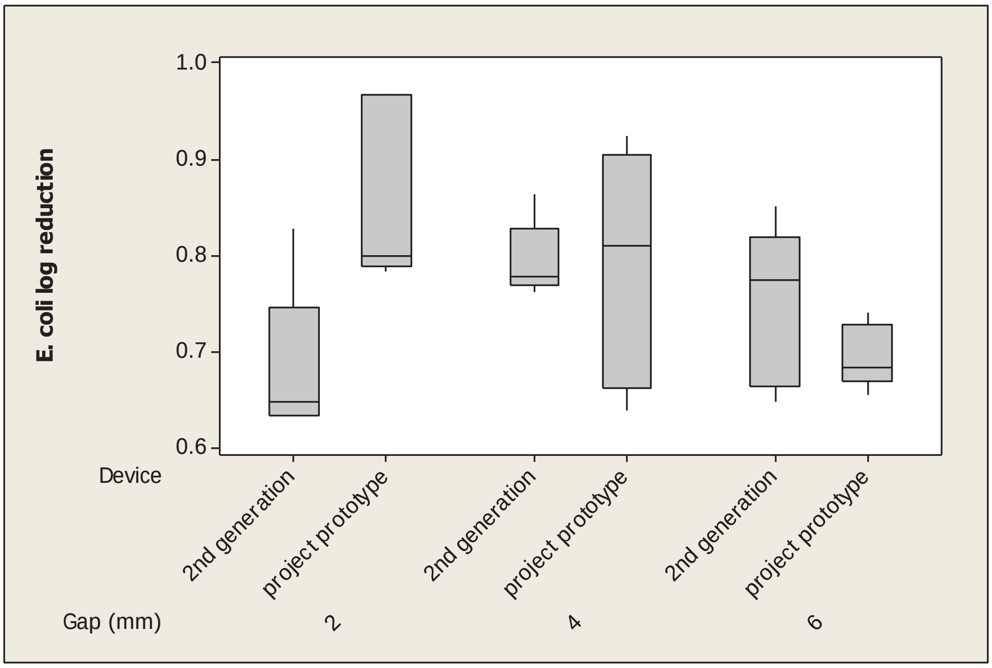


Figure 4-1, Box plot of the project prototype performance vs. 2nd generation performance, at the sluice gate gaps of 2, 4 and 6 mm, treating low UVT wastewater

Although Figure 4-1 shows some variations in the 4 and 6 mm of the project prototype and the 2nd generation performance, the t-test actually suggests that they are statistically the same (p-values of 0.66 and 0.10, respectively). This suggests the project prototype had no difference in performance from the 2nd generation, when the sluice gate gap is greater than 4 mm. Nevertheless, the project prototype had significantly greater *E. coli* log reduction than the 2nd generation (p-value of 0.02), when the sluice gate gap was at 2 mm. This suggests that the project prototype performed better than the 2nd generation, when the sluice gate gap was at 2 mm.

Since the reactors only performed differently at the sluice gate of 2 mm, the reactors were compared again at this sluice gate gap thickness, but treating a high UVT wastewater. Again, the wastewater from the inlet of PNWWTP installed UV system was used, however, it was alum dosed (tertiary treated) this time. The wastewater had a UVT of 55%, TSS of 16 mg/L and an average *E. coli* concentration of 241.6 MPN /100 mL. The settings of the reactors remained the same as the previous test. The results of the comparison are shown in Figure 4-2.

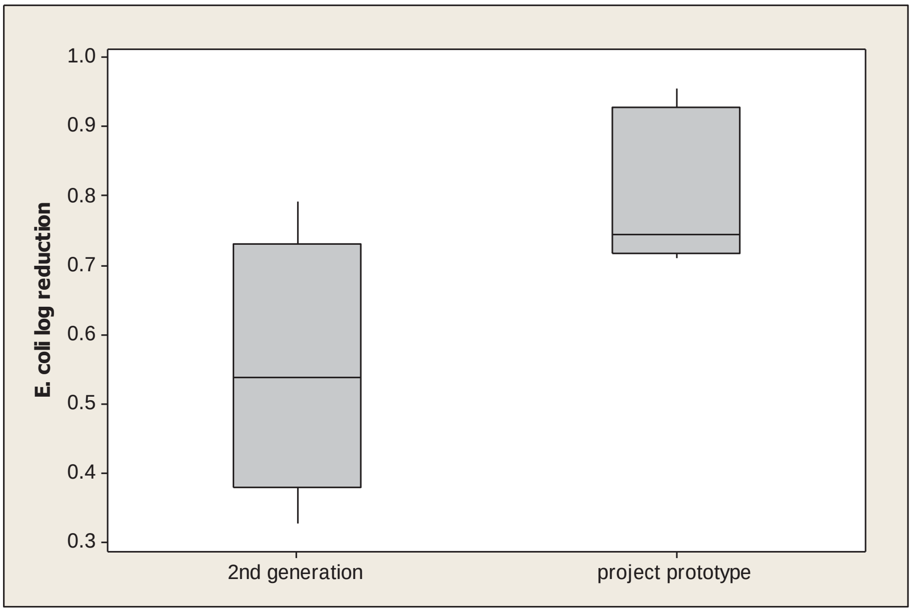


Figure 4-2, Box plot of the project prototype performance vs. 2nd generation performance, at the sluice gate gap of 2 mm, treating high UVT wastewater

Figure 4-2 shows that the project prototype had more *E.coli* log reduction than the 2nd generation (p-values of 0.01). This further confirms that the project prototype had a better performance than the 2nd generation, when the sluice gate gap was at 2 mm.

Overall, the experiments show that the project prototype performed better than the 2nd generation treating both high and low UVT wastewater, when the sluice gate gap is at 2 mm. The project prototype has a smaller tank than the 2nd generation, and an extra piece of aluminium material on the surface of the sluice gate. This suggests that the better in performance of the project prototype might be due to either the tank size or the additional piece of aluminium.

The experiments suggest that the project prototype is a better version of the 2nd generation. Therefore, it was used throughout the project as a referential reactor for evaluating the feasibility of applying supercritical flow hydraulics to wastewater disinfection.

4.2. Project prototype variable test

Three variables of the project prototype were tested, which were the thicknesses of the sluice gate gap, slope of the reaction chamber and shape of the reflector. The variables were tested under high and low UVT wastewater conditions at PNWWTP. The wastewater from the inlet of the installed UV system was used. In the high UVT wastewater condition, the influent was tertiary treated (alum dosed), which had a UVT of 55%, TSS of 16 mg/L and an average *E. coli* concentration of 241.6 MPN /100 mL. In the low UVT wastewater condition, the influent was only secondary treated, which had a UVT of 19%, TSS of 81 mg/L and average *E. coli* concentration of 183,900 MPN/100 mL.

4.2.1. The effect of sluice gate gap thickness on UV disinfection

As discussed in section 3.1.2.1, It was believed that a thinner film thickness (shorter UV light travelling distance) would result in better performance, even though the HRT of the fluid would decrease (shorter UV exposure time). Therefore, the project prototype was tested at different film thickness levels, which was controlled by the sluice gate gap. Three levels of sluice gate gap were tested, which were 2, 4 and 6 mm. In the experiment, the project prototype used six UV lamps and the parabola shaped reflector. The slope of the reaction chamber was fixed at zero degree. The operated flow rate was set at 500 L/min. The performance of the project prototype at 2, 4 and 6 mm of sluice gate gap thickness, on high and low UVT wastewater conditions is shown in Figure 4-3.

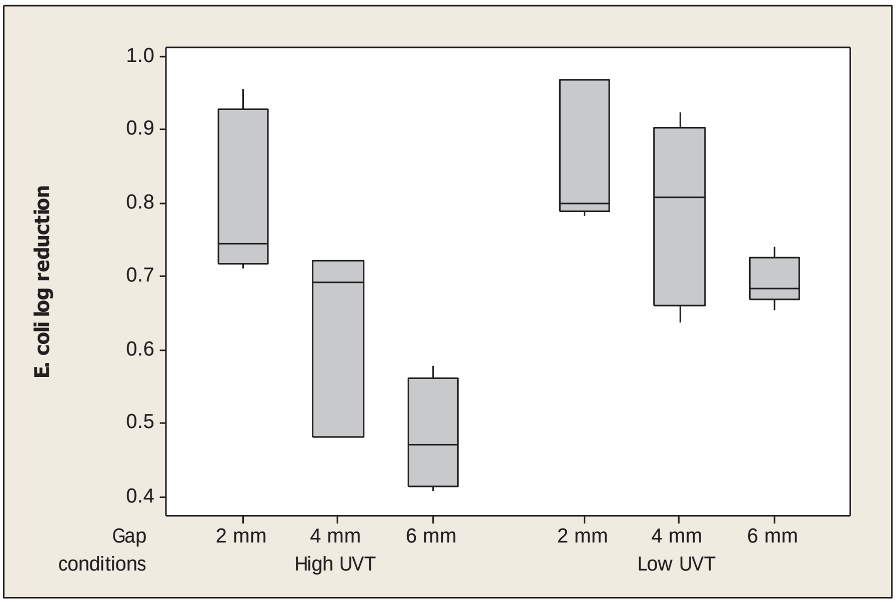


Figure 4-3, Box plot of the project prototype performance at the sluice gate gaps of 2, 4, and 6 mm, treating high and low UVT wastewater

Figure 4-3 shows that the project prototype had less *E. coli* log reduction as the sluice gate gap thickness increase. However, the results from t-tests suggest that in both UVT conditions, only the data at 2 mm have greater *E. coli* log reduction than the data at 6 mm (p-values of 0.00 and 0.01), and the data at 2 mm has similar *E. coli* log reduction to the data at 4 mm (p-values of 0.09 and 0.31). This suggests that the effect of gap thickness on the performance will only become significant when the gap is altered greater than 4 mm. In addition, on the base of the prototype had better performance at 2 mm than 6 mm, it is confirmed that a thinner film will result a better UV disinfection. Finally, based on this experiment, it is found that the project prototype performs the best at 2 mm of sluice gate gap, and therefore this setting was used throughout the rest of the experiments.

Interestingly, Figure 4-3 shows that the project prototype had similar performance on treating high and low UVT wastewater, when the sluice gate gap was less than 4mm (p-values see Appendix 11). This suggests that within the range tested, the performance of the project prototype is not significantly affected by the UVT, when the sluice gate gap is less or equal to 4 mm.

4.2.2. The effect of reaction chamber slope on UV disinfection

As discussed in section 3.1.2.2, it was believed that the increases of the reaction chamber slope would reduce the film thickness, and therefore improves the performance of the project prototype. Thus, the project prototype was tested at reaction chamber slopes of 0, 30 and 60 degree. In the experiment, the project prototype used six UV lamps and the parabola shaped reflector. The sluice gate gap and the flow rate of the prototype were fixed at 2 mm and 500 L/min, respectively. The performance of the project prototype at the slopes of 0, 30 and 60 degree, on high and low UVT wastewater conditions is shown in Figure 4-4.

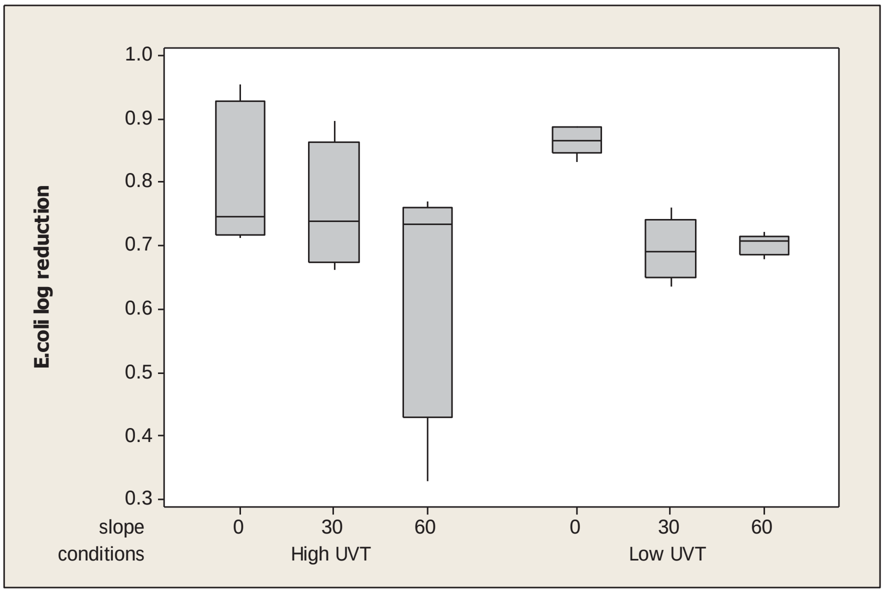


Figure 4-4, Box plot of the project prototype performance at the reaction chamber slopes of 0, 30 and 60 degree, treating high and low UVT wastewater

Figure 4-4 appears to show that when the high UVT wastewater was disinfected, the overall performance of the project prototype decreases as the slope increases. However, the results from t-test suggest that the project prototype performed the same at different level of slope (p-values see Appendix 11). This suggests that within the range tested, the slope of the reaction chamber has no significant effect on the performance, when high UVT wastewater is treated. At low UVT conditions, the results show that performance of the prototype was similar at the slopes of 30 and 60 degree (p-vlaue of 0.77). However, the prototype had better performance at zero degree of slope than at 30 and 60 degree (p-values of 0.00 in both cases). This suggests that the zero degree of reaction chamber slope is more preferable when the prototype is treating low UVT wastewater.

Overall, the results indicate an opposite conclusion from the hypothesis that the increases of slope will decrease the film thickness, and therefore would result in better performance. This suggests that film thickness might not be the only important factors, which can affect the performance of the project prototype.

Since the slope has no effect on the project prototype when treating high UVT wastewater, and zero degree of slope is preferable when low UVT wastewater is treated; reaction chamber slope of zero degree was then used throughout the rest of the experiments.

Figure 4-4 also shows that at a given slope, the performance of the project prototype were the same when treating high and low UVT wastewater (p-values see Appendix 11). This further confirms the observation from the previous (3.3.2.1) section that the performance of project prototype is not significantly affect by the UVT, when the sluice gate gap is at 2 mm.

4.2.3. The effect of reflector shape on UV disinfection

While the parabola shaped reflector should be more effective at focusing and reflecting UV light; it was questions that if this extra complexity of design would really make a substantial difference, compared to a simple square shaped reflect. The parabola and squared shaped reflectors were then tested on the project prototype to evaluate the effect of the reflector shape. In the experiment, the project prototype used six UV lamps. The sluice gate gap, reaction chamber slope and the flow rate were fixed at 2 mm, 0 degree and 500 L/min, respectively. The performance of the project prototype using the parabola shaped reflector and square shaped reflectors, on high and low UVT wastewater conditions is shown in Figure 4-5.

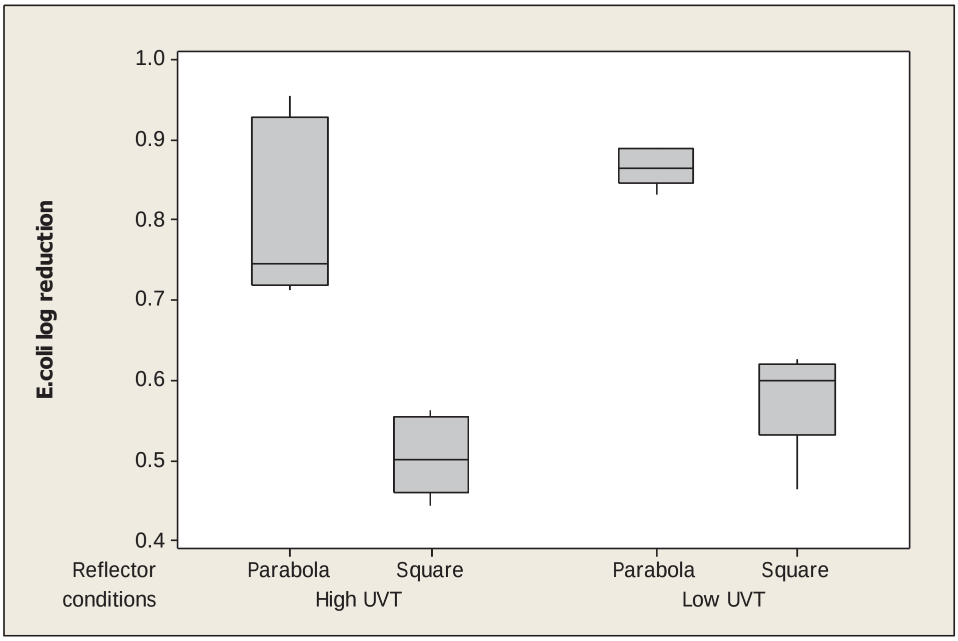


Figure 4-5, Box plot of the project prototype performance using the parabola and square shaped reflectors, treating both high and low UVT wastewater

Figure 4-5 shows that more *E. coli* was inactivated by the parabola shaped reflector than the square shaped reflector in both high and low UVT wastewater conditions (p-values of 0.00 in both cases). This clearly illustrates the significant effect of the reflector shape. Based on this experiment, the parabola shaped reflector was used throughout the rest of experiments.

Figure 4-5 also shows that the project prototype had similar performance in both high and low UVT wastewater condition, when the same reflector was used (p-values see Appendix 11). This once more confirms that the performance of the project prototype is not significantly affected by the UVT of the wastewater (within the range of values tested), when the sluice gate gap is fixed at 2 mm.

4.3. Comparisons of the project prototype and commercial unit

After the settings of the project prototype were refined (see section 4.2), the project prototype was then compared with the commercial unit after the primary, secondary and tertiary treatment stages of the conventional wastewater treatment plants. As application of UV disinfection at stabilization ponds becomes increasingly popular (Nelson, 2000), the reactors were also compared at the stabilization pond systems. In total, the reactors were compared twelve times at seven different wastewater treatment sites.

4.3.1. Primary treated wastewater test

According to Bleninger (2014), the wastewater from a marine outfall system is only primary treated and then discharged into the nearby ocean. Although, the discharged wastewater is disinfected by chlorine in some place, such as United States, Sao Paulo and Brazil, chlorination is forbidden in most of European countries, due to the eco-toxic by-products. UV disinfection is rarely used in marine outfall systems because traditional UV reactors are inefficient in disinfecting primary treated wastewater because of the low UVT and high TSS. In order to assess the applicability of the project prototype for primary treated wastewater disinfection, the reactors were compared after the primary treatment systems of PNWWTP and Levin WWTP.

4.3.1.1. PNWWTP primary treated wastewater test

The primary treated wastewater from PNWWTP had a UVT of 5 %, TSS of 103.3 and an average *E. coli* concentration of 7,462,004 MPN / 100 mL. As expected, the UVT of the wastewater is low and the TSS is high, which are undesirable for a traditional UV disinfection system. The *E. coli* log reduction of the reactors from the PNWWTP primary treated wastewater test is plotted in Figure 4-6.

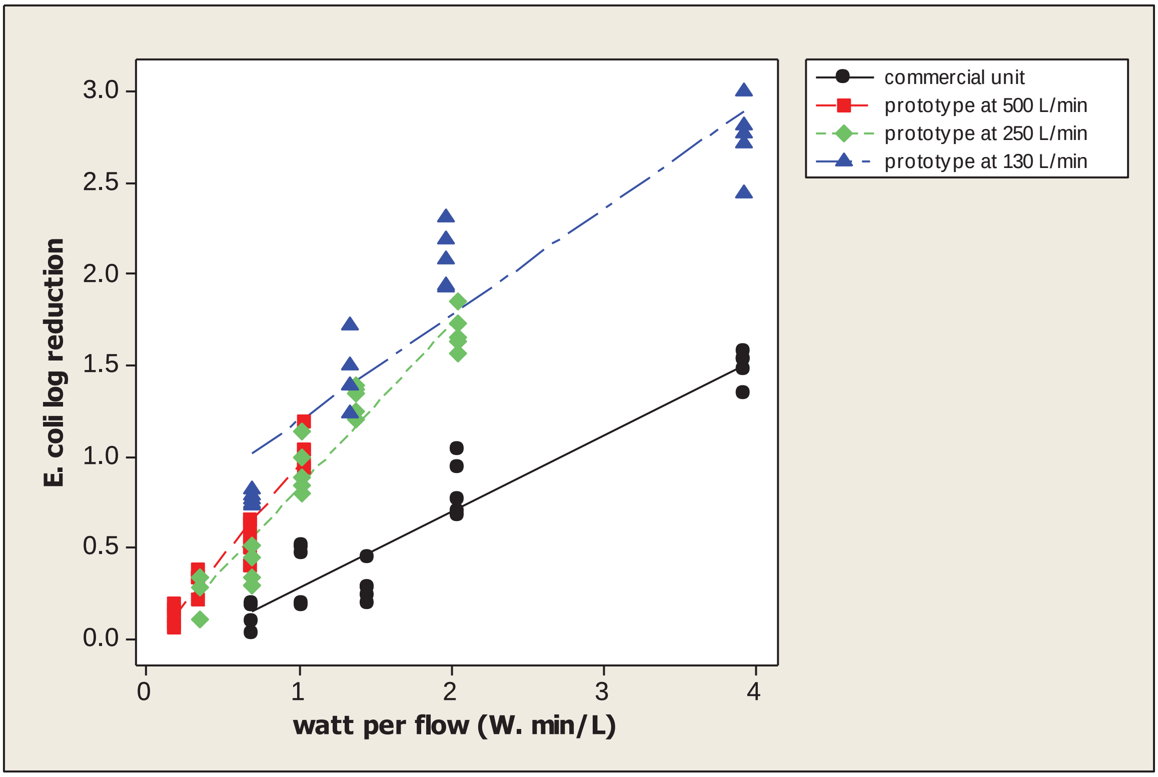


Figure 4-6, *E. coli* log reduction of the reactors in the PNWWTP primary treated test; Commercial unit: *E. coli* log reduction of the commercial unit; prototype at 500 L/min: *E. coli* log reduction of the project prototype at flow rate of 500 L/min; likewise for the rest of the figures

As would be expected, Figure 4-6 show that the *E. coli* log reduction increased as the watt per flow of the reactors increased. It is noticed that the data of the project prototype at the flow rate of 130 L/min show a slight curvature, where the data at 4 W. min/L is somewhat lower than it would be expected, based on the slopes of the project prototype regressions at 250 and 500 L/min. This indicates that the project prototype might operate at the tailing region at watt per flow of 4 W. min/L, of which the residual microorganisms were difficult to be inactivated (for more details about the tailing region see section 2.5). Overall, the appearance of Figure 4-6 is similar to a typical microbial UV dose response, which confirms that the watt per flow ratio is a good proxy of UV dose.

In Figure 4-6, the project prototype had greater *E. coli* log reduction than the commercial unit had, at any given watt per flow. This suggests that the project prototype was more effective in disinfection than the commercial unit. In addition, the figure shows that the project prototype offered similar level of treatments to the commercial unit with a much lower watt per flow condition. This suggests that the project prototype was more energy efficiently than the commercial unit. For example, the project prototype at a watt per flow of 1.5 W. min/L had similar *E. coli* log reduction to the commercial unit at 4 W. min/L (p-value of 0.15), which the project prototype used 3 times less energy than the commercial unit. This means that the project prototype would need less UV lamp to achieve the same level of disinfection of the commercial unit. This means that less UV lamp would be needed in the project prototype, and therefore reducing the operational cost and capital cost. Reciprocally, the project prototype could disinfect more wastewater than the commercial unit at a given energy input – more 'production'.

Figure 4-6 shows that the trend lines of the project prototype at the operated flow rate of 500 is similar to at 250 L/min. This is confirmed by the statistical analyses that the 95% confidence interval of the regression intercepts and slopes are overlapping (see Appendix 11). However, the trend line of the project prototype at 130 L/min is different from the other trend lines. The statistical analyses suggest that regression of the prototype at 130 L/min has a smaller slope and larger intercept than other project prototype regressions. This might be due to the data at the tailing region (as discussed above), which significantly affects the regression of the project prototype. The data of the project prototype at the watt per flow range between 0 and 2 W. min/L are generally overlapping. Based on this, it is believed that the project prototype performed similarly at the operated flow rate of 500, 250 and 130 L/min within watt per flow range. As the watt per flow of the reactors was manipulated by changing the flow rate and number of operated UV lamps, it is important to know the effect of flow rate on the performance of the reactors, and therefore further discussion will be conducted in section 4.4.

4.3.1.2. Levin primary treated wastewater test

Since the results from the PNWWTP primary treated wastewater test were promising (see section 4.3.1.1); additional primary treated wastewater tested was conducted at Levin WWTP. The wastewater had a UVT of 5%, TSS of 111 mg/L and an average *E. coli* concentration of 9,136,023 MPN / 100 mL, which was similar to the primary treated wastewater from PNWWTP. The *E. coli* reduction of the reactors in the Levin WWTP primary treated wastewater test is plotted in Figure 4-7.

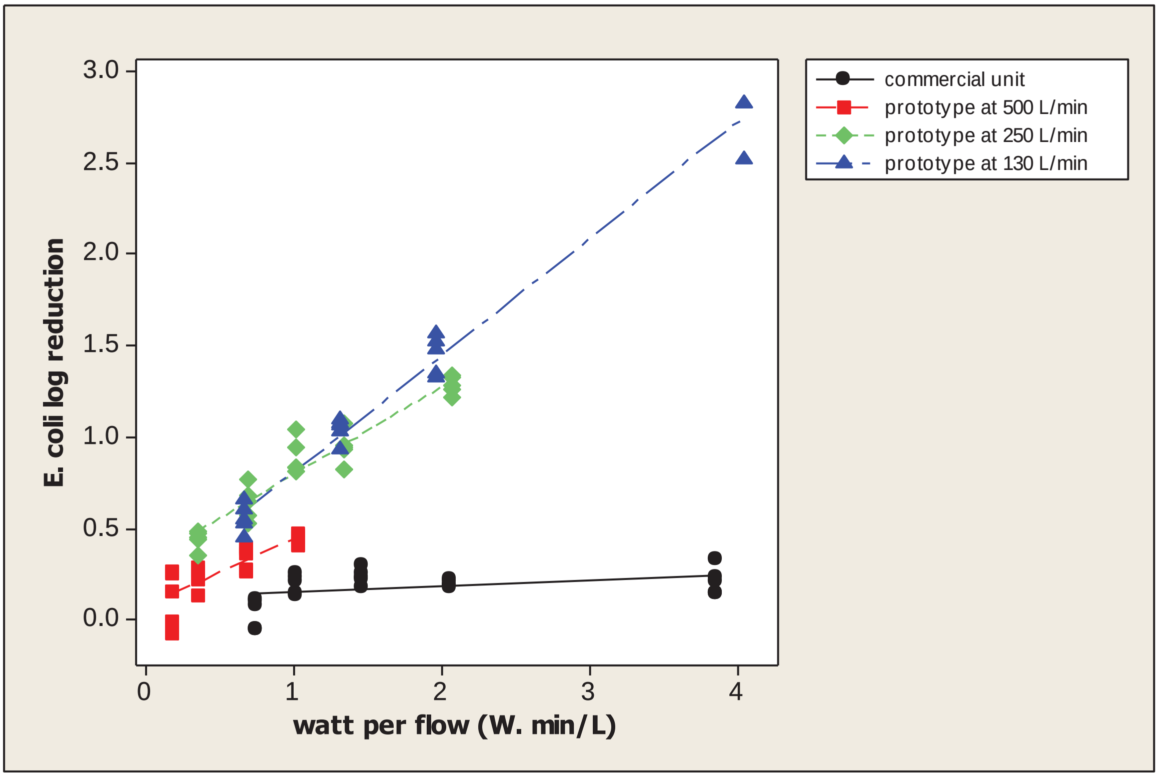


Figure 4-7, *E. coli* log reduction of the reactors in the Levin WWTP primary treated test

Figure 4-7 show that little *E. coli* could be inactivated (less than 0.5 log reduction) by the commercial unit, even though the watt per flow was raised up to 3.8 W. min/L. In contrast, 2.5 *E. coli* log reduction was achieved by the project prototype at 4 W. min/L. Overall, the project prototype always had greater *E. coli* log reduction than the commercial unit. This suggests that the project prototype is more effective than the commercial unit (in terms of UV disinfection). In addition, the figure shows that the project prototype could achieve the same level of disinfection as the commercial unit at a much lower watt per flow settings. For example, the project prototype at 0.17 W. min/L offered the same level of treatment as the commercial unit at 4 W. min/L (p-value of 0.24), which required 23 times lower watt per flow than the commercial unit. This once again suggests that the project prototype was more energy efficient than the commercial unit.

Figure 4-7 appears to show that the project prototype had similar performance at the operated flow rate of 250 and 130 L/min, and had worse performance at 500 L/min than at 250 and 13 L/min. However, the statistical analyses suggest that the regression of the prototype at 130 L/min has a greater slope than the regressions at 250 and 130 L/min. Also, the regression of the prototype at 130 L/min has a greater intercept than the regression at 500 L/min. This indicates that the project prototype had better performance as the flow rate decreased. This contradicts the observations from the previous test (PNWWTP primary treated wastewater tests, see section 4.3.1.1). The effect of flow rate on reactor performance will be further discussed in section 4.4.

4.3.1.3. Summary of primary treated wastewater test

The project prototype and commercial unit were compared after the primary treatment stage of the PNWWTP and Levin WWTP. The wastewaters had the same UVT (5%), similar TSS (103 and 111 mg/L) and the same magnitude of average *E. coli* concentration (7,462,004 and 9,136,023 MPN / 100 mL).

A ratio of the average *E. coli* log reduction of the project prototype per average *E. coli* log reduction of the commercial unit, at a given watt per flow (see Equation 4-1), is used to quantified the difference in performance between the project prototype and the commercial unit (referred to as the p/c).

$$\frac{p}{c} = \frac{average\ E.coli\ \log reduction\ of\ the\ project\ prototype}{average\ E.coli\ \log reduction\ of\ the\ commercial\ unit}$$

Equation 4-1, p/c ratio calculation

For example, if the prototype has an average *E. coli* log reduction of 2 at a given watt per flow, and the commercial unit has 1 log reduction at the same watt per flow; the p/c will equal to 2, which means the project prototype has 2 times more *E. coli* log reduction than the commercial unit. When p/c is greater than one, means the project prototype has better performance than the commercial unit has; otherwise, the commercial unit is better. The comparison of the reactors are summarized in Figure 4-8

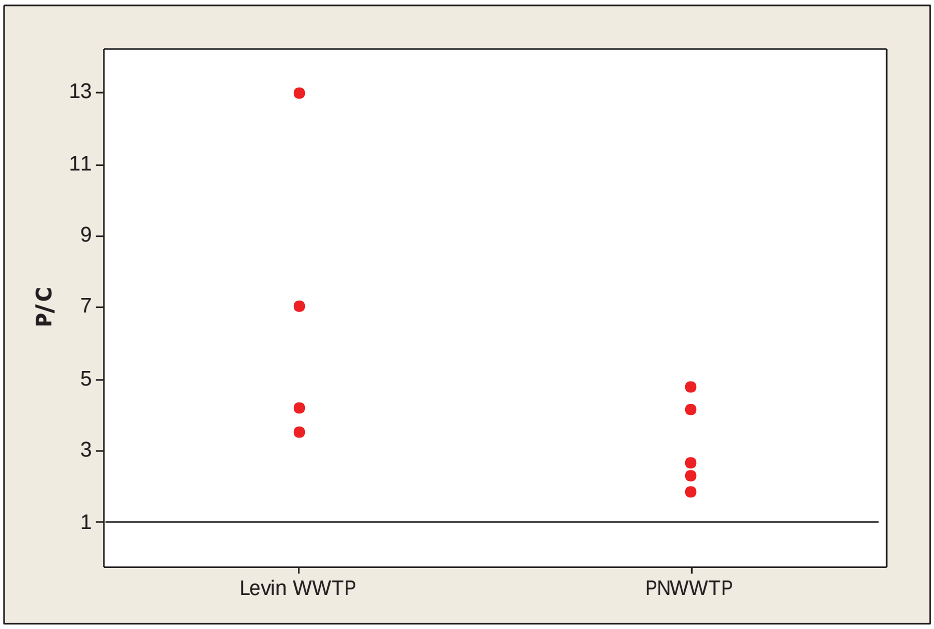


Figure 4-8, p/c of the project prototype and commercial unit in the primary treated wastewater test

Figure 4-8 shows that all the scatters have p/c greater than one, which means that the project prototype always performed better than the commercial unit. On average, the project prototype performed 6.9 times better than the commercial unit at the Levin WWTP and 3.1 times better at the PNWWTP. In the best scenario, the project prototype performed up to 13 times better than the commercial unit at the Levin WWTP and up to 5 times better at the PNWWTP. Overall, this suggests that the project prototype has a much better performance than the commercial unit on primary treated wastewater.

As mentioned earlier, the wastewater in most of marine outfalls is only primary treated. Although some marine outfalls disinfect the wastewater by chlorine before it is discharged, chlorine disinfection is forbidden in most of European countries. UV disinfection is rarely used for treating the effluent from marine outfalls, as the wastewater has low UVT and high TSS, which is unfavourable for UV disinfection. As the consent for marine outfalls might become increasingly strict, disinfection would be necessary in the future. The project prototype, a supercritical flow UV reactor, can effectively disinfect primary treated wastewater, which means a potential application in marine outfalls.

The colilert method (see section 3.4.2) does not only provide the *E. coli* concentration measurement, but also the total coliform concentration. Thus, the total coliform data were also recorded (see Appendix 1). The data of the total coliform will not be discussed, unless contradictory results are found. However, it is interesting to mention that the effluent of the project prototype at 4 W. min/L had total coliform concentration of 53,027 MPN/100 mL in PNWWTP test and 36,606 MPN/100 mL in Levin test. According to the WHO recommendation, wastewater should contains faecal coliform less than 100,000 MPN/100 mL for restricted irrigation, such as industrial and fodder crops, pasture and trees irrigation (Blumenthal et al., 2000). Faecal coliform is a subset of coliform bacteria (IDEXX Laboratories, 2013), which means that if the total coliform is lower than 100,00 MPN/100 mL, the faecal coliform concentration will not exceed this level. These results indicate the potential application of the project prototype for primary treated wastewater irrigation.

4.3.2. Secondary treated wastewater test

In a conventional wastewater treatment plant, UV disinfection is usually used after the secondary treatment (biological and chemical treatment). The project prototype and commercial unit were therefore compared after the secondary treatment stages (prior to the installed UV system) of the PNWWTP, Levin WWTP and Paraparaumu WWTP.

4.3.2.1. PNWWTP secondary treated wastewater test

In the PNWWTP secondary treated wastewater test, the influent of the installed UV system in the plant was used, which is treated by the aerated lagoon and clarifier. The wastewater had a UVT of 22 %, TSS of 27 mg/ L and average *E. coli* concentration of 18,395 MPN / 100 mL. The *E. coli* log reduction of the reactors in the PNWWTP secondary treated wastewater test is plotted in Figure 4-9.

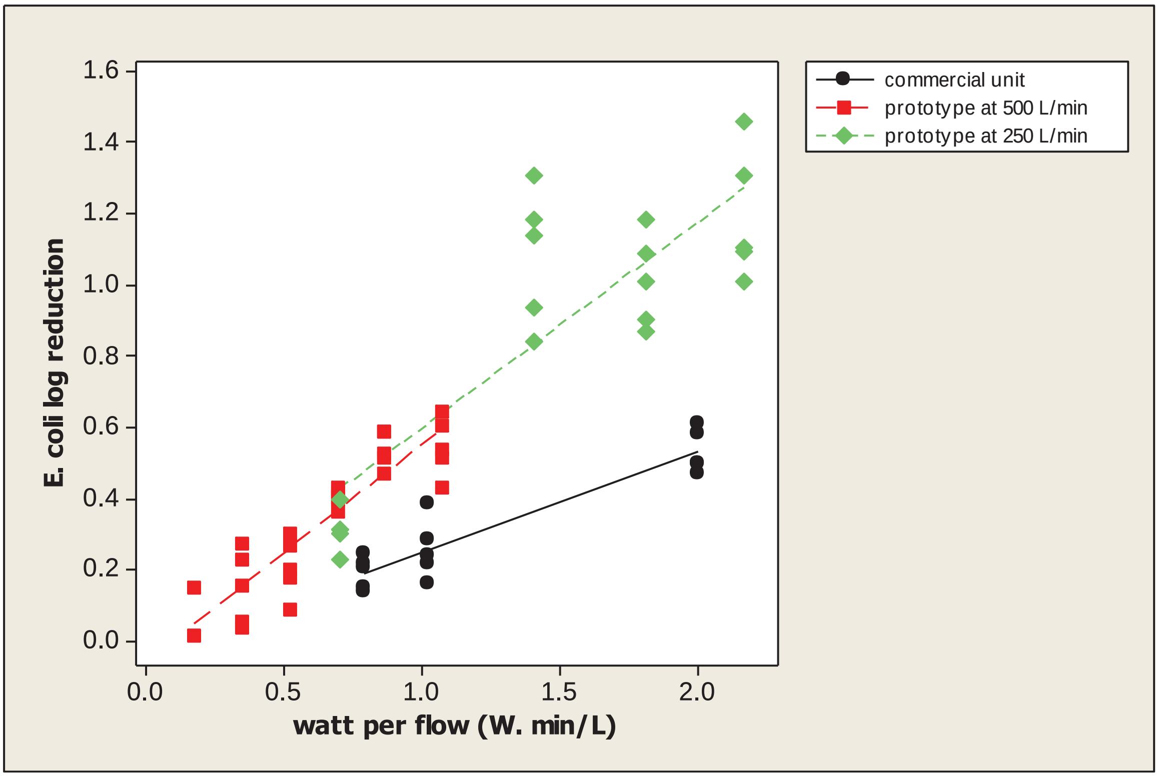


Figure 4-9, *E. coli* log reduction of the reactors in the PNWWTP secondary treated wastewater test

Figure 4-9 shows that the project prototype generally had greater *E. coli* log reduction than the commercial unit, at a given watt per flow. This suggests that the project prototype was more effective in disinfection than the commercial unit. In addition, the figure shows that the project prototype offered the same level of performance as the commercial unit, at a lower watt per flow. For example, the project prototype at 1 W. min/L had as much *E. coli* log reduction as the commercial unit at 2 W. min/L (p-value of 0.76), which required 2 times lower watt per flow than the commercial unit. This suggests that the project prototype was more energy efficient than the commercial unit.

In Figure 4-9, although only one set of data points of the project prototype at 500 and 250 L/min is comparable, the trend lines of the prototype data are almost match. The statistical analyses also agree that the regression of the prototype at 500 L/min is similar to the regression of the prototype at 250 L/min. This suggests that the project prototype performed similarly at the operated flow rate of 500 and 250 L/min, as long as the watt per flow remained the same.

4.3.2.2. Levin WWTP secondary treated wastewater test

The wastewater from the aerated lagoon in the Levin WWTP was used, which had a UVT of 30%, TSS of 5 mg/L and an average *E. coli* concentration of 549,307 MPN/100 mL. The UVT was similar to the wastewater in previous test (see section 4.3.2.1), but the average *E. coli* concentration was 10 times higher. Also, the TSS was lower than expected for this level of UVT and *E. coli* concentration. This might be due to the effluents of the meatworks (as mentioned in section 3.3.3.2). The *E. coli* log reduction of the reactors from Levin secondary treated wastewater test is plotted in Figure 4-10. Unfortunately, some data are missing from this test, due to the insufficient dilution of the samples in the enumeration analysis and therefore exceed the Colilert measurement limit.

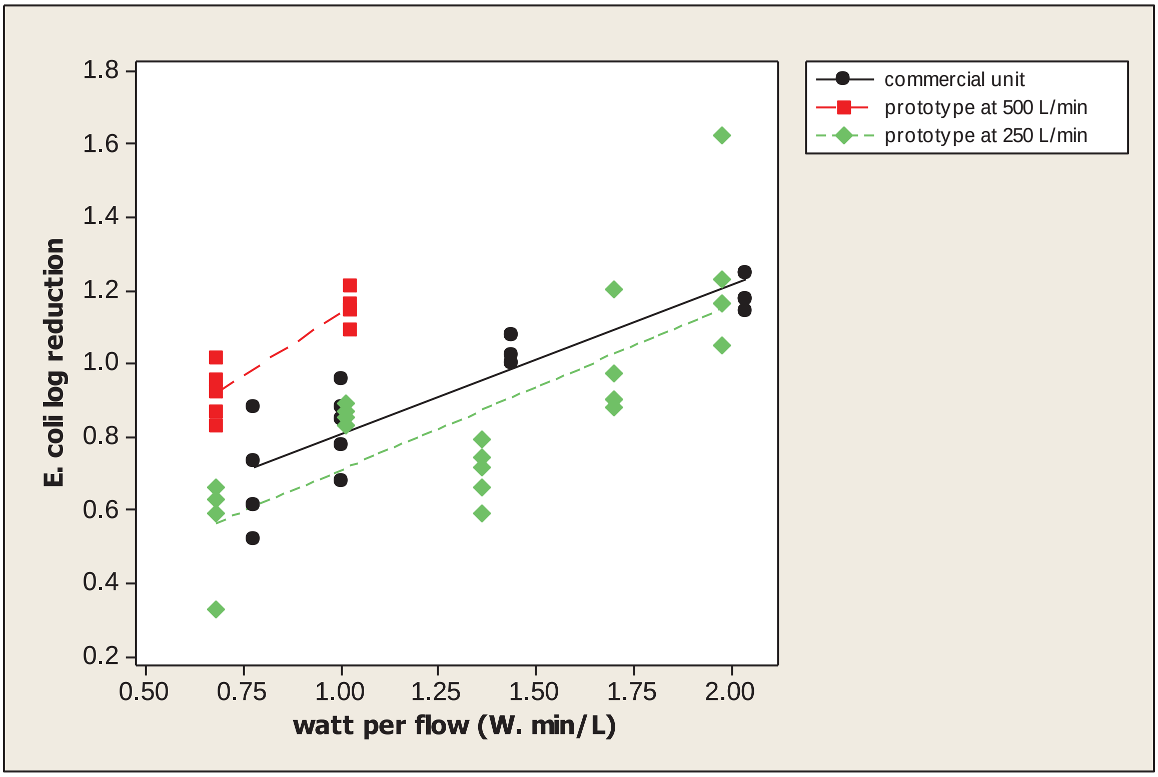


Figure 4-10, *E. coli* log reduction of the reactors in the Levin WWTP secondary treated wastewater test

Figure 4-10 appears that the project prototype had better *E. coli* log reduction than the commercial unit, at the operated flow rate of 500 L/min, but had similar log reduction at 250 L/min. However, the statistical analyses suggest that the regressions of the project prototype data are similar to the commercial unit data. This suggests that the project prototype performed as good as the commercial unit, but did not demonstrate superior disinfection.

As mentioned, although Figure 4-10 appears to show that the trend line of the project prototype at 500 L/min had higher *E. coli* log reduction than the trend line at 250 L/min, the statistical analyses suggest that the regressions of the project prototype data are the same. This suggests that the project prototype performed similarly at the operated flow rate of 500 and 250 L/min (more discussion will be in section 4.4).

4.3.2.3. Paraparaumu WWTP secondary treated wastewater test

As mentioned in section 3.3.3.3, Paraparaumu WWTP is the most advanced WWTP used in the study. The influent of the installed UV system in was used, which had a UVT of 55%, TSS of 5 mg/L and an average *E. coli* concentration of 32,551 MPN/100 mL. The wastewater had a high UVT and low TSS after the secondary treatment, which was an ideal influent for the UV system. The *E. coli* log reduction of the reactors in the Paraparaumu WWTP secondary treated wastewater test is plotted in Figure 4-11. Once more, some data are missing in the figure due to the dilution errors. The *E. coli* concentration was somehow higher than the concentration that had been found from the prior dilution test (details of dilution test see section 3.4.2).

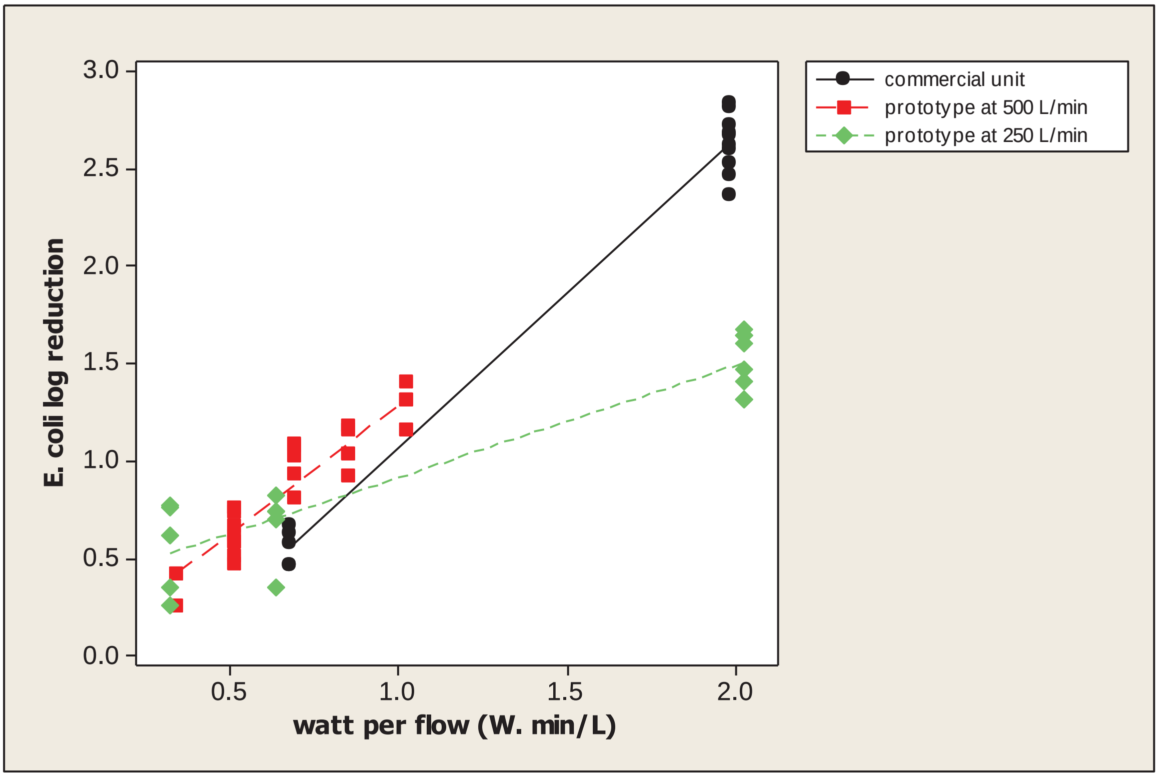


Figure 4-11, *E. coli* log reduction of the reactors in the Paraparaumu WWTP secondary treated wastewater test

The commercial unit only had two data points in Figure 4-11. At watt per flow of 0.6 W. min/L, the *E. coli* log reduction of the commercial unit was similar to the prototype at 250 L/min (p-value of 0.26), but significantly lower than the prototype at 500 L/min (p-value of 0.00). At watt per flow of 2 W. min/L, the commercial unit performed significantly better than the prototype (at 250 L/min). This suggests that the project prototype performed better than or equal to the commercial unit at a low watt per flow regime, but performed significantly worse at a high watt per flow regime.

Figure 4-11 shows the project prototype had similar performance at the operated flow rate of 500 and 130 L/min, when the watt per flow was 0.3 W. min/L, but the reactor performed better at 500 L/min, when the watt per flow was 0.6 W. min/L. The statistical analyses also suggest that the regression of the prototype at 500 L/min has greater slope than the regression at 250 L/min. This suggests that the project had better performance at the operated flow rate of 500 L/min than at 250 L/min (further discussion see section 4.4).

4.3.2.4. Summary of the secondary treated wastewater test

The project prototype and commercial unit were compared after the secondary treatment of the PNWWTP, Levin WWTP and Paraparaumu WWTP. The comparisons of the project prototype and the commercial unit are summarized in Figure 4-12.

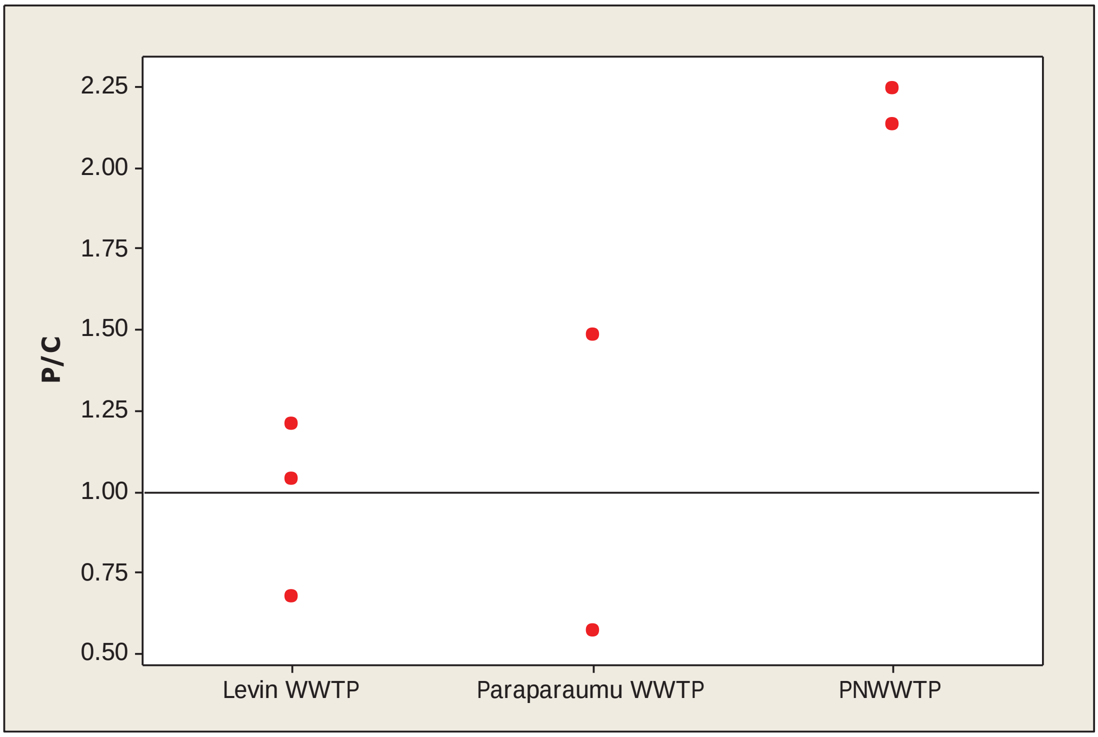


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Figure 4-12, p/c of the project prototype and commercial unit in the secondary treated wastewater test

Figure 4-12 shows that most of the data are above one, which suggests that the project prototype performed generally better than the commercial unit, on secondary treated wastewater. On average, the project prototype performed 2.2 times better than the commercial unit at the PNWWTP, but the reactor had similar performance to the commercial unit at the Levin and Paraparaumu WWTP (average p/c of 1 in both cases). Overall, this suggests that the project prototype might have some advantage over the commercial unit, when treating secondary treated wastewater. Therefore, it could be a viable option for secondary treated wastewater disinfection.

4.3.3. Tertiary treated wastewater test

As the resource consents become increasingly restricts, wastewater is tertiary treated before UV disinfected in some WWTP. For example, alum dosing is occasionally used in PNWWTP depending (see section 3.3.3.1), and membrane filtration is used after the secondary treatment in Fielding WWTP (see section 3.3.3.4). The tertiary treated wastewater generally has high UVT, low TSS and low *E. coli* concentration, which favours the use of a traditional UV reactor (including the commercial unit).

In theory, the project prototype might only have the advantage at treating low UVT wastewater. As mentioned in section 2.6.4, the project prototype has a non-submergible UV lamp configuration, which a significant amount of UV light can be lost due to the reflection. With low UVT wastewater disinfection, the loss of UV light as it pass through the fluid will be significant for the commercial unit. This means that the UV loss due to the reflection in the project prototype might be lower than the loss due to the low UVT wastewater in the commercial unit. However, with high UVT wastewater disinfection, the UV loss in the project prototype might be greater than the loss in the commercial unit. Therefore, the project prototype could only perform better than the commercial unit, when treating low UVT wastewater. In order to confirm this hypothesis and also evaluate the applicability of the project prototype for tertiary treated wastewater disinfection; the project prototype and the commercial unit were compared at the tertiary treatment of PNWWTP and Fielding WWTP.

4.3.3.1. PNWWTP tertiary treated wastewater test

Similar to the PNWWTP secondary treated wastewater test, the influent of the installed UV system was used, but the wastewater was alum dosed. Alum is a chemical, which can significantly reduce the concentrations of phosphorus, TSS and even microorganisms in wastewater. The wastewater had a UVT of 55%, TSS of 16 mg/L and an average *E. coli* concentration of 241.6 MPN /100 mL. The quality of the wastewater was overall improved, compares to secondary treated wastewater (without alum dosing). The UVT of the wastewater was high, and TSS and *E. coli* concentration is low, indicating a relatively clear and ideal effluent for UV disinfection. The *E. coli* log reduction of the reactors in the PNWWTP tertiary treated wastewater test is plot in Figure 4-13.

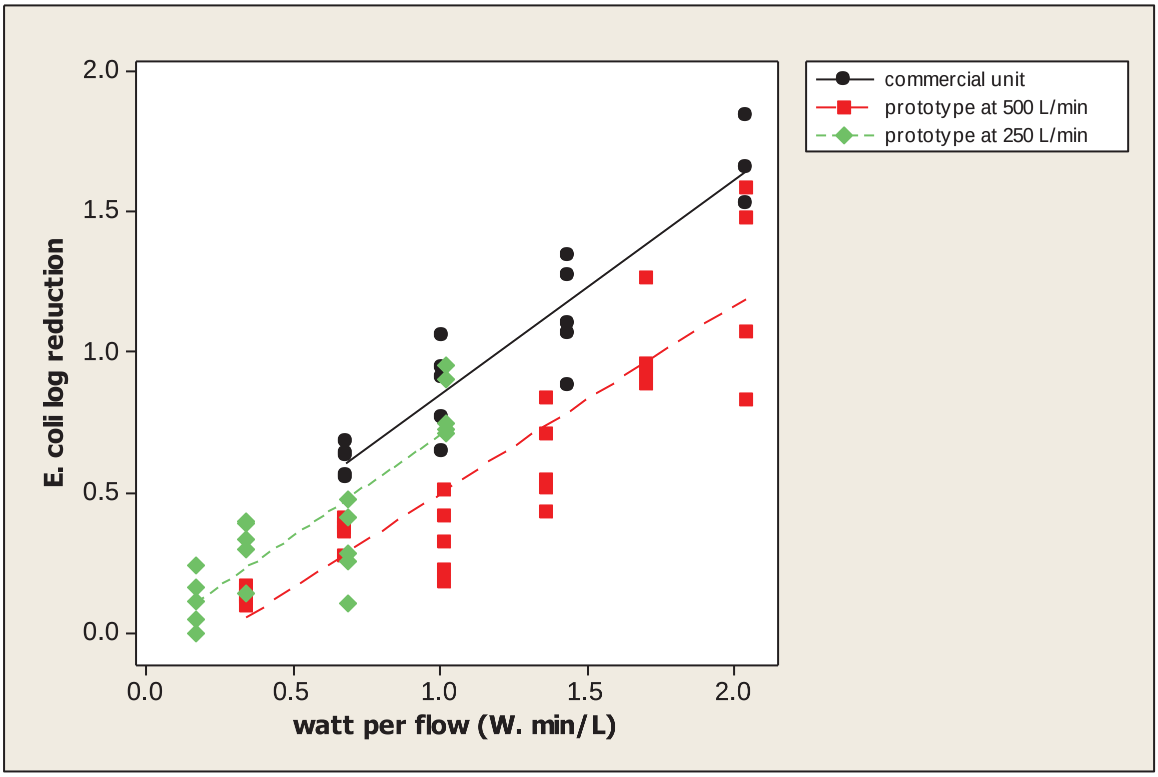

Figure 4-13, *E. coli* log reduction of the reactors in the PNWWTP tertiary treated wastewater test

It is noticed that the *E. coli* concentration of the wastewater was low, of which the UV disinfection would likely to be at the tailing region, so the microorganism will be harder to be disinfected (as discussed in section 2.4.3). However, the regressions of the project prototype and the commercial unit are reasonably linear, which suggests that the reactors were not operating at the tailing region.

While Figure 4-13 indicating that the commercial unit performed better than the project prototype, the statistical analyses suggest that the regressions of the commercial unit data and the project prototype data are the same. This suggests the project prototype performed worse than or equal to the commercial unit.

In Figure 4-13, the trend lines of the prototype at 500 and 250 L/min have similar slopes, but the trend line of 500 L/min is somewhat lower than the trend line at 250 L/min. Nevertheless, the statistical analyses suggest that the regressions of the prototype data are similar. This suggests that the project prototype performed similarly at the operated flow rate of 500 and 250 L/min.

4.3.3.2. Fielding WWTP tertiary treated wastewater test

The influent of the installed UV system in Fielding WWTP was used. The wastewater had a UVT of 64%, TSS of 7.5 mg/L and an average *E. coli* concentration of 134.3 MPN /100 mL. The quality of this wastewater was even better than the PNWWTP tertiary treated wastewater. The *E. coli* log reduction of the reactors from Fielding WWTP tertiary treated wastewater test is plotted in Figure 4-14. While the reactors were tested up to 4 W. min/L, the *E. coli* concentration of the effluent (at 4 W. min/L) was too low to be detected, and therefore is not shown in the figure. Again, the reactors were unlikely operating at the tailing region, as the regressions are reasonably linear.

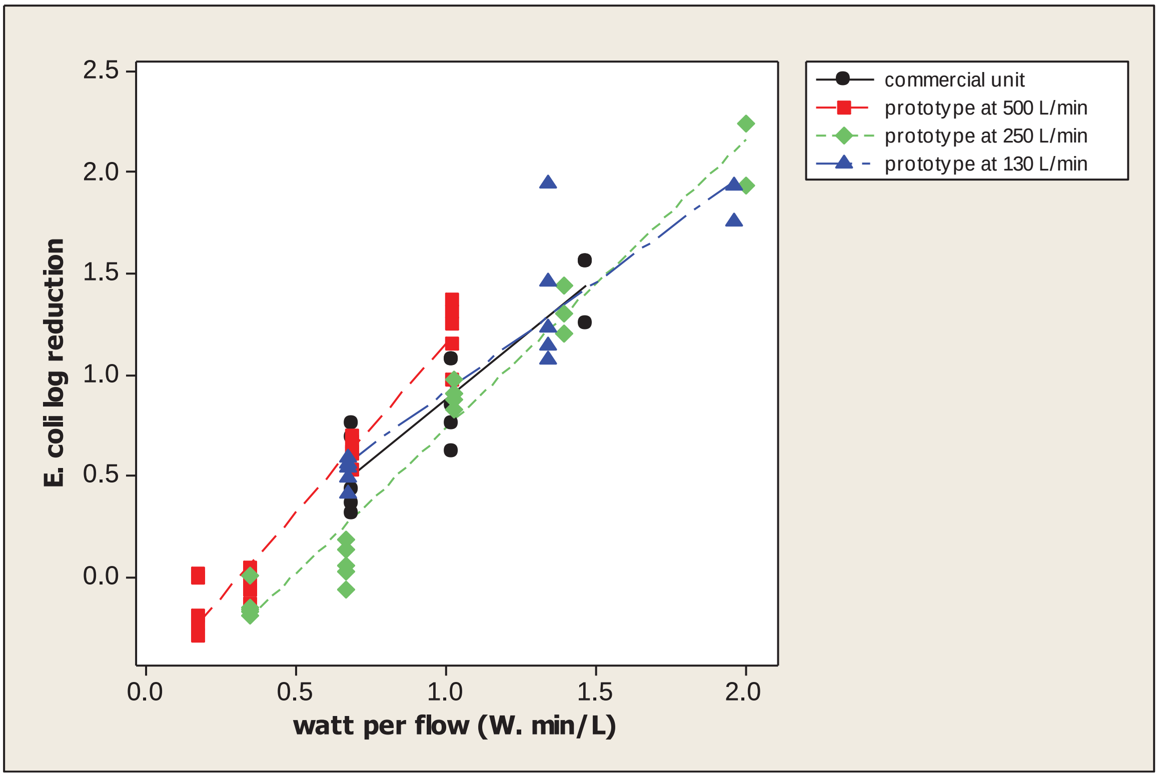

Figure 4-14, *E. coli* log reduction of the reactors in the Fielding WWTP tertiary treated wastewater test

Figure 4-14 shows the data of the commercial unit and project prototype are overlapping. Also, the statistical analyses agree that the regressions of the reactors are the same. This indicates that the project prototype performed similar to the commercial unit.

Figure 4-14 shows most of the project prototype data at 500, 250 and 130 L/min are overlapping, except for the 250 L/min prototype data at 0.6 W. min/L. Nevertheless, the statistical analyses confirms that the regressions of the prototype data are the same. This suggests that the project prototype performed similarly at the operated flow rate of 500, 250 and 130 L/min.

It is noticed that Figure 4-14 shows that some negative *E. coli* log reduction data at low watt per flow range, where negative log reduction is insensible. This negative value is due to the variation of wastewater.

4.3.3.3. Summary of the tertiary treated wastewater test

The project prototype and commercial unit were compared on the tertiary treated wastewater at the PNWWTP and Fielding WWTP. The wastewater in both tests was reasonably clear and ideal for a traditional UV reactor disinfection. The results of the tertiary treated wastewater test are summarized in Figure 4-15.

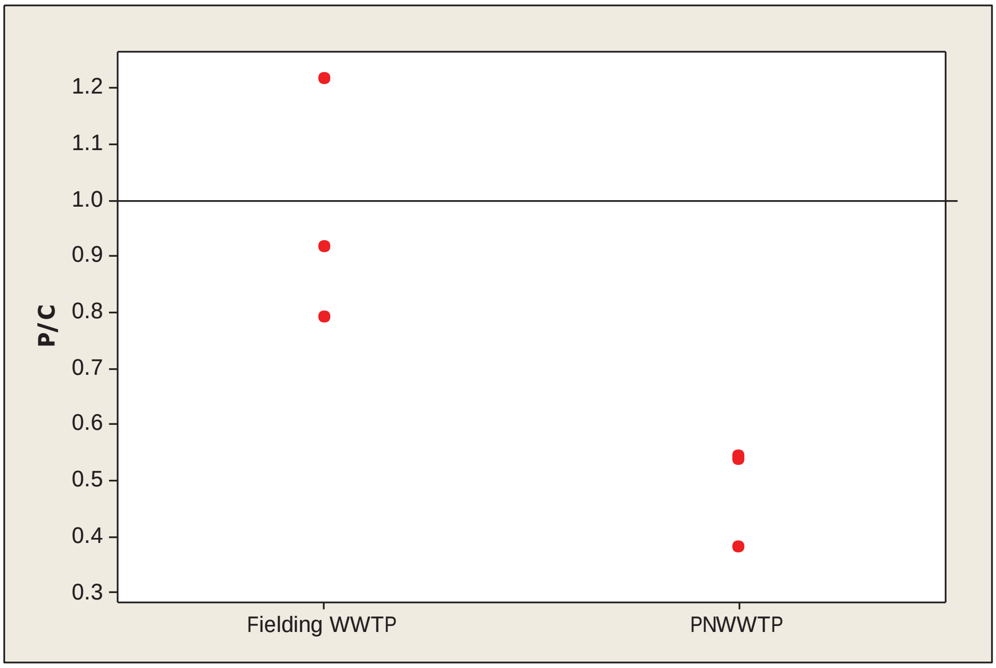

Figure 4-15, p/c of the project prototype and commercial unit in the tertiary treated wastewater test

Figure 4-15 shows that the p/c value of Fielding WWTP varied from 0.75 to 1.25 and the p/c value of PNWWTP varied from 0.35 to 0.55. On average, Fielding WWTP has p/c of 0.97 and PNWWTP has p/c of 0.48. This suggests that the project prototype performed similar to the commercial unit at Fielding WWTP, but 2.1 times (p/c of 0.48) worse at PNWWTP. This contradicts the results from the PNWWTP tertiary treated wastewater test, which suggested that the project prototype had no difference in performance from the commercial unit. The results in PNWWTP test were compared based on the overall performance of the reactors, so that the statistical analyses suggest that the performance of the reactors were similar. In contrast, the p/c value compares the performance of the reactors at individual points, where the result in Figure 4-13 does appear to show that the commercial unit was better than the project prototype, at certain points of watt per flow. Overall, the test confirms that the project prototype only has advantage at treating low UVT wastewater, but not high UVT wastewater.

4.3.4. Stabilization pond treated wastewater test

Traditionally, UV disinfection is not commonly used in stabilization ponds, as it was believed that the high TSS of stabilization pond wastewater could not be efficiently disinfected by UV light. Later, Emerick *et al.* (1999) found that effect of TSS on UV disinfection not only depends on TSS concentration, but also how the bacteria are embedded in particles (discussions see section 2.4.2). Based on this, Nelson (2000) argue that UV disinfection is applicable in stabilization ponds, and showed that UV disinfection has been already used at the stabilization ponds in Canada and the United States. Now, UV disinfection is commonly used in New Zealand stabilization ponds; such as in Himatangi Beach, Featherson and Martinborough (Crimp & Sloan, 2014).

In order to test the applicability of the project prototype in stabilization ponds, the project prototype and commercial unit were tested five times at three different stabilization ponds. The ponds are allocated at Rongotea, Shannon and Foxton Beach.

4.3.4.1. Rongotea stabilization pond treated wastewater tests

First test

In the first test, the Rongotea wastewater had a UVT of 20.1 % and TSS of 90 mg/L. The *E. coli* concentration was 965 MPN/100 mL in the beginning, but 4,219 MPN/100 mL in the middle of the UV test and 3,940 MPN/100 mL at the end of the UV test. Although the *E. coli* concentration varied, the UVT and TSS were consistent throughout the UV test. At this stage, no possible reason could explain the variation of the *E. coli* concentration. It is interesting to note that the wastewater had a low UVT and high TSS, but the *E. coli* concentration was unexpectedly low for this level of UVT and TSS. This is due to the intrinsic disinfection mechanism of the pond (Pearson, 2003). The *E. coli* log reduction of the reactors in the first Rongotea stabilization pond test is plotted in Figure 4-16.

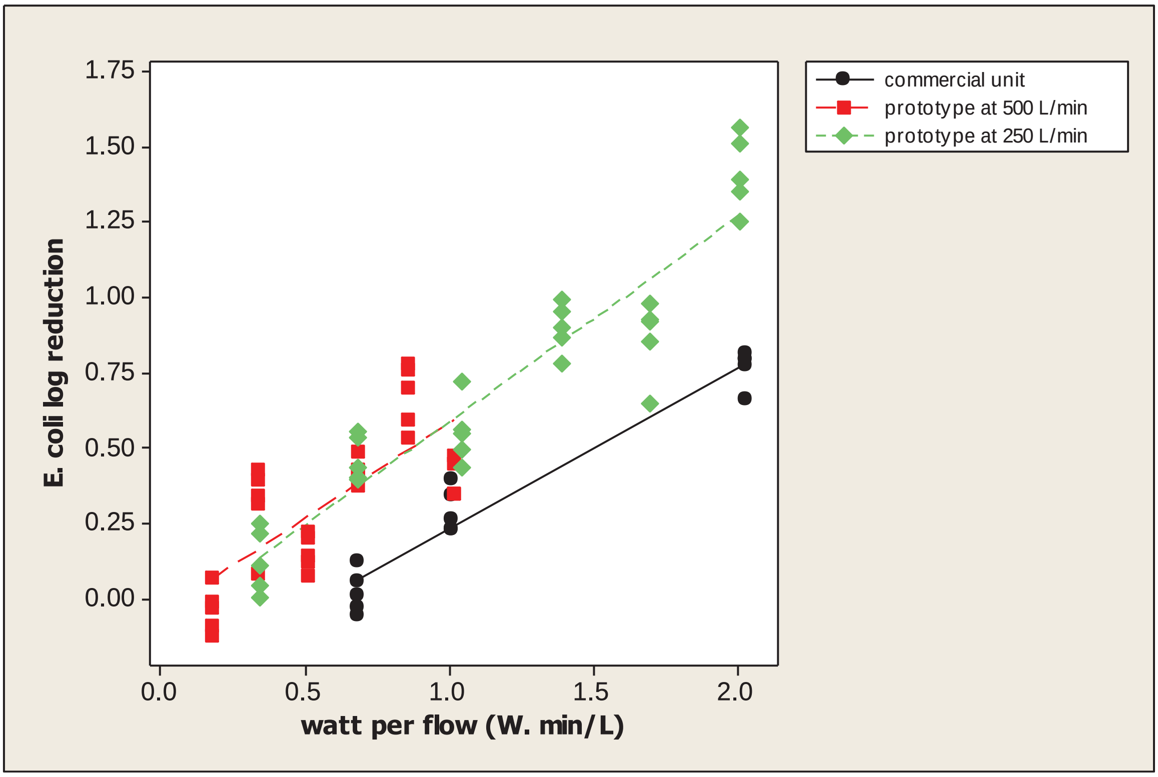

Figure 4-16, *E. coli* log reduction of the reactors in the first Rongotea stabilization pond test

Although Figure 4-16 appears to show that the project prototype performed better than the commercial unit, the statistical analyses argue that the regressions of the project prototype data and commercial unit data are similar. This suggests that the prototype performed better than or equal to the commercial unit in the test.

In Figure 4-16 , the trend lines of the project prototype are almost matched, and the statistical analyses agree that the regressions of the prototype data are similar. This suggests that the prototype performed similarly at the operated flow rate of 250 and 500 L/min.

Second test

In the second Rongotea test, the wastewater had a UVT of 11.5%, TSS of 171.5 mg/L and an average *E. coli* concentration of 19,014 MPN/100 mL. Comparing to the previous test, the UVT was almost 2 times lower, the TSS was almost 2 times higher and the *E. coli* concentration was 10 times greater. This demonstrates the variation of the stabilization pond wastewater. The *E. coli* log reduction of the reactors in the second Rongotea stabilization pond test is plotted in Figure 4-17.

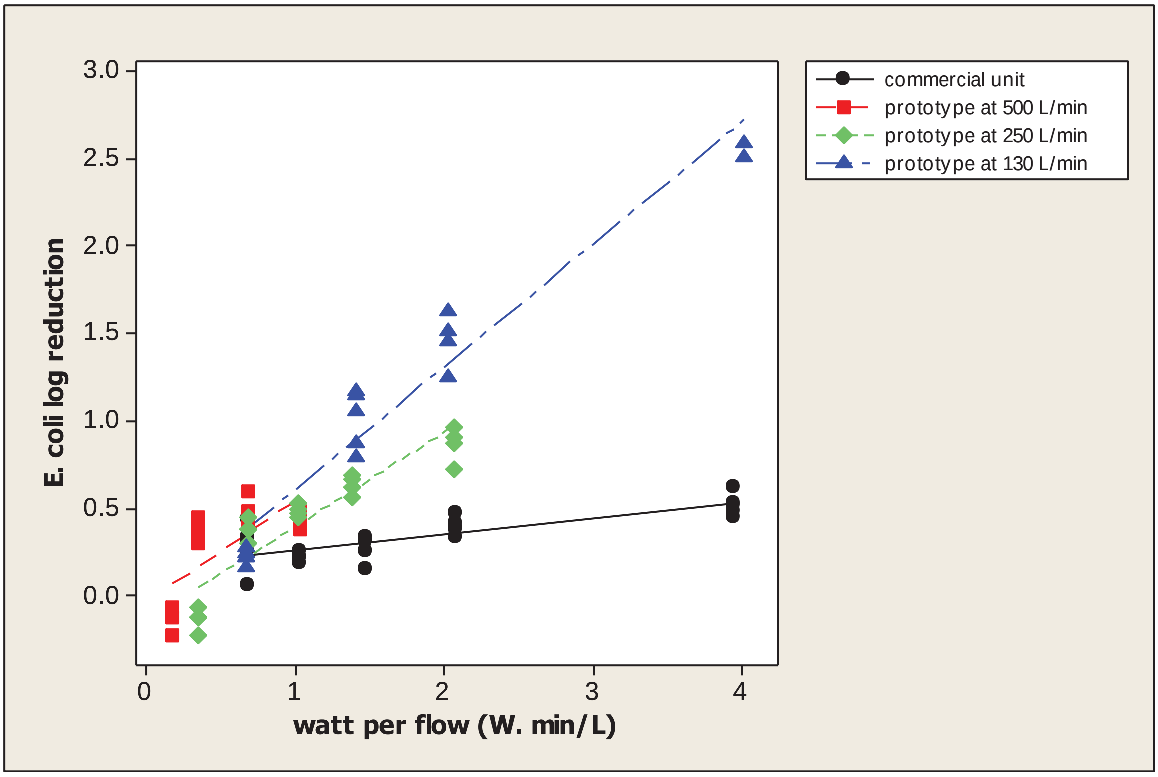

Figure 4-17, *E. coli* log reduction of the reactors in the second Rongotea stabilization pond test

Figure 4-17 shows that at a watt per flow of 1 W. min/L or greater, the project prototype had greater *E. coli* log reduction than the commercial unit. Although the watt per flow of the commercial unit was increased up to 4 W. min/L, little *E. coli* can be inactivated (less than 0.5 log reduction). In contrast, the project prototype could achieved up to 2.5 *E. coli* log reduction at 4 W. min/L. This suggests that the project prototype was more effective at disinfecting the wastewater. Moreover, the project prototype required much less watt per flow to offer a similar disinfection level of the commercial unit. For example, the project prototype at 1 W. min/L had similar *E. coli* log reduction to the commercial unit at 4 W, (p-value of 0.42), which needed 4 times less watt per flow. This suggests that the project prototype was more energy efficient than the commercial unit, in the test.

Figure 4-17 also indicates that the project prototype had similar performance at the operated flow rate of 500, 250 and 130 L/min. The statistical analyses suggest that the regressions of the project prototype data at these flow rates are the same. This suggests that the project prototype performed similarly at the operated flow rate of 500, 250 and 130 L/min.

4.3.4.2. Shannon stabilization pond treated wastewater tests

First test

In the first test, the wastewater had a UVT of 20%, TSS of 75 mg/L and an average *E. coli* concentration of 49,078 MPN/100 mL. These are the typical wastewater characteristics in a stabilization pond system. The *E. coli* log reduction of the reactors in the first Shannon stabilization pond test is plotted in Figure 4-18.

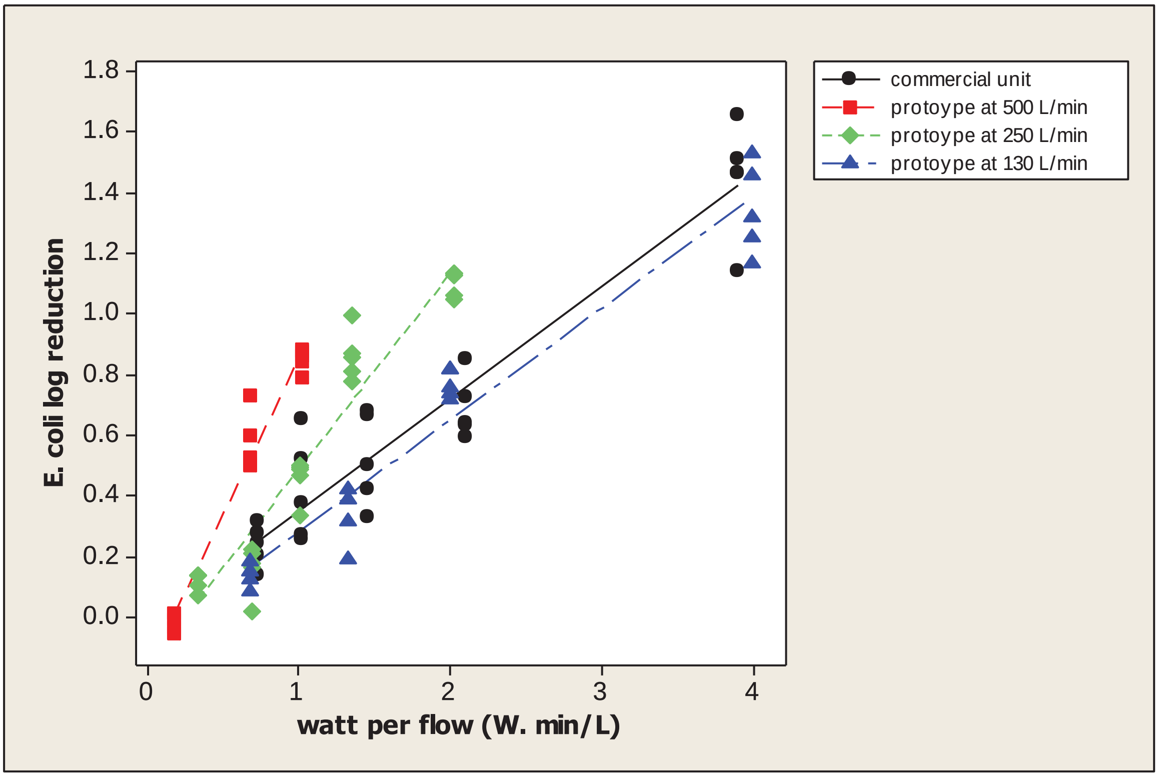

Figure 4-18, *E. coli* log reduction of the reactors in the first Shannon stabilization pond test

Figure 4-18 shows that the project prototype performed differently at 500, 250 and 300 L/min, at a given watt per flow. This is confirmed by the statistical analyses, which the regressions of the project prototype at 500, 250 and 130 L/min are different (more discussion see section 4.4). At the operated flow rate of 130 L/min, the project prototype had similar performance to the commercial unit, where the data are overlapping and the regressions are statically the same. At the operated flow rate of 250 L/min, the project prototype had better performance than the commercial unit, when watt per flow was greater than 1.3 W. min/L. At the operated flow rate of 500 L/min, the project prototype generally performed better than the commercial unit did. Overall, this suggests that the project prototype performed better than or equal to the commercial unit, depending on the operated flow rate.

Second test

In the second trail, the wastewater had a UVT of 24%, TSS of 66 mg/L and average *E. coli* concentration of 93,298 MPN/ 100 mL, which was reasonably similar to the first test. The *E. coli* log reduction of the reactors in the second Shannon stabilization pond test is plotted in Figure 4-19. The data at 4 W. min/L are missing, due to the over dilution of the samples during the enumeration analysis.

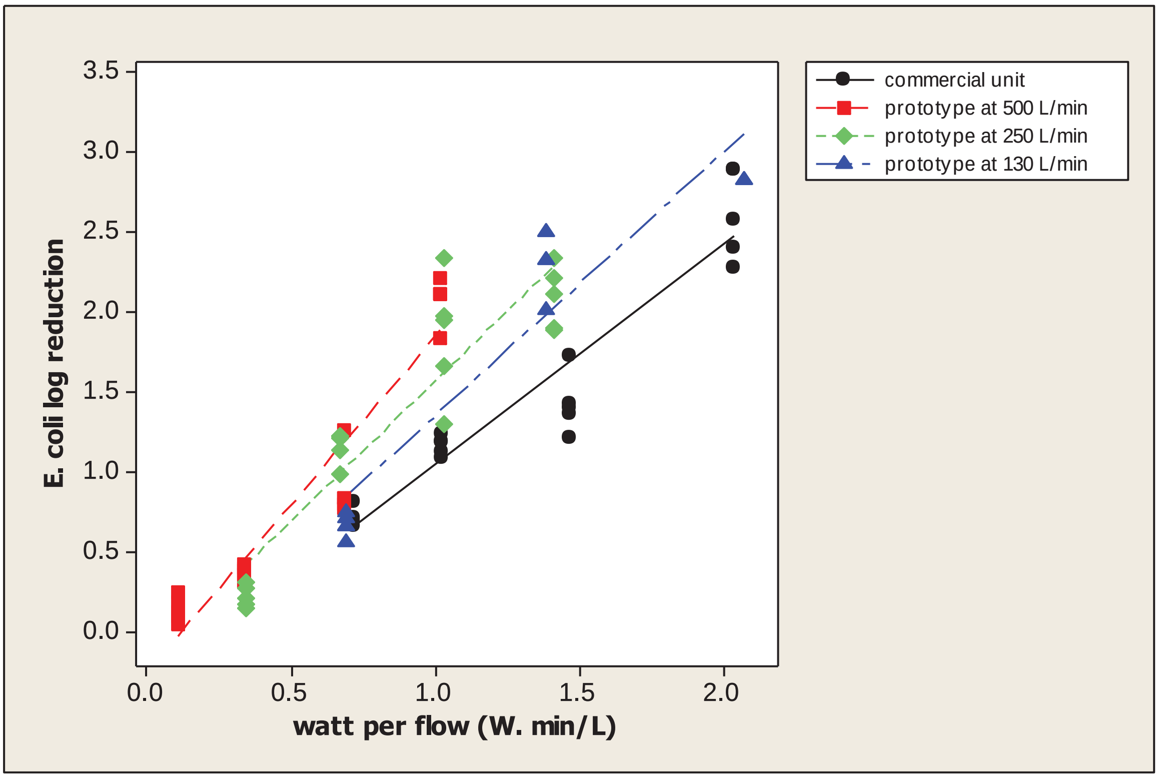

Figure 4-19, *E. coli* log reduction of the reactors in the second Shannon stabilization pond test

Figure 4-19 shows that the project prototype generally had better performance than the commercial unit, after the watt per flow was greater than 1 W. min/L. However, the statistical analyses suggest that only the regression of the project prototype at 500 L/min is different from the regression of the commercial unit. This suggests that the project prototype performed equal to or better than the commercial unit, depending on the operated flow rate.

Figure 4-19 shows that most of the project prototype data at 500, 250 and 130 L/min are overlapping at, when the watt per flow was similar. Also, the statistical analyses suggests that the regressions of the prototype are the same. This suggests that the prototype performed similarly at the operated flow rate of 500, 250 and 130 L/min.

Interestingly, both reactors performed unexpectedly well comparing to the first test. For example, the reactors achieved up to 2.5 *E. coli* log reduction at 2 W. min /L, in this test, but achieved less than 1.2 log reduction in the first test. According to the experimental notes, the second test was conducted in winter, but the first test was in summer. This suggests that the UV disinfection in pond system has seasonal effect. However, USEPA *et al.* (2006) stated that the temperature of the fluid has no effect on UV disinfection, but only the UV dose. Therefore, the observation is unexplainable at the current stage.

4.3.4.3. Foxton Beach stabilization pond treated wastewater tests

In this test, the secondary pond wastewater was used. The wastewater characteristics changed significantly within the test. In the beginning, the wastewater had a UVT of 25%, TSS of 97 mg/L and an average *E. coli* concentration of 54,447 MPN/100 mL. This wastewater was used in the commercial unit test. Later, the UVT of the wastewater became 13.3 % and the TSS became 269 mg/L. In the end, the wastewater had a UVT of 20% and TSS of 160 mg/L. These wastewaters were used in the project prototype test. During the test, the UVT varied more than 10 % and the TSS more than 100 mg/L. The wastewaters used in the project prototype were harder to be disinfected than the commercial unit. It was noticed that the wastewater became greener after the UVT had dropped to 13 %. This might be due to the movement of the algal band, which the algal band is able to move as the climate condition change at certain times of the day (Pearson, 2003). The *E. coli* log reduction of the reactors in the Foxton Beach stabilization pond test is plotted in Figure 4-20.

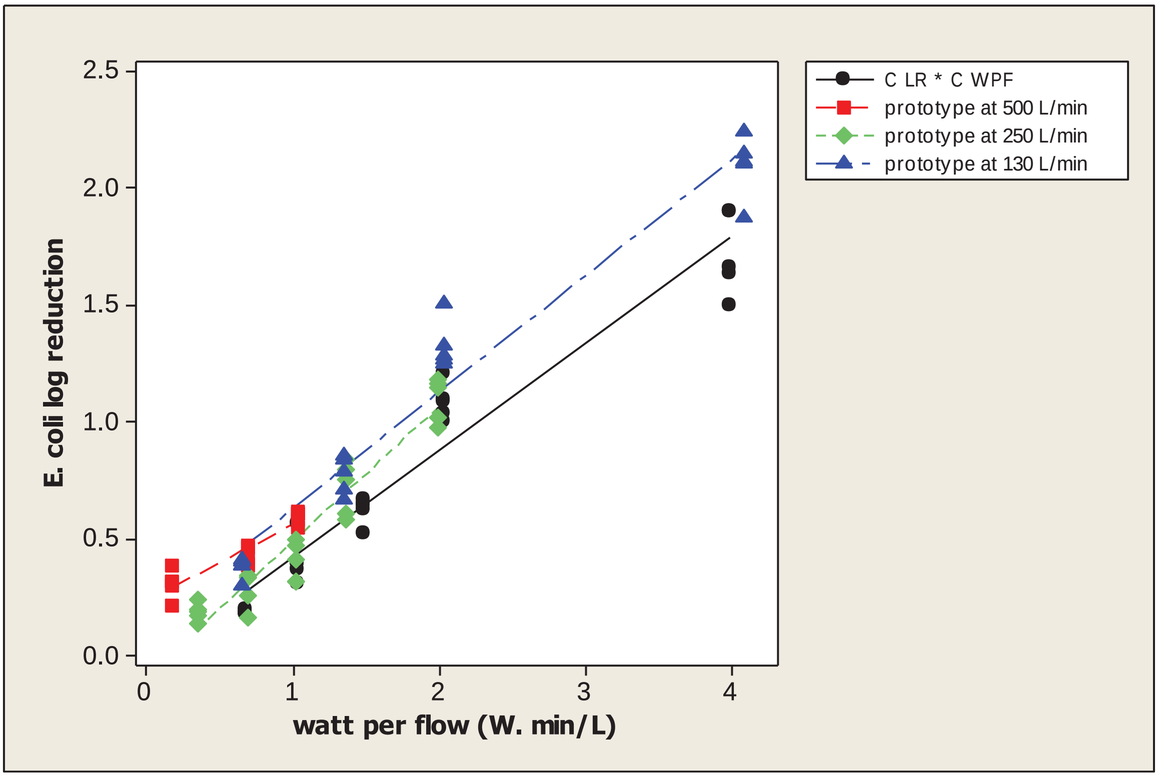

Figure 4-20, *E. coli* log reduction of the reactors in the Foxton Beach stabilization pond test

Although the reactors were compared under unequal conditions, Figure 4-20 shows that the data of project prototype and the commercial unit are mostly overlapping. Also, the statistical analyses agree that the regressions of the project prototype are similar to the regression of the commercial unit. This suggests that the project prototype performed no difference from the commercial unit. In addition, this indicates that the project prototype has consistent performance, even though the wastewater characteristics vary significantly.

Figure 4-20 also shows that the data of the project prototype at 500, 250 and 130 L/min are overlapping, and the statistical analyses suggest that the regressions of the prototype are the same. This suggests that the project prototype performed similarly at the operated flow rate of 500, 250 and 130 L/min.

4.3.4.4. Summary of stabilization pond treated test

The project prototype and commercial unit were compared five times across three different stabilization pond systems. The results of the stabilization pond treated test are summarized in Figure 4-21

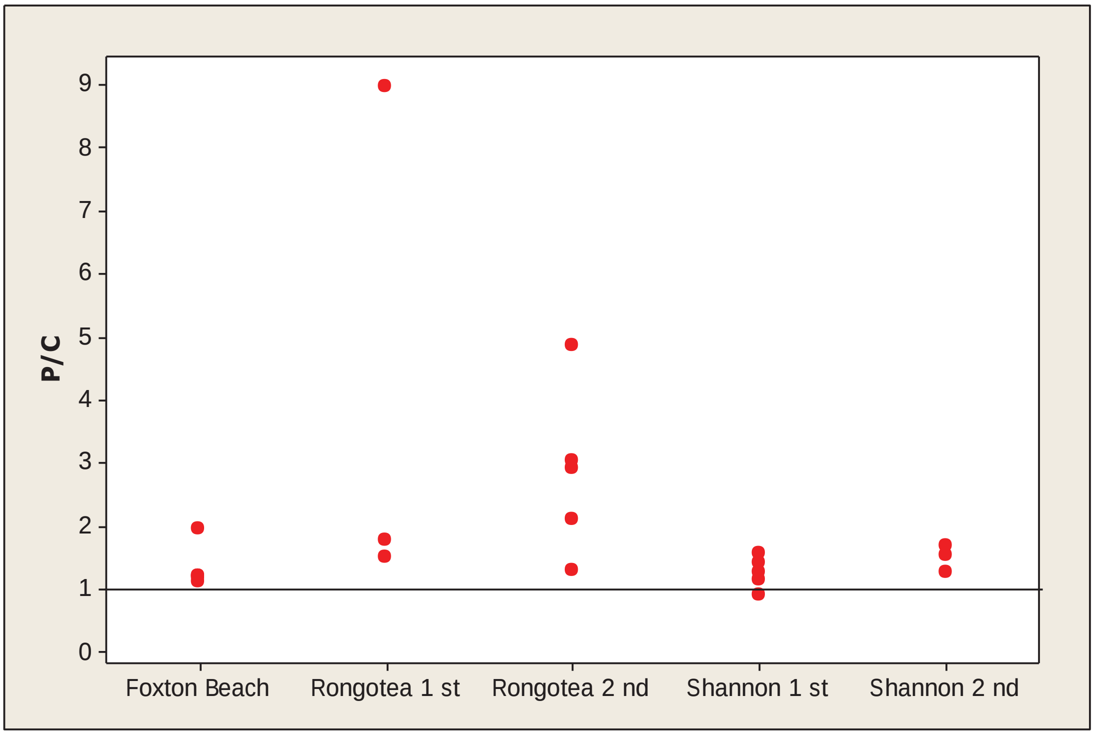

Figure 4-21, p/c of the project prototype and commercial unit in the stabilization pond treated wastewater test

Generally, Figure 4-21 shows that only one data in the first Shannon test is slightly below one. On average, the Foxton Beach test had p/c of 1.3, the first Rongotea test had p/c of 4.1, the second Rongotea test had p/c of 2.9, the first Shannon test had p/c of 1.3 and the second Shannon test had p/c of 1.5. In one case, the p/c can be as big as 9 (in the first Rongotea test). In addition, although the wastewaters were significantly different in these five tests, the project prototype consistently performed better than the commercial unit. This suggests that the project prototype has advantage at treating stabilization pond wastewater.

4.3.5. Summary of the project prototype and commercial unit comparison

The project prototype and commercial unit were compared twelves times at seven different wastewater treatment sites, which were at the conventional wastewater treatment plant and the stabilization ponds. The overall results are summarized in Figure 4-22.

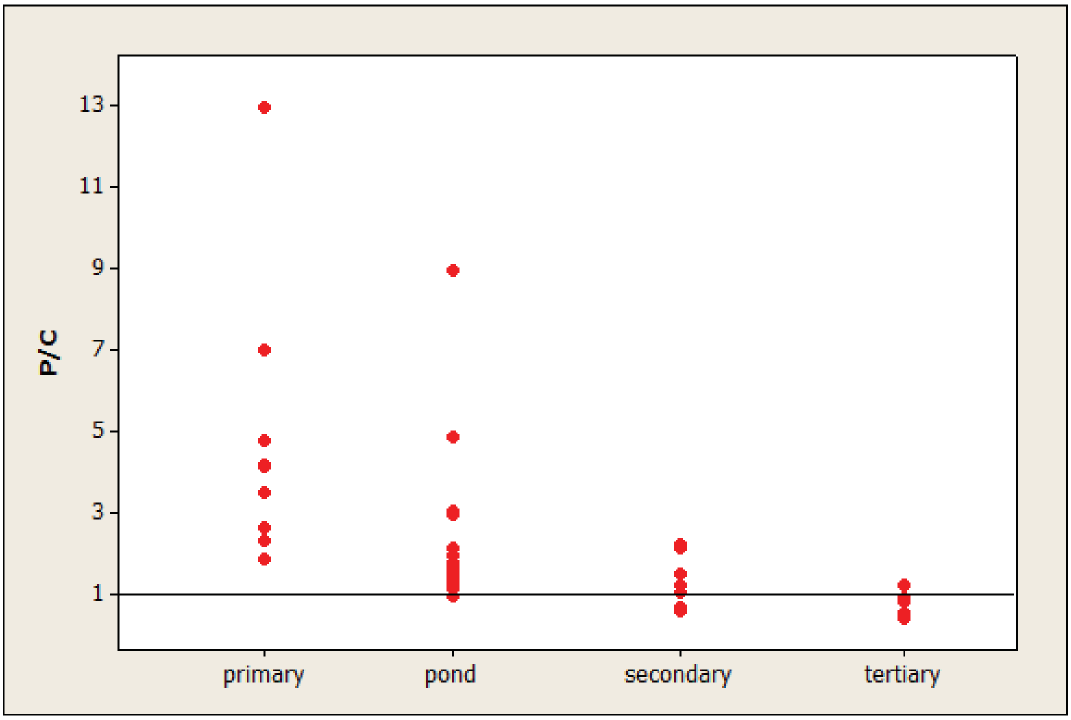

Figure 4-22, summary of the reactor comparison in different type of wastewaters

Figure 4-22 shows that the project prototype had the best performance on primary treated wastewater and the second best on stabilization pond treated wastewater. The project prototype performed occasionally better than the commercial unit on secondary treated wastewater, but generally performed worse than the commercial unit on tertiary treated wastewater. On average, the project prototype performed 4.5 times better than the commercial unit and up to 13 times better in one case, on primary treated wastewater. In stabilization pond test, the reactor performed, on average, 2.1 times better than the commercial unit and up to 9 times better at one location. The reactor performed on average 1.4 times better than the commercial unit on secondary treated wastewater, but 1.4 times worse on tertiary treated wastewater. Overall, this suggests that the project prototype has advantage at treating primary, secondary and stabilization pond treated wastewater. Also, this confirms the feasibility of applying supercritical flow hydraulics for wastewater UV disinfection.

4.4. Effect of flow rate on UV disinfection

The watt per flow of the reactors was manipulated by changing the flow rate and numbers of operated UV lamps, which means that the effect of flow rate on the performance of the prototype is important. If the flow rate could affect the performance of the reactor, the watt per flow would not be a good proxy of UV dose and therefore the difference in performance between the reactors might not be truly demonstrated. This section summarizes the observations (see Table 4-1) from the comparison tests (section 4.3) and then discusses the possible effect of the flow rate and number of operated UV lamps on UV disinfection.

Table 4-1, summary of the effect of flow rate on the project prototype

Test	Observations
PNWWTP primary treated wastewater test	The project prototype at 130 L/min has slightly different performance from at other flow rate, which might be due to the tailing region effect.
Levin WWTP primary treated wastewater test	The project prototype had better performance as the operated flow rate decreased.
PNWWTP secondary treated wastewater test	No effect
Levin WWTP secondary wastewater test	No effect
Paraparaumu WWTP secondary wastewater test	The project prototype had better performance at the operated flow rate of 500 L/min than at 250 L/min.
PNWWTP tertiary treated wastewater test	No effect
Fielding WWTP tertiary treated wastewater test	No effect
1st trial Rongotea	No effect
2nd trial Rongotea	No effect
1st Shannon	The project prototype had better performance as the operated flow rate increases
2nd Shannon	No effect
Foxton Beach	No effect

Table 4-1 shows that three out of the twelves tests, the experiments found that flow rate has effect on the performance of the project prototype. However, the effect was not consistent. For example, while the Levin primary treated wastewater test and Paraparaumu secondary treated wastewater tests suggested that the project prototype would have better performance as the flow rate decrease, the first Shannon test suggested an opposite conclusion. Considering the reactors were tested in an uncontrolled and highly variable environment, these inconsistent observations might be to do with the experimental variations. Overall, insufficient of evidence is found to conclude that flow rate can affect the performance of the project prototype. Therefore, watt per flow could be used for UV dose proxy. Based on this conclusion, watt per flow is recommended to use for future supercritical flow reactors design. If a figure of watt per flow vs. microorganism log reduction is constructed, the flow rate and number of operated UV lamp of the reactor can be easily determined.

4.5. Wastewater characteristics that affect the UV disinfection

As discussed in section 2.4, it is believed that the concentration of microorganisms can affect UV disinfection. Therefore, the data of the experiments were analysed to evaluate the effect of the wastewater characteristics.

Throughout the project, the project prototype and commercial unit were tested four times in the PNWWTP, using secondary treated wastewater. The watt per flow for both reactors was at 1 W. min/L. The common settings for the project prototype were sluice gate gap at 2 mm, reaction chamber slope of zero degree, six operated UV lamps and using the parabola shaped reflector. The *E. coli* log reduction of the reactors and the wastewater characteristics of these four tests are shown in Figure 4-23.

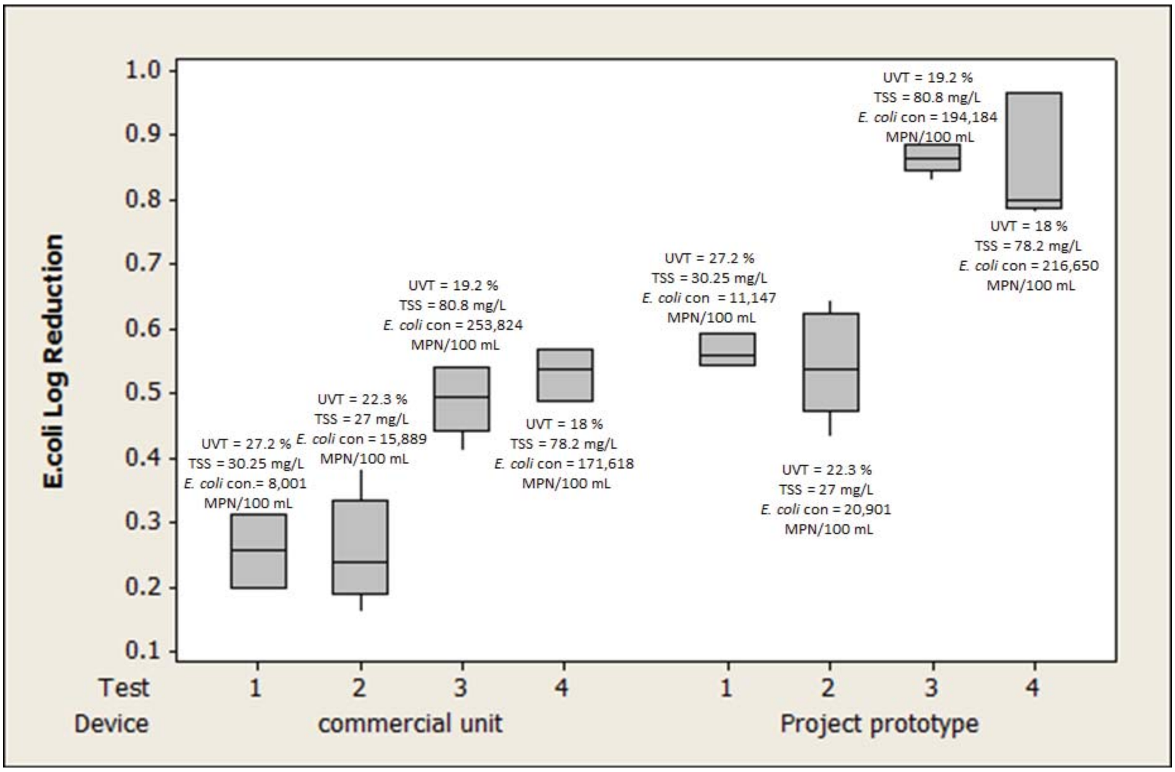

Figure 4-23, performances of the reactors at PNWWTP

In Figure 4-23, although the wastewater in the first and second test has slightly higher UVT and lower TSS than the third and fourth tests, both reactors had greater log reduction in the third and fourth tests. In addition, the wastewater in the third and four tests had 10 times higher *E. coli* concentration than the first and second tests. This indicates that UV reactors will have better *E. coli* log reduction when the initial *E. coli* concentration in the wastewater is high. Therefore, this confirms the hypothesis that microorganism concentration can affect UV disinfection.

4.5.1. The desirable wastewater for the project prototype

It is known that the UVT, TSS and initial microorganism concentration of wastewater could affect the performance of a UV reactor. Throughout the research, the commercial unit and project prototype were tested at seven different wastewater treatment sites and treating a variety of wastewater. This section is to determine the favourable wastewater conditions for the project prototype.

The project prototype and commercial unit were compared on different UVT wastewater, which the variation of the UVT was 5 to 65 %. The p/c of the reactors vs. the UVT value is plot in Figure 4-24.

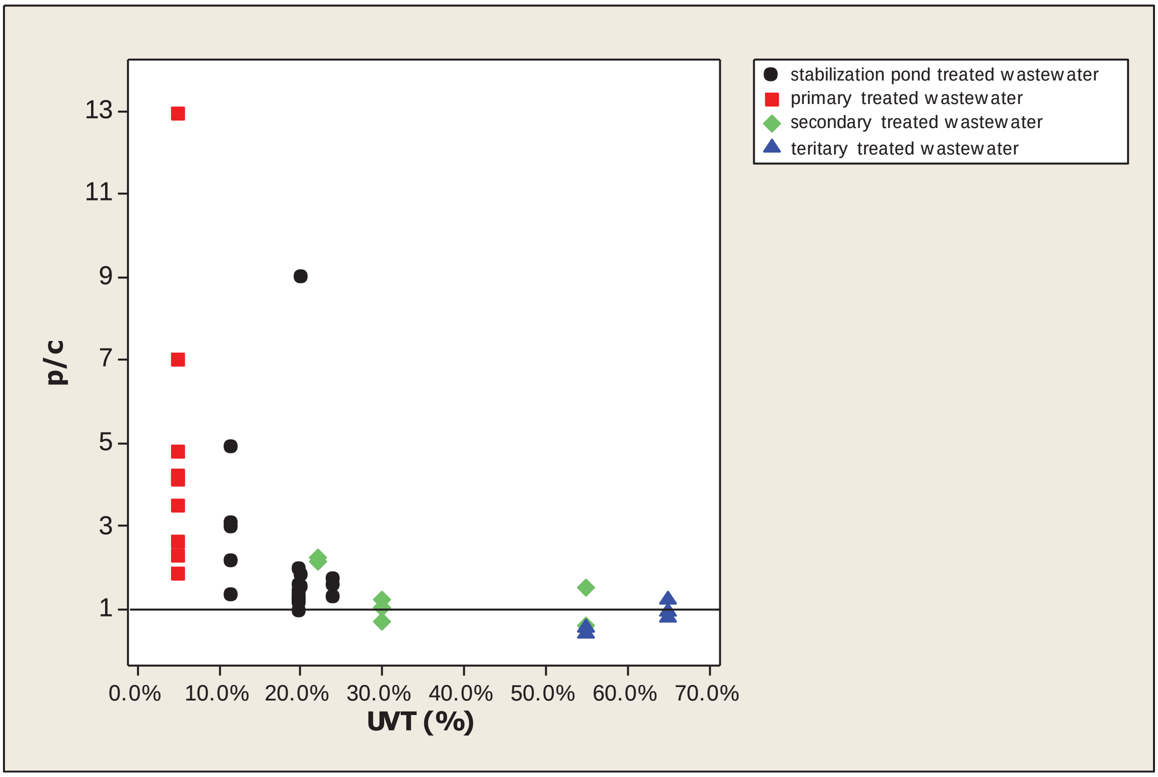

Figure 4-24, p/c vs. UVT

Figure 4-24 shows that the data, which have p/c greater than one, are generally distributed at UVT lower than 30%. These data are from the stabilization pond, primary and secondary treated wastewater tests. Despite the effect of TSS and initial microorganism concentration, this suggests that the project prototype would have the advantage at treating wastewater with UVT lower than 30%.

Throughout the project, the project prototype and the commercial unit were compared on the wastewaters that had TSS of 5 to 171 mg/L. The p/c of the reactors vs. the TSS value is plot in Figure 4-25.

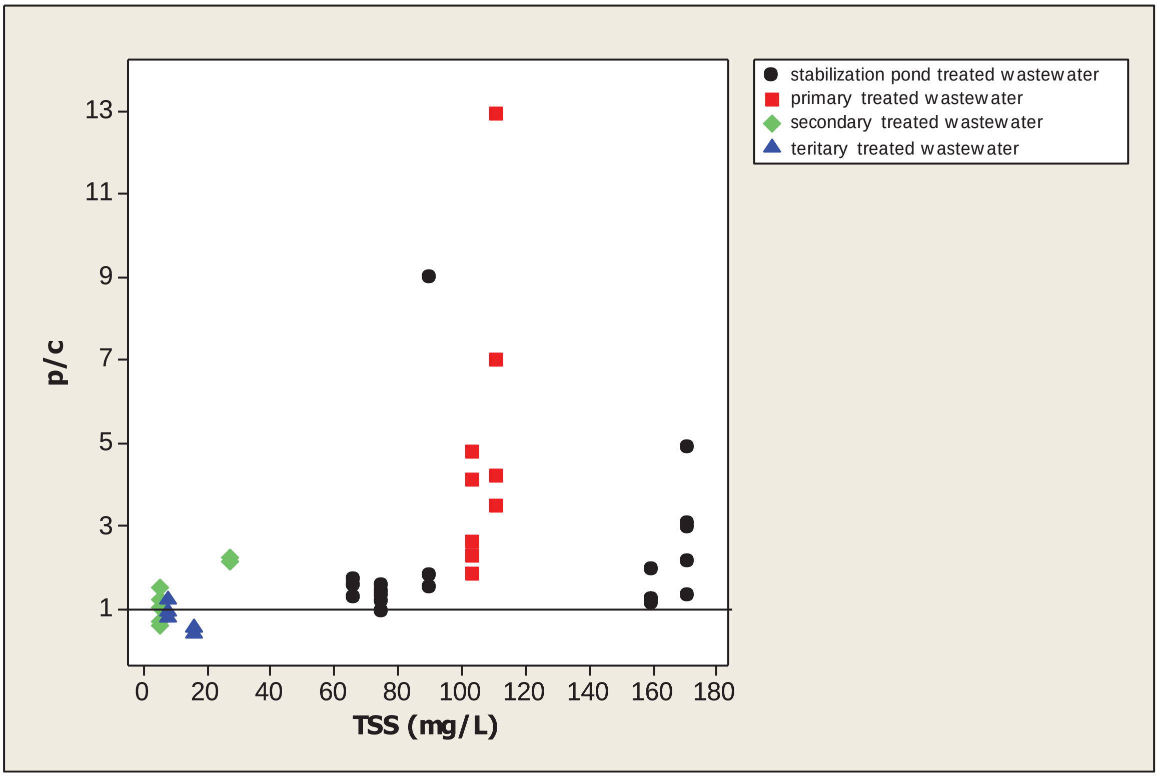

Figure 4-25, p/c vs. TSS

Figure 4-25 shows that the data, which have p/c greater than one, are mostly distributed after the TSS of 65 mg/L, and the wastewater that had these TSS values were the stabilization pond and primary treated wastewater. Despite the effect of UVT and initial microorganism concentration, this suggests that the project prototype would have the advantage at treating wastewater that has TSS greater than 65 mg/L.

The initial *E. coli* concentration of the tested wastewater was varied from 134 to 9,136,023 MPN/100 mL, and the p/c of the reactors vs. the initial *E. coli* concentration is plot in Figure 4-26.

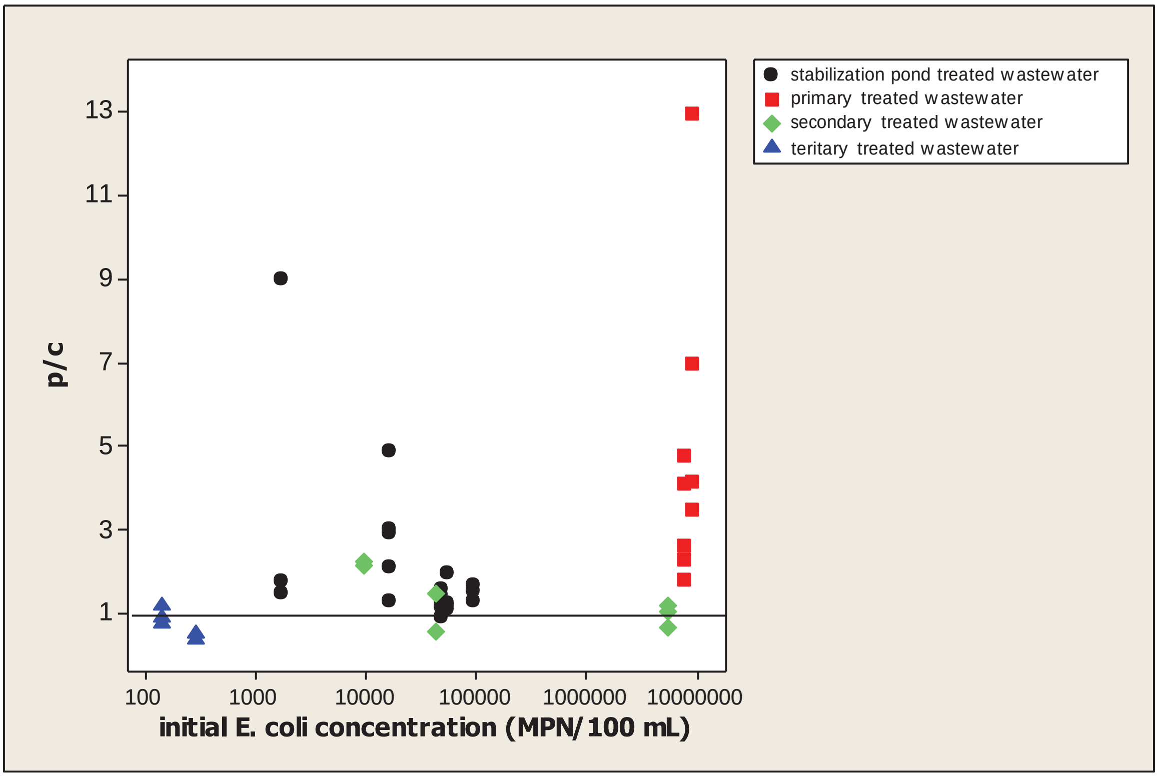

Figure 4-26, p/c vs. initial *E. coli* concentration

Figure 4-26 shows the data, which have p/c greater than one, are normally distribute after the initial *E. coli* of 1000 MPN/100 mL. In generally, these data are provided by the stabilization pond, primary and secondary treated wastewater. Despite the effect of TSS and UVT, this suggests that the project prototype would have advantage at treating wastewater that has *E. coli* concentration greater than 1000 MPN/100 mL.

In fact, the UVT, TSS and initial microorganism concentration are interdependent (as discussed in section 2.4). For example, the wastewater has a low UVT and high TSS will generally have a high initial *E. coli* concentration, such as the primary treated wastewater; the wastewater has a high UVT and low TSS will generally have a low initial *E. coli* concentration, such as the tertiary treated wastewater. Therefore, the comparisons suggest that the project prototype would perform better than the commercial unit when the wastewater has a UVT below 30%, TSS above 65 mg/L and initial microorganism concentration greater than 1000 MPN/100 mL.

5. Conclusions and recommendations

It is confirmed that the project prototype (3rd generation) is an improved version of the 2nd generation prototype. Based on the experimental tests in PNWWTP, the desirable settings of the project prototype are at 2 mm sluice gate gap, zero degrees reaction chamber slope and using the parabola shaped reflector. Under these settings, the project prototype was compared against with the commercial unit at the primary, secondary and tertiary treatments of the conventional wastewater treatment plants, and also compared at stabilization ponds.

Although the primary treated wastewater had a low UVT and high TSS, the project prototype offered superior performance on primary treated wastewater with the reactor on average, 4.5 times better than the commercial unit, in terms of *E. coli* log reduction. In one case, the reactor was up to 13 times better than the commercial unit. UV disinfection is not used in marine outfalls, because the current UV reactor is not effective and efficient at disinfecting the effluent from marine outfalls, which usually are primary treated wastewater. The results indicate the potential application of the project prototype at marine outfalls. Furthermore, the test found that the microbial level of the primary treated wastewater meets the WHO irrigation standard, after it is disinfected by the project prototype. This suggests the possibility of primary wastewater disinfection for irrigation.

In the secondary treated wastewater test, the project prototype, on average, had 1.4 times more *E. coli* log reduction than the commercial unit. It is known that wastewater is generally secondary treated and then disinfected by a UV reactor in a wastewater treatment plant. The results indicate that the project prototype does have some advantage over the traditional commercial UV reactors.

The project prototype performed, on average, 1.4 times worse than the commercial unit on tertiary treated wastewater, as the wastewater had a high UVT value. This suggests that the project prototype only has advantage at treating low UVT wastewater.

In the stabilization pond tests, the project prototype also provided superior performance, as the reactor was, on average, 2.1 times better than the commercial unit, and up to 9 times better at one location. UV disinfection at stabilization ponds is a common practise in many countries, and the results suggest that the project prototype could be a viable alternative to the traditional commercial UV reactors.

The experiments also found that the performance of the project prototype is not significantly affected by the operated flow rate or number of operated UV lamps, but depends on the watt per flow ratio. Therefore, this ratio can be used for future reactor design.

Interestingly, the experiments found that not only the UVT and TSS have important effect on UV disinfection, but also the initial concentration of microorganisms. UV reactors will have more microbial inactivation when the initial microorganism concentration is high.

In summary, the research found that the project prototype provides superior performance on primary, secondary and stabilization pond treated wastewater. Overall, the experimental results confirms the feasibility of applying supercritical flow hydraulics to wastewater UV disinfection, and indicates the potential of a supercritical flow UV reactor in the commercial market.

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7. Appendix

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Appendix 1, Raw data

Pre-experimental data (no used in the discussion)

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	1000	481347.7	8770.6
	10000	686942.1	0.0
Commercial unit effluent without UV light	1000	326058.7	7232.0
	10000	497955.0	13894.3
Commercial unit at 500 L/min	100	98387.0	5057.6
	1000	188565.5	7232.0
	100	72795.8	3907.4
	1000	117467.0	0.0
Influent	1000	419920.6	11952.3
	10000	372396.6	0.0
Project prototype effluent without UV light	1000	406377.7	10343.4
	10000	367236.1	0.0
Project prototype at 2 mm gap, 30° slope, parabola reflector, 6 lamps 500 L/min	100	41992.1	5172.8
	1000	45950.9	2806.1
	100	48134.8	4151.1
	1000	56493.3	1389.4
	100	48134.8	2939.4
	1000	82120.9	5673.9
Project prototype at 2 mm gap, 0° slope, parabola reflector, 6 lamps 500 L/min	100	46475.8	3070.1
	1000	56334.6	4251.2
	100	36366.2	2841.2
	1000	43386.1	1389.4
	100	46475.8	3184.4
	1000	27723.9	1389.4
Influent	1000	632455.5	6247.6
	10000	433860.9	1389.4
Project prototype at 2 mm gap, 60° slope, parabola reflector, 6 lamps 500 L/min	100	66136.2	6149.2
	1000	82958.0	18609.4
	100	81044.3	3106.8
	1000	149099.9	0.0
	100	69302.6	5285.8
	1000	86023.3	4251.2
Project prototype at 4 mm gap, 30° slope, parabola reflector, 6 lamps 500 L/min	100	128693.4	3225.4
	1000	193351.0	2806.1
	100	60590.2	4034.5
	1000	144072.1	1389.4
	100	53740.1	3702.8
	1000	60474.3	1389.4

Project prototype at 6 mm gap, 30^o slope, parabola reflector, 6 lamps 500 L/min	100	37977.7	2939.4
	1000	63812.5	5623.2
	100	72795.8	1665.9
	1000	104290.3	7232.0
	100	49890.8	11719.2
	1000	86023.3	13894.3

Project prototype vs. second generation

Low UVT

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	1000	N/A	151445.6
	1000	N/A	201320.9
	1000	N/A	162088.6
	10000	5175492	149738.2
	10000	4341216	135989.5
	10000	4063777	151272.3
Commercial unit at 500 L/min	100	N/A	46475.8
	100	N/A	55861.67
	100	N/A	55861.67
	100	N/A	46475.8
	100	N/A	49890.79
	1000	3004164	85568.88
	1000	2101904	85104.98
	1000	2101904	69114.83
	1000	N/A	86497.78
	1000	3004164	63812.49
Influent	1000	N/A	238746.7
	1000	N/A	245094.7
	1000	N/A	166107.9
	10000	5813777	185828.9
	10000	4989079	387664.9
	10000	4813477	277239.4
Project prototype at 2 mm gap 503 L/min	100	N/A	34370.27
	100	N/A	35777.09
	100	N/A	34680.36
	100	N/A	23321.8
	100	N/A	23321.8
	1000	498907.9	49795.5
	1000	917060.5	43386.09
	1000	661362.2	40915.16
	1000	601040.8	32254.39
	1000	693026.5	31844.07
Project prototype at 4 mm gap 503 L/min	100	N/A	49890.79
	100	300416.4	44904.34
	100	N/A	33624.22
	100	N/A	28284.27
	100	N/A	25819.89
	1000	1697940	71004.69

	1000	661362.2	30125.79
	1000	1161895	56334.58
	1000	727958.2	36723.61
	1000	1454648	53393.9
Project prototype at 6 mm gap 503 L/min	100	N/A	48134.77
	100	N/A	44904.34
	100	N/A	44904.34
	100	N/A	41992.06
	100	N/A	39343.75
	1000	1161895	52541.06
	1000	1161895	50575.63
	1000	1454648	34001.02
	1000	1161895	58480.16
	1000	1161895	45950.91
2nd generation at 2 mm gap 503 L/min	100	8212.09	0
	100	5339.39	0
	100	6869.421	425.1152
	100	N/A	48134.77
	100	N/A	30740.85
	1000	N/A	44904.34
	1000	N/A	46475.8
	1000	N/A	48134.77
	1000	1161895	49400.74
	1000	703606.8	50575.63
2nd generation at 4 mm gap 503 L/min	100	1063753	38010.21
	100	766811.6	39797.39
	100	766811.6	52858.49
	100	N/A	35777.09
	100	N/A	33420.4
	1000	N/A	34680.36
	1000	N/A	28284.27
	1000	N/A	34370.27
	1000	605902.3	36723.61
	1000	537401.2	29393.88
2nd generation at 6 mm gap 503 L/min	100	860000	48337.75
	100	517549.2	42163.7
	100	727958.2	34001.02
	100	N/A	29080.61
	100	N/A	46475.8
	1000	N/A	43412.16
	1000	N/A	34680.36
	1000	N/A	33624.22
	1000	605902.3	26058.49
	1000	860000	44614.41
Influent	1000	917060.5	34001.02

	1000	810443.2	33567.25
	1000	581377.7	37028.43

High UVT

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	1.00	3723.966	138.9
	1.00	3964.125	280.6
	1.00	3876.649	278.2
	10.00	4063.777	222.2
	10.00	4341.216	274.0
	10.00	3468.036	164.9
Project prototype at 2 mm gap 500 L/min	10.00	203.7728	28.06068
	10.00	166.5902	28.06068
	10.00	326.8099	0
	10.00	152.8545	0
	10.00	170.1393	0
	100.00	120.6499	7.231961
	100.00	537.4012	32.35924
	100.00	166.1079	5.725983
	100.00	208.837	7.231961
	100.00	245.0947	18.58289
Influent	1.00	10737.51	138.9425
	1.00	9116.729	868.7445
	5.00	5772.614	271.979
2nd generation at 2 mm gap 503 L/min	10.00	749.1095	72.31961
	10.00	349.2151	28.06068
	10.00	573.1628	13.89425
	10.00	3074.085	72.31961
	100.00	N/A	151.4456
	100.00	558.6167	51.72783
	100.00	605.9023	91.90885
	100.00	766.8116	93.76145

Project prototype variation test

Low UVT

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	1000.00	N/A	238746.7
	1000.00	N/A	326058.7
	1000.00	N/A	196668.7
	10000.00	6324555	352953.6
	10000.00	5175492	318440.7
	10000.00	5586167	459509.1
Commercial unit at 500 L/min	100.00	N/A	53740.12
	100.00	N/A	60590.23
	100.00	N/A	55861.67
	100.00	N/A	48134.77
	1000.00	1454648	75659.1
	1000.00	2101904	61509.87
	1000.00	1454648	93267.33
	1000.00	1697940	86023.25
Influent	1000.00	N/A	158113.9
	1000.00	N/A	191220.3
	1000.00	N/A	233218
	10000.00	4989079	235702.3
	10000.00	5813777	457692.9
	10000.00	3577709	117191.7
Project prototype at 2 mm gap, 0^{o} slope, parabola reflector, 6 lamps 498 L/min	100.00	N/A	39343.75
	100.00	210190.4	26753.41
	100.00	145464.8	14263.99
	100.00	300416.4	28863.07
	100.00	N/A	26016.82
	1000.00	464758	25752.91
	1000.00	537401.2	30125.79
	1000.00	661362.2	37509.69
	1000.00	275088.9	5725.983
	1000.00	357770.9	27723.94
Project prototype at 2 mm gap, 30^{o} slope, parabola reflector, 6 lamps 498 L/min	100.00	N/A	26496.71
	100.00	300416.4	28621.67
	100.00	N/A	25157.68
	100.00	N/A	25103.07
	100.00	N/A	26753.41
	1000.00	498907.9	28061.82
	1000.00	419920.6	30512.86
	1000.00	419920.6	24397.5

	1000.00	346803.6	13327.85
	1000.00	558616.7	39797.39
Project prototype at 2 mm gap, 60^o slope, parabola reflector, 6 lamps 498 L/min	100.00	N/A	36917.52
	100.00	N/A	33624.22
	100.00	N/A	39634.7
	100.00	N/A	44904.34
	100.00	N/A	41992.06
	1000.00	727958.2	56334.58
	1000.00	537401.2	39074.47
	1000.00	537401.2	38531.32
	1000.00	605902.3	86023.25
	1000.00	661362.2	26779.13
Project prototype at 4 mm gap, 0^o slope, parabola reflector, 6 lamps 478 L/min	100.00	N/A	38105.12
	100.00	N/A	38105.12
	100.00	N/A	36917.52
	100.00	N/A	40637.77
	100.00	N/A	39343.75
	1000.00	1454648	72664.79
	1000.00	537401.2	44721.36
	1000.00	537401.2	49050.39
	1000.00	464758	45191.77
	1000.00	810443.2	53393.9
Influent	1000.00	N/A	20557.45
	1000.00	300416.4	19335.1
	1000.00	N/A	24509.47
Project prototype at 6 mm gap, 0^o slope, parabola reflector, 6 lamps 478 L/min	100.00	N/A	31607.35
	100.00	169794	24596.75
	100.00	369175.2	29393.88
	100.00	357770.9	34001.02
	100.00	481347.7	36723.61
	1000.00	326058.7	30125.79
	1000.00	336242.2	20155.64
	1000.00	983869.9	150293.8
	1000.00	N/A	112853.2
	1000.00	N/A	205574.5
Project prototype at 2 mm gap, 0^o slope, square reflector, 6 lamps 478 L/min	100.00	N/A	43412.16
	100.00	N/A	27644.36
	100.00	N/A	29080.61
	100.00	210190.4	21091.54
	100.00	210190.4	21634.69
	1000.00	369175.2	28061.82
	1000.00	420291.8	45191.77
	1000.00	537401.2	37239.66
	1000.00	369175.2	20606.39
	1000.00	537401.2	45950.91

Influent	1000.00	N/A	53740.12
	1000.00	N/A	38105.12
	1000.00	N/A	39343.75

High UVT

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	1.00	3723.966	138.9425
	1.00	3964.125	280.6068
	1.00	3876.649	278.1536
	10.00	4063.777	222.1942
	10.00	4341.216	273.9798
	10.00	3468.036	164.897
Project prototype at 2 mm gap, 0^o slope, parabola reflector, 6 lamps 500 L/min	10.00	203.7728	28.06068
	10.00	166.5902	28.06068
	10.00	326.8099	0
	10.00	152.8545	0
	10.00	170.1393	0
	100.00	120.6499	7.231961
	100.00	537.4012	32.35924
	100.00	166.1079	5.725983
	100.00	208.837	7.231961
	100.00	245.0947	18.58289
Influent	1.00	8272.607	716.4824
	1.00	7491.095	572.5983
	5.00	6724.844	336.6734
Project prototype at 2 mm gap, 30^o slope, parabola reflector, 6 lamps 494 L/min	10.00	502.2338	0
	10.00	505.7563	28.06068
	10.00	911.6729	87.7058
	10.00	809.3703	28.06068
	100.00	1161.895	73.32629
	100.00	605.9023	57.31628
	100.00	517.5492	42.7618
	100.00	605.9023	65.73757
Project prototype at 2 mm gap, 60^o slope, parabola reflector, 6 lamps 494 L/min	10.00	960.1136	56.73902
	10.00	471.5596	28.06068
	10.00	1167.639	28.06068
	10.00	#VALUE!	#VALUE!
	100.00	632.4555	61.50987
	100.00	581.3777	62.62946
	100.00	917.0605	57.31628
	100.00	1697.94	158.1139

Project prototype at 4 mm gap, 0^o slope, parabola reflector, 6 lamps 505 L/min	10.00	1076.713	87.7058
	10.00	1700.815	87.7058
	10.00	331.4968	13.89425
	10.00	1303.545	72.31961
	100.00	983.8699	84.00417
	100.00	1161.895	68.2191
	100.00	632.4555	111.1769
	100.00	727.9582	63.81249
Influent	1.00	10737.51	138.9425
	1.00	9116.729	868.7445
	5.00	5772.614	271.979
Project prototype at 5 mm gap, 0^o slope, parabola reflector, 6 lamps 505 L/min	10.00	2145.907	117.1917
	10.00	1951.525	56.73902
	10.00	2975.337	72.31961
	10.00	2750.889	72.31961
	100.00	1697.94	119.8403
	100.00	1286.934	98.77296
	100.00	1697.94	126.0638
	100.00	1697.94	85.10498
Project prototype at 2 mm gap, 0^o slope, square reflector, 6 lamps 494 L/min	10.00	1951.525	42.51152
	10.00	2055.745	28.06068
	10.00	2274.947	57.25983
	10.00	2391.16	84.51543
	10.00	2450.947	86.87445
	100.00	917.0605	88.19529
	100.00	1454.648	101.5524
	100.00	1697.94	116.1895
	100.00	1161.895	91.52575
	100.00	917.0605	107.6713

Comparison of project prototype and commercial unit

PNWWTP primary wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	10000	N/A	6059023.4
	10000	N/A	4813477.5
	10000	N/A	4063777.3
	100000	60590234.1	8944271.9
	100000	69302648.9	7253185.2
	100000	76681158.1	5561280.0
Commercial unit at 743 L/min	10000	21019039.0	3250000.0
	10000	N/A	4647580.0
	10000	N/A	3162277.7
	10000	N/A	4063777.3
	10000	30041637.8	3260587.2
	100000	48134774.6	4595091.4
	100000	28863072.0	3445204.8
	100000	33624221.0	3356725.4
	100000	29899055.0	2411214.1
	100000	38105117.8	2677912.6
Commercial unit at 499 L/min	10000	N/A	1701727.4
	10000	11618950.0	1574645.4
	10000	N/A	3160734.7
	10000	21019039.0	1532971.0
	10000	30041637.8	3250000.0
	100000	34680358.6	3012578.7
	100000	30672639.4	2411214.1
	100000	28863072.0	1034344.7
	100000	30672639.4	2060638.5
	100000	31622776.6	2247564.5
Commercial unit at 350 L/min	10000	N/A	2581988.9
	10000	16979399.3	1786629.6
	10000	21019039.0	3160734.7
	10000	21019039.0	2886307.2
	10000	30041637.8	2634930.2
	100000	28621670.1	2060638.5
	100000	36917519.2	3225439.2
	100000	28000000.0	1512722.6
	100000	34680358.6	2772394.3
	100000	29753372.2	2708325.2
Commercial unit at 250 L/min	10000	7668115.8	869894.5

	10000	5813776.7	452678.7
	10000	9838699.1	988597.8
	10000	6613622.3	574169.3
	10000	7668115.8	1044776.7
	100000	14555562.7	572598.3
	100000	6601096.0	723196.1
	100000	10737509.8	1195228.6
	100000	6731250.6	425115.2
	100000	14523687.5	572598.3
Commercial unit at 130 L/min	1000	1161895.0	165748.4
	1000	1063753.5	146446.6
	1000	1697939.9	147740.6
	1000	336242.2	133643.1
	1000	766811.6	227494.7
	10000	1742842.5	134613.5
	10000	1746075.7	187867.3
	10000	1885655.4	219717.7
	10000	2975337.2	222194.2
	10000	2450947.3	235702.3
Influent	10000	N/A	8600000.0
	10000	N/A	9170605.2
	10000	N/A	8600000.0
	100000	86000000.0	12162236.6
	100000	76681158.1	9376144.6
	100000	69302648.9	16154821.6
Project prototype at 495 L/min with 6 lamps	10000	4199206.3	810162.7
	10000	4080824.1	961694.1
	10000	3067263.9	564932.7
	10000	3162277.7	809370.3
	10000	4647580.0	1016001.0
	100000	7043701.7	1359895.2
	100000	3575277.4	425115.2
	100000	4034466.9	709952.3
	100000	2637521.9	877058.0
	100000	4151056.5	567390.2
Project prototype at 250 L/min with 6 lamps	1000	983869.9	240416.3
	1000	727958.2	207062.8
	1000	766811.6	165772.5
	1000	581377.7	195156.9
	1000	517549.2	122788.1
	10000	1464465.8	543251.3
	10000	1615482.2	480670.3
	10000	1076712.7	392718.0
	10000	1838477.6	440908.2

	10000	934953.4	344846.2
Project prototype at 130 L/min with 6 lamps	1000	93083.6	17013.9
	1000	63508.5	8770.6
	1000	86989.4	14825.0
	1000	47869.9	13461.4
	1000	54289.7	31449.0
	10000	27815.4	28060.7
	10000	152854.5	13894.3
	10000	42511.5	0.0
	10000	13894.3	0.0
	10000	28060.7	13894.3
Project prototype at 500 L/min with 4 lamps	10000	7279581.6	2387467.3
	10000	10637534.6	2750889.2
	10000	16979399.3	3468035.9
	10000	10637534.6	2060369.4
	10000	9838699.1	1933510.2
	100000	23252734.4	2939387.7
	100000	24596747.8	3672361.4
	100000	20557448.7	2975308.2
	100000	18012758.2	2841236.6
	100000	16664761.8	2331262.0
Project prototype at 247 L/min with 4 lamps	10000	1404393.6	362284.4
	10000	2828427.1	380102.1
	10000	2264314.2	494007.4
	10000	2975337.2	554016.5
	10000	2750889.2	397973.9
	100000	2637521.9	572598.3
	100000	1195228.6	138942.5
	100000	1359895.2	425115.2
	100000	1332785.0	138942.5
	100000	2806182.4	723196.1
Project prototype at 247 L/min with 3 lamps	10000	4199206.3	1420439.0
	10000	4341215.7	1137104.7
	10000	4063777.3	898984.5
	10000	4490434.3	1262523.5
	10000	3342039.9	647821.1
	100000	6044826.2	1307234.0
	100000	4905038.8	1359895.2
	100000	5254106.4	1183400.9
	100000	4151056.5	1149919.1
	100000	3235924.0	1183400.9
Project prototype at 130 L/min with 3 lamps	10000	583511.6	72319.6
	10000	257529.1	42511.5
	10000	415105.7	102432.9

	10000	263752.2	103434.5
	10000	263752.2	57259.8
	100000	280606.8	138942.5
	100000	572598.3	138942.5
	100000	877058.0	0.0
	100000	877058.0	0.0
	100000	138942.5	0.0
Project prototype at 503 L/min with 2 lamps	10000	N/A	5374011.5
	10000	N/A	4063777.3
	10000	N/A	3691751.9
	10000	N/A	4063777.3
	10000	N/A	4063777.3
	100000	29899055.0	7332628.6
	100000	36917519.2	4338609.2
	100000	29080609.0	6044826.2
	100000	36917519.2	5366690.8
	100000	32500000.0	5057563.4
Project prototype at 128 L/min with 2 lamps	10000	1838477.6	168336.7
	10000	1137104.7	362284.4
	10000	1385640.6	362284.4
	10000	1161895.0	277239.4
	10000	937614.5	513936.2
	100000	1359895.2	138942.5
	100000	1838554.2	567390.2
	100000	877058.0	138942.5
	100000	572598.3	280606.8
	100000	1512722.6	138942.5
Project prototype at 247 L/min with 2 lamps	10000	N/A	4063777.3
	10000	12869343.4	2718879.9
	10000	12869343.4	3162277.7
	10000	16979399.3	4490434.3
	10000	21019039.0	4490434.3
	100000	16574838.6	2605849.4
	100000	17428425.1	4103913.4
	100000	21091537.2	1858288.8
	100000	17919573.4	3575277.4
	100000	23874672.8	4861724.3
Project prototype at 250 L/min with 1 lamps	10000	30041637.8	4647580.0
	10000	N/A	4063777.3
	10000	N/A	4063777.3
	10000	N/A	6930264.9
	10000	21019039.0	4063777.3
	100000	35777087.6	4151056.5
	100000	22187219.9	5741692.5

	100000	25157684.5	5225262.7
	100000	31607347.1	4861724.3
	100000	36917519.2	5339390.5
Project prototype at 123 L/min with 1 lamps	10000	3850515.6	1526772.6
	10000	4647580.0	1436762.2
	10000	5374011.5	1581138.8
	10000	4647580.0	1351155.0
	10000	4647580.0	1620886.4
	100000	4595091.4	1024329.3
	100000	6573757.4	1528544.6
	100000	3979739.1	868744.5
	100000	4276179.9	572598.3
	100000	3400102.0	868744.5
Project prototype at 503 L/min with 1 lamps	10000	N/A	6613622.3
	10000	N/A	7279581.6
	10000	N/A	7668115.8
	10000	N/A	6059023.4
	10000	N/A	5586167.1
	100000	49890789.8	9885977.9
	100000	51754917.0	13558153.6
	100000	44904342.8	6821910.4
	100000	58137767.4	10156667.5
	100000	44904342.8	9376144.6
Influent	10000	N/A	10637534.6
	10000	N/A	8600000.0
	10000	N/A	6613622.3
	100000	69302648.9	14204390.4
	100000	76681158.1	10978875.8
	100000	55861671.3	12709316.2

Levin primary wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	10000	N/A	7279582
	10000	N/A	7279582
	10000	N/A	5586167
	100000	48134775	11323070
	100000	35777088	11371047
	100000	33624221	11285322
Commercial unit at 688 L/min	10000	12869343	5374012
	10000	30041638	5175492
	10000	21019039	7668116
	10000	21019039	7668116
	10000	21019039	5586167
	100000	13169762	3907447
	100000	38105118	10155237
	100000	35777088	9116729
	100000	36917519	8649778
	100000	35777088	8152395
Commercial unit at 504 L/min	10000	14546477	3934375
	10000	9170605	4199206
	10000	21019039	4989079
	10000	16979399	4813477
	10000	7279582	3810512
Commercial unit at 504 L/min	10000	6930265	3934375
	10000	11618950	3362422
	10000	21019039	3810512
	10000	21019039	4490434
	10000	21019039	4063777
Commercial unit at 249 L/min	10000	10637535	4490434
	10000	11618950	4063777
	10000	14546477	4341216
	10000	11618950	4341216
	10000	10637535	4199206
Commercial unit at 133 L/min	10000	N/A	3162278
	10000	14546477	4199206
	10000	21019039	4813477
	10000	12869343	3934375
	10000	10637535	4813477
Influent	10000	30041638	9838699
	10000	N/A	7668116
	10000	N/A	10637535

	100000	40637773	13856406
	100000	58137767	18754844
	100000	60590234	18384776
Project prototype at 126 L/min with 6 lamps	10000	42511.52	13894.25
	10000	42511.52	28060.68
	10000	28060.68	0
	10000	42132.5	13894.25
	10000	27815.36	284123.7
Project prototype at 247 L/min with 6 lamps	10000	704370.2	427618
	10000	1157256	446144.1
	10000	1249516	517278.3
	10000	1850583	494007.4
	10000	821209	573162.8
Project prototype at 502 L/min with 6 lamps	10000	4647580	3162278
	10000	5374012	3260587
	10000	6059023	3362422
	10000	5175492	3691752
	10000	5374012	3577709
Project prototype at 254 L/min with 4 lamps	10000	3067264	1071656
	10000	1933510	1043498
	10000	2264314	1404394
	10000	2031334	797053.4
	10000	2055745	1106797
Project prototype at 504 L/min with 4 lamps	10000	7668116	3810512
	10000	6613622	5175492
	10000	7668116	4063777
	10000	8600000	3934375
	10000	9838699	4989079
	100000	11916938	5339390
	100000	12064987	7491095
	100000	20313335	3979739
	100000	13169762	6150987
	100000	20318886	8093703
Influent	10000	N/A	14546477
	10000	N/A	6930265
	10000	N/A	9838699
	100000	63245553	15628847
	100000	58137767	15811388
	100000	66136223	14774056
Project prototype at 130 L/min with 3 lamps	10000	780032.5	415105.7
	10000	1102927	505756.3
	10000	1016001	466658.4
	10000	809370.3	686942.1
	10000	1297489	725318.5
Project prototype at 254	10000	4199206	2274947

L/min with 3 lamps	10000	4490434	2387467
	10000	3577709	1746076
	10000	4199206	1385641
	10000	3934375	2264314
Project prototype at 130 L/min with 2 lamps	10000	2828427	1440721
	10000	2936401	1323841
	10000	2218722	1316976
	10000	3160735	1251937
	10000	3810512	1791957
Project prototype at 502 L/min with 2 lamps	10000	12869343	5813777
	10000	14546477	5813777
	10000	14546477	4063777
	10000	30041638	4063777
	10000	16979399	4989079
	100000	25719642	7970534
	100000	31622777	9326733
	100000	23321798	11504877
	100000	22749472	8400417
	100000	25157685	8900492
Project prototype at 250 L/min with 2 lamps	10000	7668116	4647580
	10000	6059023	2649671
	10000	5586167	3250000
	10000	6059023	3468036
	10000	6930265	4199206
	100000	14555563	5943979
	100000	6821910	4276180
	100000	11676388	3529536
	100000	7490253	2708325
	100000	9601136	3225439
Project prototype at 129 L/min with 1 lamps	10000	400000	4989079
	10000	410000	4063777
	10000	320000	3160735
	10000	320000	4199206
	10000	350000	3577709
	100000	700000	5633458
	100000	800000	7730207
	100000	900000	4905039
	100000	1300000	5095122
	100000	500000	4741520
Project prototype at 500 L/min with 1 lamps	10000	21019039	3162278
	10000	N/A	4063777
	10000	30041638	3468036
	10000	N/A	3362422
	10000	N/A	3577709
	100000	36917519	9877296

	100000	38105118	14407205
	100000	48134775	8035886
	100000	35777088	7800325
	100000	48134775	17000000
Project prototype at 250 L/min with 1 lamps	10000	30041638	5175492
	10000	14546477	4813477
	10000	16979399	4989079
	10000	14546477	4647580
	10000	10637535	6324555
	100000	28621670	9637060
	100000	24509473	6478211
	100000	20557449	8858796
Influent	10000	N/A	5586167
	10000	N/A	6930265
	10000	N/A	10637535
	100000	53740115	13238409
	100000	48134775	13558154
	100000	51754917	15739820

PNWWTP secondary wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	1000.00	632455.5	15127.23
	1000.00	661362.2	13598.95
	1000.00	605902.3	16833.67
	10000.00	657375.7	0
	10000.00	864977.8	0
	10000.00	542896.7	0
Commercial unit at 650 L/min	100.00	N/A	8989.845
	100.00	N/A	11323.07
	100.00	N/A	11572.56
	100.00	N/A	9660.918
	100.00	N/A	9877.296
	1000.00	419920.6	8770.58
	1000.00	434121.6	10243.29
	1000.00	498907.9	13461.35
	1000.00	369175.2	8770.58
	1000.00	298990.5	11834.01
Commercial unit at 501 L/min	100.00	128693.4	8272.607
	100.00	300416.4	6573.757
	100.00	210190.4	9190.885
	100.00	N/A	9637.06
	100.00	N/A	11000
	1000.00	346803.6	8770.58
	1000.00	297533.7	7231.961
	1000.00	419920.6	8687.445
	1000.00	307408.5	10243.29
	1000.00	346803.6	7231.961
Commercial unit at 255 L/min	100.00	98386.99	4151.057
	100.00	145464.8	5057.563
	100.00	169794	3876.649
	100.00	116189.5	5022.338
	100.00	210190.4	5366.691
	1000.00	147740.6	2806.068
	1000.00	174607.6	5725.983
	1000.00	226431.4	5725.983
	1000.00	141275.5	5725.983
	1000.00	219469.1	1389.425
Influent	1000.00	581377.7	5725.983
	1000.00	917060.5	25752.91
	1000.00	1161895	19941.09

	10000.00	686942.1	0
	10000.00	678644.1	0
	10000.00	915257.5	27815.36
Project prototype at 476 L/min with 6 lamps	100.00	300416.4	6048.584
	100.00	128693.4	5225.263
	100.00	106375.3	4715.596
	100.00	128693.4	6361.942
	100.00	300416.4	7730.207
	1000.00	95114.29	10051.41
	1000.00	142043.9	1389.425
	1000.00	192078.4	4251.152
	1000.00	151445.6	5725.983
	1000.00	244981.9	8687.445
Project prototype at 235 L/min with 6 lamps	100.00	26496.71	1648.97
	100.00	26989.78	2037.728
	100.00	23252.73	1683.367
	100.00	22045.41	1024.329
	100.00	21459.07	723.1961
	1000.00	25752.91	0
	1000.00	20377.28	0
	1000.00	25752.91	0
	1000.00	34001.02	1389.425
	1000.00	22475.65	0
Project prototype at 493 L/min with 5 lamps	100.00	169794	5428.967
	100.00	56288.54	6251.717
	100.00	128693.4	7129.507
	100.00	210190.4	6381.249
	100.00	128693.4	5428.967
	1000.00	214590.7	10243.29
	1000.00	196668.7	10145.99
	1000.00	221872.2	2806.068
	1000.00	336242.2	8770.58
	1000.00	210915.4	2806.068
Project prototype at 235 L/min with 5 lamps	100.00	49890.79	1359.895
	100.00	34680.36	1701.393
	100.00	44904.34	2806.182
	100.00	40637.77	2037.728
	100.00	55861.67	2605.849
	1000.00	33567.25	0
	1000.00	45950.91	2806.068
	1000.00	53393.9	1389.425
	1000.00	43386.09	1389.425
	1000.00	46665.84	8304.548
Project prototype at 242 L/min	100.00	48134.77	1512.723

with 4 lamps	100.00	43412.16	1359.895
	100.00	43412.16	1034.345
	100.00	58137.77	2411.214
	100.00	48134.77	3012.579
	1000.00	52541.06	4176.345
	1000.00	27397.98	0
	1000.00	62828.09	2806.068
	1000.00	89004.92	5725.983
	1000.00	57316.28	1389.425
Project prototype at 493 L/min with 4 lamps	100.00	300416.4	9083.737
	100.00	300416.4	8272.607
	100.00	N/A	7730.207
	100.00	169794	7970.534
	100.00	300416.4	8400.417
	1000.00	227494.7	15285.45
	1000.00	223606.8	15285.45
	1000.00	357770.9	5673.902
	1000.00	325000	5725.983
	1000.00	233218	8451.543
Project prototype at 492 L/min with 3 lamps	100.00	N/A	11256.4
	100.00	300416.4	17017.27
	100.00	N/A	13169.76
	100.00	N/A	13880.44
	100.00	N/A	10468.48
	1000.00	3004164	84004.17
	1000.00	605902.3	16833.67
	1000.00	464758	13461.35
	1000.00	406377.7	13598.95
	1000.00	406377.7	11834.01
Project prototype at 242 L/min with 2 lamps	100.00	N/A	8347.3
	100.00	N/A	10434.98
	100.00	210190.4	10156.67
	100.00	300416.4	10155.24
	100.00	300416.4	12294.02
	1000.00	357770.9	10243.29
	1000.00	346803.6	11719.17
	1000.00	393437.5	11952.29
	1000.00	336242.2	7231.961
	1000.00	381051.2	5725.983
Project prototype at 492 L/min with 2 lamps	100.00	N/A	12294.02
	100.00	N/A	11117.69
	100.00	N/A	18384.78
	100.00	N/A	14644.66
	100.00	N/A	19207.84

	1000.00	406377.7	7099.523
	1000.00	449043.4	20606.39
	1000.00	498907.9	18385.54
	1000.00	605902.3	18786.73
	1000.00	481347.7	16833.67
Project prototype at 497 L/min with 1 lamps	100.00	N/A	20132.09
	100.00	N/A	20132.09
	100.00	N/A	14909.99
	1000.00	632455.5	26375.22
	1000.00	537401.2	7231.961
	1000.00	517549.2	17013.93

Levin secondary test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	10000.00	N/A	6.3
	10000.00	21.0	9.2
	10000.00	30.0	5.4
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
Commercial unit at 656 L/min	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	N/A	169.8
	1000.00	N/A	91.7
	1000.00	N/A	169.8
	1000.00	N/A	128.7
	1000.00	N/A	210.2
Commercial unit at 508 L/min	1000.00	N/A	91.7
	1000.00	N/A	116.2
	1000.00	N/A	76.7
	1000.00	N/A	145.5
	1000.00	N/A	98.4
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	2101.9	N/A
Commercial unit at 355 L/min	1000.00	98.4	58.1
	1000.00	145.5	58.1
	1000.00	169.8	69.3
	1000.00	169.8	66.1
	1000.00	169.8	69.3
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
Commercial unit at 250 L/min	1000.00	98.4	46.5
	1000.00	116.2	46.5
	1000.00	86.0	49.9

	1000.00	72.8	39.3
	1000.00	81.0	39.3
	100.00	N/A	3004.2
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
Influent	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	10000.00	10.6	5.4
	10000.00	8.1	4.3
	10000.00	14.5	5.4
Project prototype at 500 L/min with 6 lamps	1000.00	N/A	35.8
	1000.00	72.8	34.7
	1000.00	46.5	30.7
	1000.00	145.5	40.6
	1000.00	51.8	35.8
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
Project prototype at 258 L/min with 6 lamps	1000.00	69.3	29.8
	1000.00	63.2	11.9
	1000.00	145.5	44.6
	1000.00	35.8	34.4
	1000.00	51.8	34.7
	100.00	N/A	N/A
	100.00	N/A	1697.9
	100.00	1697.9	517.5
	100.00	N/A	N/A
	100.00	N/A	1697.9
Project prototype at 250 L/min with 5 lamps	100.00	N/A	3004.2
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	51.8	31.6
	1000.00	210.2	63.2
	1000.00	145.5	53.7
	1000.00	210.2	63.2
	1000.00	N/A	66.1
Project prototype at 250 L/min with 4 lamps	100.00	N/A	N/A
	100.00	N/A	N/A

	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	169.8	72.8
	1000.00	N/A	116.2
	1000.00	300.4	81.0
	1000.00	300.4	86.0
	1000.00	N/A	98.4
Project prototype at 500 L/min with 4 lamps	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	106.4	60.6
	1000.00	128.7	49.9
	1000.00	169.8	66.1
	1000.00	58.1	43.4
	1000.00	300.4	53.7
Project prototype at 252 L/min with 3 lamps	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	145.5	66.1
	1000.00	210.2	66.1
	1000.00	116.2	58.1
	1000.00	300.4	60.6
	1000.00	210.2	63.2
Project prototype at 250 L/min with 2 lamps	100.00	N/A	1063.8
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	300.4	116.2
	1000.00	N/A	210.2
	1000.00	210.2	98.4
	1000.00	N/A	N/A
	1000.00	N/A	106.4
Project prototype at 500 L/min with 2 lamps	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	N/A	210.2
	1000.00	N/A	145.5

	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
Project prototype at 500 L/min with 1 lamps	100.00	N/A	3004.2
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
Project prototype at 253 L/min with 1 lamps	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	100.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
Influent	1000.00	N/A	N/A
	1000.00	N/A	N/A
	1000.00	N/A	N/A
	10000.00	10.6	4.3
	10000.00	12.9	4.6
	10000.00	9.8	4.5

Paraparaumu secondary test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	100.00	N/A	38105.12
	100.00	N/A	60590.23
	100.00	N/A	48134.77
	10.00	N/A	N/A
	10.00	N/A	N/A
	10.00	N/A	N/A
Commercial unit at 257 L/min	1.00	1286.934	166.6476
	1.00	860	93.76145
	1.00	1454.648	124.4601
	1.00	983.8699	71.83811
	1.00	1161.895	143.8084
	1.00	3004.164	104.2903
	1.00	517.5492	101.6347
	1.00	1063.753	118.1678
	1.00	537.4012	75.10409
	1.00	2101.904	210.8185
Commercial unit at 495 L/min	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
Commercial unit at 750 L/min	10.00	N/A	12869.34
	10.00	N/A	16979.4
	10.00	N/A	11618.95
	10.00	N/A	10637.53
	10.00	N/A	16979.4
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
Influent	100.00	N/A	51754.92
	100.00	N/A	40637.77
	100.00	N/A	36917.52

	10.00	N/A	N/A
	10.00	N/A	N/A
	10.00	N/A	N/A
Project prototype at 499 L/min with 6 lamps	1.00	N/A	3004.164
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	1697.94
	1.00	N/A	N/A
	1.00	N/A	2101.904
	1.00	N/A	2101.904
	1.00	N/A	3004.164
	1.00	N/A	2101.904
Project prototype at 252 L/min with 6 lamps	1.00	N/A	983.8699
	1.00	N/A	2101.904
	1.00	N/A	917.0605
	1.00	N/A	2101.904
	1.00	N/A	983.8699
	1.00	N/A	1063.753
	1.00	N/A	N/A
	1.00	N/A	1697.94
	1.00	N/A	N/A
	1.00	N/A	1454.648
Project prototype at 500 L/min with 5 lamps	10.00	30041.64	5175.492
	10.00	N/A	3934.375
	10.00	11618.95	2828.427
	10.00	16979.4	2975.337
	10.00	16979.4	3934.375
	1.00	N/A	3004.164
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	3004.164
	1.00	N/A	N/A
Project prototype at 255 L/min with 5 lamps	1.00	N/A	N/A
	1.00	N/A	2101.904
	1.00	N/A	N/A
	1.00	N/A	2101.904
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	3004.164
	1.00	N/A	N/A
	1.00	N/A	3004.164
	1.00	N/A	N/A
Project prototype at 493 L/min	10.00	16979.4	4080.824

with 4 lamps	10.00	N/A	4989.079
	10.00	N/A	6613.622
	10.00	N/A	3577.709
	10.00	12869.34	3535.152
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
Project prototype at 244 L/min with 4 lamps	1.00	N/A	3004.164
	1.00	N/A	3004.164
	1.00	N/A	3004.164
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
Project prototype at 502 L/min with 3 lamps	10.00	N/A	9838.699
	10.00	N/A	9170.605
	10.00	N/A	8104.432
	10.00	N/A	12869.34
	10.00	N/A	11618.95
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
Project prototype at 499 L/min with 3 lamps	10.00	N/A	6613.622
	10.00	N/A	9838.699
	10.00	N/A	6613.622
	10.00	N/A	6613.622
	10.00	N/A	6930.265
Project prototype at 247 L/min with 3 lamps	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
	1.00	N/A	N/A
Project prototype at 498 L/min	10.00	N/A	21019.04

with 2 lamps	10.00	N/A	14546.48
	10.00	N/A	14546.48
	10.00	N/A	14546.48
	10.00	N/A	21019.04
Project prototype at 267 L/min with 2 lamps	10.00	N/A	7668.116
	10.00	N/A	5813.777
	10.00	N/A	6930.265
	10.00	N/A	6930.265
	10.00	N/A	16979.4
	1.00	N/A	2101.904
	1.00	N/A	N/A
	1.00	N/A	1697.94
	1.00	N/A	632.4555
	1.00	N/A	N/A
Project prototype at 500 L/min with 1 lamps	10.00	N/A	30041.64
	10.00	N/A	30041.64
	10.00	N/A	N/A
	10.00	N/A	14546.48
	10.00	N/A	N/A
Project prototype at 264 L/min with 1 lamps	10.00	N/A	16979.4
	10.00	N/A	21019.04
	10.00	N/A	9170.605
	10.00	N/A	6417.61
	10.00	N/A	6646.804
Influent	100.00	300416.4	40637.77
	100.00	300416.4	36917.52
	100.00	N/A	36917.52

PNWWTP tertiary treated wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	1.00	6821.91	138.9425
	1.00	5339.39	0
	1.00	4861.724	278.1536
	10.00	3577.709	135.9895
	10.00	3810.512	263.7522
	10.00	3468.036	185.8289
Commercial unit at 750 L/min	10.00	2324.204	103.4345
	10.00	1752.712	134.6135
	10.00	2264.314	101.4599
	10.00	2145.907	71.64824
	10.00	2264.314	170.1393
	100.00	860	40.91516
	100.00	661.3622	53.3939
	100.00	917.0605	45.26787
	100.00	693.0265	44.72136
	100.00	632.4555	54.28967
Commercial unit at 506 L/min	10.00	881.9529	42.51152
	10.00	988.5978	42.51152
	10.00	1206.499	56.73902
	10.00	638.1249	57.25983
	10.00	552.3209	72.31961
	100.00	381.0512	17.01393
	100.00	498.9079	23.83656
	100.00	369.1752	44.03855
	100.00	537.4012	33.14968
	100.00	369.1752	22.21942
Commercial unit at 355 L/min	10.00	486.1724	13.89425
	10.00	452.6787	0
	10.00	301.2579	13.89425
	10.00	380.1021	13.89425
	10.00	427.618	28.06068
	100.00	343.7027	10.34345
	100.00	290.8061	16.83367
	100.00	232.4204	8.77058
	100.00	393.4375	25.75291
	100.00	307.4085	15.28545
Commercial unit at 250 L/min	10.00	42.51152	0
	10.00	168.3367	0
	10.00	102.4329	0

	10.00	103.4345	0
	10.00	0	0
	100.00	179.1957	5.725983
	100.00	60.44826	4.251152
	100.00	146.4466	0
	100.00	24.11214	0
	100.00	131.6976	2.806068
Influent	1.00	3723.966	138.9425
	1.00	3964.125	280.6068
	1.00	3876.649	278.1536
	10.00	4063.777	222.1942
	10.00	4341.216	273.9798
	10.00	3468.036	164.897
Project prototype at 250 L/min with 6 lamps	10.00	203.7728	28.06068
	10.00	166.5902	28.06068
	10.00	326.8099	0
	10.00	152.8545	0
	10.00	170.1393	0
	100.00	120.6499	7.231961
	100.00	537.4012	32.35924
	100.00	166.1079	5.725983
	100.00	208.837	7.231961
	100.00	245.0947	18.58289
Project prototype at 500 L/min with 6 lamps	10.00	206.0639	42.51152
	10.00	318.4407	57.25983
	10.00	103.4345	0
	10.00	1746.076	0
	10.00	387.6649	13.89425
	100.00	498.9079	39.64125
	100.00	381.0512	24.3975
	100.00	369.1752	41.59002
	100.00	252.9822	27.72394
	100.00	766.8116	42.7618
Project prototype at 250 L/min with 5 lamps	10.00	170.1393	28.06068
	10.00	415.1057	28.06068
	10.00	421.3274	42.51152
	10.00	421.3274	0
	10.00	185.8289	0
	100.00	434.1216	26.37522
	100.00	381.0512	28.41237
	100.00	326.0587	24.3975
	100.00	210.9154	11.95229
	100.00	393.4375	24.11214
Project prototype at 250 L/min	10.00	2088.37	170.1393

with 4 lamps	10.00	1573.982	72.31961
	10.00	1249.516	13.89425
	10.00	725.3185	13.89425
	10.00	686.9421	72.31961
	100.00	1063.753	82.1209
	100.00	693.0265	62.62946
	100.00	693.0265	42.7618
	100.00	537.4012	31.84407
	100.00	558.6167	66.39471
Project prototype at 495 L/min with 4 lamps	10.00	1933.51	151.2723
	10.00	1573.982	151.2723
	10.00	1885.655	72.31961
	10.00	1532.971	28.06068
	10.00	1426.399	102.4329
	100.00	1697.94	174.3044
	100.00	1697.94	74.11662
	100.00	1286.934	122.9402
	100.00	860	86.02325
	100.00	727.9582	115.7256
Project prototype at 252 L/min with 3 lamps	10.00	2529.822	28.06068
	10.00	1657.484	57.25983
	10.00	2055.745	57.25983
	10.00	860.2325	57.25983
	10.00	466.6584	118.3401
	100.00	1161.895	104.29
	100.00	537.4012	84.54889
	100.00	537.4012	67.86441
	100.00	1286.934	145.5556
	100.00	1161.895	131.6976
Influent	1.00	5838.742	275.7637
	1.00	6150.987	280.6068
	5.00	5950.674	375.7346
Project prototype at 252 L/min with 2 lamps	10.00	2088.37	87.7058
	10.00	2515.768	87.7058
	10.00	1388.73	152.8545
	10.00	1900.658	241.1214
	10.00	2529.822	185.8289
	100.00	1697.94	158.1139
	100.00	1286.934	146.4466
	100.00	2101.904	198.2062
	100.00	N/A	153.2971
	100.00	3004.164	162.7882
Project prototype at 506 L/min with 2 lamps	10.00	3260.587	215.0033
	10.00	2716.256	103.4345

	10.00	2555.887	134.6135
	10.00	2828.427	151.2723
	10.00	2163.469	134.6135
	100.00	N/A	151.4456
	100.00	N/A	154.1826
	100.00	N/A	271.888
	100.00	3004.164	174.6076
	100.00	1697.94	190.0658
Project prototype at 508 L/min with 1 lamps	10.00	3691.752	152.8545
	10.00	4199.206	293.9388
	10.00	3260.587	219.7177
	10.00	3691.752	301.2579
	10.00	3691.752	168.3367
	100.00	3004.164	336.2422
	100.00	N/A	381.0512
	100.00	N/A	258.1989
	100.00	N/A	216.3469
	100.00	N/A	290.8061
Project prototype at 251 L/min with 1 lamps	10.00	3810.512	238.3656
	10.00	2936.401	170.1393
	10.00	2218.722	135.9895
	10.00	3067.264	185.8289
	10.00	3260.587	206.0639
	100.00	2101.904	264.9671
	100.00	N/A	276.4436
	100.00	3004.164	298.9905
	100.00	N/A	252.9822
	100.00	3004.164	282.8427
Influent	1.00	8272.607	716.4824
	1.00	7491.095	572.5983
	5.00	6724.844	336.6734

Fielding WWTP tertiary treated wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	10	466.6584	28.06068
	10	297.5308	27.81536
	10	372.3966	42.51152
	1	245.0947	28.41237
	1	178.663	59.40885
	1	336.2422	62.62946
Commercial unit at 743 L/min	10	57.25983	13.89425
	10	117.1917	0
	10	42.1325	13.89425
	10	87.7058	28.06068
	10	134.6135	13.89425
	1	78.70559	18.58289
	1	38.01021	10.34345
	1	45.26787	8.77058
	1	71.83811	24.3975
	1	78.00325	21.73221
Commercial unit at 500 L/min	1	30.12579	11.95229
	1	36.22844	8.77058
	1	27.39798	4.251152
	1	24.11214	4.251152
	1	29.39388	7.099523
Commercial unit at 348 L/min	1	4.251152	1.389425
	1	7.231961	2.806068
	1	2.806068	1.389425
	1	2.806068	0
	1	4.251152	0
Commercial unit at 250 L/min	1	4.251152	1.389425
	1	1.37751	1.37751
	1	0	0
	1	0	0
	1	0	0
Commercial unit at 130 L/min	1	2.781536	0
	1	0	0
	1	0	0
	1	0	0
	1	0	0
Influent	10	1830.771	254.5783
	10	1368.417	238.3656
	10	1464.466	263.7522

	1	693.0265	232.5273
	1	581.3777	232.5273
	1	581.3777	260.1682
Project prototype at 255 L/min with 6 lamps	1	1.389425	1.389425
	1	8.77058	0
	1	1.389425	2.806068
	1	2.806068	0
	1	4.251152	0
	1	0	0
	1	0	0
	1	0	0
	1	0	0
	1	0	0
Project prototype at 500 L/min with 6 lamps	1	47.86988	11.83401
	1	84.00417	13.59895
	1	68.2191	17.01393
	1	39.07447	10.34345
	1	117.467	25.45783
Project prototype at 244 L/min with 4 lamps	1	31.84407	15.28545
	1	20.37728	8.77058
	1	37.23966	11.95229
	1	33.56725	15.28545
	1	24.3975	8.77058
Project prototype at 497 L/min with 4 lamps	1	216.3469	59.43979
	1	326.0587	58.38742
	1	245.9675	51.39362
	1	150.2938	48.61724
	1	200.3212	71.00469
Project prototype at 249 L/min with 3 lamps	1	91.52575	25.75291
	1	57.41693	30.12579
	1	91.16729	36.22844
	1	88.58796	32.25439
	1	82.1209	30.12579
Project prototype at 130 L/min with 3 lamps	1	2.806068	0
	1	4.21325	2.806068
	1	13.59895	4.251152
	1	0	0
	1	0	0
Project prototype at 127 L/min with 2 lamps	1	32.68099	10.34345
	1	7.231961	4.251152
	1	13.46135	1.389425
	1	35.75277	7.099523
	1	26.37522	8.77058
Project prototype at 255 L/min with 2 lamps	10	459.5091	103.4345
	10	474.152	206.0639

	10	433.8609	103.4345
	1	406.3777	107.3751
	1	406.3777	116.7639
	1	381.0512	142.6399
	1	346.8036	79.70534
	1	316.2278	89.89845
Project prototype at 497 L/min with 2 lamps	10	433.8609	119.5229
	10	478.6988	87.7058
	10	397.9739	135.9895
	1	449.0434	142.0439
	1	326.0587	165.7484
	1	419.9206	131.6976
	1	406.3777	142.0532
	1	419.9206	110.2927
Project prototype at 127 L/min with 1 lamps	1	82.72607	34.00102
	1	133.2785	31.84407
	1	178.4436	47.86988
	1	116.7639	35.75277
	1	154.1826	39.2718
Project prototype at 249 L/min with 1 lamps	10	890.0492	219.7177
	10	673.1251	170.1393
	10	1015.667	119.5229
	10	733.2629	119.5229
	10	647.8211	257.5291
	1	406.3777	178.663
	1	316.2278	175.2712
	1	406.3777	121.5287
	1	449.0434	190.0658
	1	449.0434	183.0771
Project prototype at 496 L/min with 1 lamps	10	733.2629	185.8289
	10	829.5796	135.9895
	10	638.1249	238.3656
	10	1042.903	318.4407
	10	937.6145	260.5849
	1	498.9079	193.351
	1	464.758	119.8403
	1	346.8036	123.8584
	1	517.5492	210.9154
	1	449.0434	238.7467
Influent	10	827.2607	168.3367
	10	1102.927	119.5229
	10	960.1136	134.6135
	1	434.1216	174.6076
	1	464.758	119.8403
	1	537.4012	142.0439

First Rongotea stabilization pond treated wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	10	8104.432	650.652
	10	7279.582	773.0207
	10	9838.699	626.2946
	1	N/A	1697.94
	1	N/A	661.3622
	1	N/A	537.4012
Project prototype at 500 L/min with 6 lamps	10	2003.212	183.8554
	10	3162.278	203.7728
	10	1885.655	305.1286
	10	1303.545	257.5291
	10	1206.499	206.0639
	1	2101.904	434.1216
	1	N/A	434.1216
	1	3004.164	343.7027
	1	1697.94	326.0587
	1	3004.164	0
Project prototype at 254 L/min with 6 lamps	10	344.5205	42.51152
	10	314.4902	57.25983
	10	170.1393	0
	10	102.4329	0
	10	72.31961	0
	1	223.6068	42.7618
	1	2101.904	54.28967
	1	983.8699	39.07447
	1	357.7709	26.37522
	1	346.8036	29.75308
Project prototype at 497 L/min with 5 lamps	10	855.6888	263.7522
	10	554.0165	222.1942
	10	1073.751	219.7177
	10	780.0325	238.3656
	10	1143.095	187.8673
	1	983.8699	245.9675
	1	558.6167	161.2087
	1	1454.648	282.8427
	1	860	166.6476
	1	727.9582	193.351
Project prototype at 250 L/min with 5 lamps	10	660.1096	87.7058
	10	201.5564	13.89425
	10	367.2361	42.51152

	10	415.1057	28.06068
	10	187.8673	42.51152
	1	1161.895	216.3469
	1	1161.895	101.5667
	1	517.5492	135.1155
	1	661.3622	114.3095
	1	693.0265	116.1895
Project prototype at 496 L/min with 4 lamps	10	2264.314	673.1251
	10	1502.938	471.5596
	10	1620.886	301.2579
	10	2450.947	301.2579
	10	2055.745	206.0639
	1	3004.164	369.1752
	1	1697.94	406.3777
	1	N/A	357.7709
	1	3004.164	357.7709
	1	2101.904	316.2278
Project prototype at 244 L/min with 4 lamps	10	687.7303	102.4329
	10	201.5564	87.7058
	10	604.8584	152.8545
	10	305.1286	42.51152
	10	119.5229	13.89425
	1	860	108.0686
	1	727.9582	120.6499
	1	N/A	98.85978
	1	1697.94	131.6976
	1	3004.164	158.9686
Project prototype at 498 L/min with 3 lamps	10	3934.375	1070.309
	10	4490.434	1198.403
	10	4647.58	1097.888
	10	4063.777	1486.301
	10	4341.216	1238.584
	1	N/A	727.9582
	1	N/A	810.4432
	1	N/A	693.0265
	1	N/A	605.9023
	1	N/A	581.3777
Project prototype at 243 L/min with 3 lamps	10	733.2629	118.3401
	10	905.4063	168.3367
	10	890.0492	293.9388
	10	894.4272	246.2996
	10	686.9421	151.2723
	1	581.3777	183.0771
	1	N/A	353.5152

	1	661.3622	264.9671
	1	983.8699	275.0889
	1	661.3622	307.4085
Project prototype at 500 L/min with 2 lamps	10	6930.265	3468.036
	10	8104.432	1700
	10	9838.699	1933.51
	10	6613.622	2055.745
	10	8104.432	1573.982
	1	N/A	1286.934
	1	N/A	2101.904
	1	N/A	1454.648
	1	N/A	3004.164
	1	N/A	2101.904
Project prototype at 247 L/min with 2 lamps	10	4341.216	1661.079
	10	4490.434	1700.815
	10	4341.216	1229.402
	10	4813.477	1541.826
	10	4813.477	1174.67
	1	N/A	983.8699
	1	N/A	983.8699
	1	N/A	1286.934
	1	N/A	983.8699
	1	N/A	917.0605
Project prototype at 497 L/min with 1 lamps	10	30041.64	5586.167
	10	12869.34	4341.216
	10	N/A	4490.434
	10	21019.04	3577.709
	10	30041.64	5175.492
	1	N/A	N/A
	1	N/A	N/A
	1	N/A	N/A
	1	N/A	N/A
	1	N/A	N/A
Project prototype at 246 L/min with 1 lamps	10	14546.48	3260.587
	10	10637.53	3810.512
	10	9838.699	4199.206
	10	10637.53	2387.467
	10	10637.53	2581.989
	1	N/A	N/A
	1	N/A	2101.904
	1	N/A	3004.164
	1	N/A	N/A
	1	N/A	3004.164
Influent	10	30041.64	3810.512

	10	N/A	4647.58
	10	30041.64	4199.206
Commercial unit at 251 L/min	10	4063.777	869.8945
	10	4647.58	1073.751
	10	4199.206	726.6479
	10	3577.709	911.6729
	10	3577.709	1042.903
	1	N/A	661.3622
	1	N/A	632.4555
	1	N/A	632.4555
	1	N/A	605.9023
	1	3004.164	860
Commercial unit at 505 L/min	10	7279.582	1581.139
	10	9170.605	2145.907
	10	6324.555	1786.63
	10	6930.265	2325.273
	10	6930.265	2332.18
	1	N/A	1286.934
	1	N/A	983.8699
	1	N/A	1697.94
	1	N/A	1286.934
	1	N/A	1063.753
Commercial unit at 742 L/min	10	10637.53	2989.905
	10	14546.48	4202.918
	10	16979.4	3468.036
	10	21019.04	3850.516
	10	11618.95	4490.434
	1	N/A	N/A
	1	N/A	1286.934
	1	N/A	N/A
	1	N/A	3004.164
	1	N/A	2101.904

Second Rongotea stabilization pond treated wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	10	N/A	9170.605
	10	N/A	8600
	10	N/A	9170.605
	100	169794	15418.26
	100	72795.82	12709.32
	100	66136.22	13695.92
Commercial unit at 750 L/min	10	N/A	9170.605
	10	N/A	14546.48
	10	N/A	7668.116
	10	N/A	8104.432
	10	N/A	6059.023
	100	60590.23	17017.27
	100	81044.32	9376.145
	100	81044.32	17919.57
	100	60590.23	15739.82
	100	86000	14204.39
Commercial unit at 496 L/min	10	N/A	9838.699
	10	N/A	9838.699
	10	N/A	9838.699
	10	N/A	9170.605
	10	N/A	10637.53
	100	44904.34	16574.84
	100	86000	18856.55
	100	66136.22	13880.44
	100	55861.67	20313.34
	100	69302.65	15739.82
Influent	20	N/A	18341.21
	20	N/A	14559.16
Commercial unit at 348 L/min	10	N/A	9170.605
	10	N/A	11618.95
	10	N/A	7668.116
	10	N/A	8104.432
	10	N/A	8104.432
	100	69302.65	13145.48
	100	116189.5	17866.3
	100	60590.23	15739.82
	100	76681.16	31705.16
	100	49890.79	14204.39
Commercial unit at 246 L/min	10	N/A	7668.116
	10	N/A	6613.622

	10	N/A	5586.167
	10	N/A	6930.265
	10	N/A	6324.555
	100	60590.23	13684.17
	100	53740.12	16208.86
	100	51754.92	9885.978
Commercial unit at 129 L/min	1	N/A	N/A
	1	N/A	N/A
	1	N/A	3004.164
	10	N/A	3934.375
	10	N/A	5813.777
	10	3603.505	4989.079
	10	4494.17	5374.012
	10	4291.961	4813.477
Influent	10	N/A	14546.48
	10	N/A	16979.4
	100	300416.4	23874.67
	100	145464.8	27188.8
	100	N/A	28284.27
Project prototype at 495 L/min with 6 lamps	10	N/A	6613.622
	10	N/A	5586.167
	10	30041.64	5586.167
	10	21019.04	5175.492
	10	N/A	5374.012
	100	30672.64	9190.885
	100	38105.12	7100.469
	100	38105.12	8400.417
	100	30672.64	7905.694
	100	44904.34	7730.207
Project prototype at 247 L/min with 6 lamps	1	N/A	3004.164
	1	N/A	2101.904
	1	N/A	1697.94
	10	6613.622	1933.51
	10	11618.95	1455.556
	10	8600	2183.688
	10	5813.777	3577.709
	10	6324.555	2325.273
Project prototype at 127 L/min with 6 lamps	1	219.089	198.2062
	1	280	40.34467
	1	271.6256	49.05039
	10	181.9435	13.89425
	10	41.76345	0
	10	86.87445	13.89425
	10	206.0639	57.25983
	10	628.2809	72.31961

Influent	100	145464.8	23252.73
	100	116189.5	23252.73
Project prototype at 247 L/min with 4 lamps	1	N/A	N/A
	1	N/A	N/A
	1	N/A	N/A
	10	N/A	4813.477
	10	30041.64	5586.167
	10	N/A	5586.167
	10	30041.64	4989.079
	10	N/A	6324.555
Project prototype at 500 L/min with 4 lamps	10	N/A	7668.116
	10	N/A	5813.777
	10	N/A	9170.605
	10	N/A	8104.432
	10	N/A	7668.116
	100	76681.16	17866.3
	100	49890.79	11285.32
	100	39343.75	12294.02
	100	35777.09	10737.51
	20	60083.28	8127.555
Influent	100	210190.4	24509.47
	100	116189.5	16610.79
Project prototype at 250 L/min with 3 lamps	10	30041.64	6059.023
	10	N/A	7279.582
	10	N/A	6930.265
	10	N/A	6613.622
	10	N/A	6059.023
	100	39343.75	8783.101
	100	38105.12	9376.145
	100	39343.75	10447.77
	100	38105.12	11323.07
	100	36917.52	10429.03
Project prototype at 126 L/min with 3 lamps	10	3691.752	486.1724
	10	16979.4	626.2946
	10	6613.622	1150.488
	10	2886.307	712.9507
	100	13327.85	572.5983
	100	5940.885	877.058
Influent	20	N/A	18341.21
	100	145464.8	32605.87
Project prototype at 123 L/min with 2 lamps	10	12869.34	4063.777
	10	8600	1705.478
	10	9838.699	1830.771
	10	6930.265	3468.036
	10	N/A	2218.722

	100	30672.64	1858.289
	100	16574.84	1878.673
	100	15739.82	5523.209
Project prototype at 249 L/min with 2 lamps	10	N/A	10637.53
	10	N/A	10637.53
	10	N/A	10637.53
	10	N/A	9170.605
	10	N/A	12869.34
	100	76681.16	18384.78
	100	69302.65	23252.73
	100	60590.23	22045.41
	100	63245.55	15811.39
	100	60590.23	23252.73
Project prototype at 497 L/min with 2 lamps	10	N/A	11618.95
	10	N/A	12869.34
	10	N/A	9170.605
	10	N/A	10637.53
	10	N/A	9838.699
	100	51754.92	23252.73
	100	43412.16	19335.1
	100	60590.23	16154.82
	100	63245.55	17919.57
Project prototype at 500 L/min with 1 lamps	10	N/A	21019.04
	10	N/A	14546.48
	10	N/A	16979.4
	10	N/A	16979.4
	10	N/A	21019.04
	100	86000	25157.68
	100	91706.05	20318.89
	100	76681.16	25819.89
	100	116189.5	26348.38
	100	72795.82	18307.71
Project prototype at 245 L/min with 1 lamps	10	N/A	16979.4
	10	N/A	16979.4
	10	N/A	16979.4
	10	N/A	21019.04
	10	N/A	14546.48
	100	81044.32	23874.67
	100	53740.12	21946.91
	100	76681.16	24509.47
	100	91706.05	19006.58
Project prototype at 127 L/min with 1 lamps	100	86000	26348.38
	10	N/A	8600
	10	N/A	7668.116
	10	N/A	7668.116

	10	N/A	7279.582
	10	N/A	6613.622
	100	44904.34	17430.44
	100	44904.34	15739.82
	100	49890.79	18505.83
	100	34680.36	13856.41
	100	44904.34	15811.39
Influent	10	N/A	11618.95
	10	N/A	9170.605
	10	N/A	16979.4
	100	66136.22	22187.22
	100	63245.55	20313.34
	100	55861.67	29080.61

First Shannon stabilization pond treated wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	100	N/A	60590.23
	100	N/A	44904.34
	100	N/A	55861.67
	1000	449043.4	48617.24
	1000	434121.6	71838.11
	1000	464758	66943.87
Commercial unit at 700 L/min	100	300416.4	30672.64
	100	66136.22	28621.67
	100	98386.99	26016.82
	100	98386.99	33624.22
	100	98386.99	39343.75
	1000	165615.7	57316.28
	1000	110679.7	30512.86
	1000	154182.6	24112.14
	1000	140439.4	34001.02
	1000	214590.7	68694.21
Commercial unit at 500 L/min	100	72795.82	16154.82
	100	63245.55	29753.37
	100	91706.05	22749.47
	100	55861.67	29080.61
	100	40637.77	11916.94
	1000	113710.5	20606.39
	1000	84548.89	15127.23
	1000	94060.45	23836.56
	1000	96370.6	21500.33
	1000	62828.09	11952.29
Commercial unit at 350 L/min	100	46475.8	11572.56
	100	51754.92	17017.27
	100	41992.06	11371.05
	100	66136.22	20313.34
	100	76681.16	25157.68
Commercial unit at 243 L/min	100	48134.77	13856.41
	100	33624.22	10160.01
	100	39343.75	12294.02
	100	38105.12	12495.16
	100	39343.75	7565.91
Commercial unit at 131 L/min	100	6150.987	1665.902
	100	9376.145	1838.554
	100	11832.16	3907.447

	100	9083.737	1858.289
	100	7970.534	1183.401
Influent	100	300416.4	55861.67
	100	N/A	60590.23
	100	N/A	55861.67
	1000	481347.7	82726.07
	1000	419920.6	82726.07
	1000	498907.9	96370.6
Project prototype at 128 L/ min with 6 lamps	100	10160.01	2772.394
	100	10434.98	1701.393
	100	9406.045	3927.18
	100	5633.458	2015.564
	100	12064.99	3184.407
Project prototype at 252 L/ min with 6 lamps	100	27508.89	4276.18
	100	18307.71	4979.55
	100	30740.85	4216.37
	100	20557.45	5139.362
	100	23904.57	4216.37
Project prototype at 500 L/ min with 6 lamps	100	22187.22	7870.559
	100	33624.22	8272.607
	100	30672.64	7640.574
	100	26753.41	7491.095
	100	40637.77	9349.534
	1000	20377.28	7231.961
	1000	18582.89	4251.152
	1000	39074.47	8770.58
	1000	29753.08	13461.35
	1000	20377.28	7231.961
Project prototype at 253 L/ min with 4 lamps	100	23911.6	7730.207
	100	25157.68	5838.742
	100	23252.73	8858.796
	100	29899.05	7970.534
	100	31607.35	9616.941
Project prototype at 500 min/L with 4 lamps	100	48134.77	14555.56
	100	44904.34	10703.09
	100	41992.06	17054.78
	100	60590.23	17847.39
	100	49890.79	18307.71
	1000	71004.69	18582.89
	1000	54289.67	11719.17
	1000	40915.16	10145.99
	1000	41510.57	26058.49
	1000	51393.62	21971.77
Influent	100	N/A	63245.55

	100	N/A	63245.55
	100	N/A	63245.55
	1000	537401.2	110000
	1000	419920.6	111176.9
	1000	346803.6	89004.92
Project prototype at 128 L/ min with 3 lamps	100	34680.36	11504.88
	100	23911.6	9590.335
	100	25157.68	9601.136
	100	28284.27	11067.97
	100	31705.16	12064.99
Project prototype at 354 L/ min with 3 lamps	100	81044.32	33624.22
	100	72795.82	29899.05
	100	66136.22	29899.05
	100	76681.16	30740.85
	100	69302.65	33420.4
	1000	93267.33	28061.82
	1000	113710.5	24112.14
	1000	107375.1	23836.56
	1000	110292.7	27723.94
	1000	110292.7	40915.16
Project prototype at 253 L/ min with 3 lamps	100	55861.67	21634.69
	100	58137.77	20318.89
	100	81044.32	20032.12
	100	81044.32	29080.61
	100	55861.67	20557.45
Project prototype at 248 L/ min with 2 lamps	100	98386.99	43412.16
	100	145464.8	60590.23
	100	128693.4	41992.06
	100	116189.5	39343.75
	100	106375.3	38105.12
	1000	174607.6	52252.63
	1000	174607.6	61623.6
	1000	129211.7	32254.39
	1000	245967.5	46665.84
	1000	234338	62517.17
Project prototype at 498 L/ min with 1 lamps	100	169794	69302.65
	100	300416.4	81044.32
	100	106375.3	72795.82
	100	N/A	76681.16
	100	210190.4	69302.65
	1000	239116	79705.34
	1000	282842.7	69570.11
	1000	306726.4	110000
	1000	239116	114309.5

	1000	316227.8	88195.29
Project prototype at 252 L/ min with 1 lamps	100	N/A	60590.23
	100	N/A	51754.92
	100	300416.4	51754.92
	100	210190.4	55861.67
	100	300416.4	51754.92
	1000	346803.6	101566.7
	1000	343702.7	79705.34
	1000	357770.9	86989.45
	1000	316227.8	68219.1
	1000	325000	88587.96
Project prototype at 125 L/ min with 1 lamps	100	145464.8	53740.12
	100	145464.8	46475.8
	100	169794	49890.79
	100	145464.8	58137.77
	100	145464.8	49890.79
	1000	226431.4	45267.87
	1000	232527.3	57416.93
	1000	271888	74116.62
	1000	336242.2	81016.27
	1000	406377.7	76603
Influent	100	300416.4	69302.65
	100	300416.4	51754.92
	100	N/A	91706.05
	1000	481347.7	165748.4
	1000	558616.7	115357
	1000	434121.6	165772.5

Second Shannon stabilization pond treated wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	100	N/A	72795.82
	100	300416.4	63245.55
	100	210190.4	66136.22
	1000	369175.2	126063.8
	1000	357770.9	91908.85
	1000	393437.5	101552.4
Commercial unit at 708 L/min	100	128693.4	20813.46
	100	300416.4	16574.84
	100	210190.4	21634.69
	100	210190.4	23321.8
	100	210190.4	22187.22
	1000	89004.92	13598.95
	1000	114707.9	20377.28
	1000	120560.7	18786.73
Commercial unit at 497 L/min	100	38105.12	6957.011
	100	23321.8	6262.946
	100	38105.12	7970.534
	100	40637.77	8858.796
	100	34370.27	7043.702
Commercial unit at 347 L/min	100	9660.918	2037.728
	100	20132.09	4050.957
	100	27162.56	6639.471
	100	19335.1	4595.091
	100	14043.94	4276.18
Commercial unit at 250 L/min	100	877.058	138.9425
	100	1319.824	572.5983
	100	1346.135	138.9425
	100	1701.393	421.325
	100	3144.902	280.6068
Influent	100	N/A	86000
	100	N/A	55861.67
	100	210190.4	55861.67
	1000	369175.2	82120.9
	1000	369175.2	107165.6
	1000	316227.8	88587.96
Project prototype at 500 L/min with 6 lamps	100	2247.565	716.4824
	100	2975.308	709.9523
	100	4398.846	709.9523
	100	3400.102	567.3902

	100	3853.132	1359.895
Project prototype at 500 L/min with 4 lamps	100	16733.2	14924.37
	100	24509.47	13514.49
	100	32605.87	15739.82
	100	17017.27	5172.783
	100	19820.62	13684.17
Project prototype at 241 L/min with 1 lamps	100	3853.132	1171.917
	100	1346.135	716.4824
	100	1665.902	425.1152
	100	2247.565	572.5983
	100	3907.447	1195.229
Project prototype at 248 L/min with 3 lamps	100	18657.44	425.1152
	100	6911.483	4715.596
	100	6150.987	2015.564
	100	5848.016	1034.345
	100	1512.723	995.9432
Project prototype at 123 L/min with 3 lamps	100	425.1152	0
	100	1014.599	0
	100	425.1152	138.9425
	100	572.5983	138.9425
	100	877.058	138.9425
Influent	1000	393437.5	98859.78
	1000	326058.7	93761.45
	1000	252982.2	73326.29
Project prototype at 123 L/min with 2 lamps	100	1195.229	425.1152
	100	1359.895	280.6068
	100	2331.262	421.325
	100	2127.571	278.1536
	100	2806.182	877.058
Project prototype at 253 L/min with 2 lamps	100	16208.86	5254.106
	33.33333	19379.26	9333.333
	100	18856.55	5540.165
	100	29899.05	5339.39
	100	28000	6478.211
Project prototype at 503 L/min with 2 lamps	100	86000	36366.19
	100	76681.16	35777.09
	100	106375.3	33624.22
	100	106375.3	43412.16
	100	81044.32	39343.75
	1000	110000	28061.82
	1000	191220.3	38531.32
	1000	145555.6	59408.85
Project prototype at 503 L/min with 1 lamps	1000	306726.4	78003.25
	1000	290806.1	56334.58
	1000	213212.2	69114.83

	1000	336242.2	64782.11
	1000	275088.9	49050.39
	100	210190.4	46475.8
	100	145464.8	53740.12
	100	145464.8	46475.8
Project prototype at 249 L/min with 1 lamps	1000	185058.3	57316.28
	1000	205574.5	45267.87
	1000	166107.9	52541.06
	1000	188565.5	42132.74
	1000	144072.1	60448.26
	100	106375.3	38105.12
	100	210190.4	43412.16
	100	91706.05	40808.24
Project prototype at 123 L/min with 1 lamps	1000	40000	16833.67
	1000	41000	18786.73
	1000	32000	15127.23
	1000	32000	23836.56
	1000	35000	18786.73
Influent	100	210190.4	66136.22
	100	N/A	91706.05
	100	300416.4	55861.67
	1000	336242.2	73484.69
	1000	369175.2	84004.17
	1000	357770.9	98742.09

Foxton Beach stabilization pond treated wastewater test

test	Dilution factor	Total coliform concentration (MPN/100 mL)	*E. coli* concentration (MPN/100 mL)
Influent	100	N/A	55861.67
	100	N/A	53740.12
	100	N/A	53740.12
	1000	498907.9	85104.98
	1000	393437.5	75659.1
	1000	481347.7	64782.11
Commercial unit at 753 L/min	10	N/A	21019.04
	10	N/A	30041.64
	10	N/A	N/A
	10	N/A	N/A
	10	N/A	N/A
	100	N/A	N/A
	100	169794	35777.09
	100	300416.4	35777.09
	100	300416.4	35777.09
	100	300416.4	34680.36
Commercial unit at 494 L/min	10	N/A	30041.64
	10	N/A	14546.48
	10	N/A	30041.64
	10	N/A	9170.605
	10	N/A	N/A
	100	128693.4	14909.99
	100	116189.5	22187.22
	100	300416.4	26753.41
	100	145464.8	21836.88
	100	91706.05	23252.73
Commercial unit at 344 L/min	10	N/A	N/A
	10	N/A	N/A
	10	N/A	N/A
	10	N/A	N/A
	10	N/A	N/A
	100	40637.77	12064.99
	100	30672.64	12495.16
	100	34680.36	12921.17
	100	39343.75	16278.82
	100	49890.79	11618.95
Commercial unit at 252 L/min	10	16979.4	4341.216
	10	N/A	4490.434
	10	N/A	4989.079

	10	N/A	3362.422
	10	21019.04	5374.012
	100	40637.77	6044.826
	100	30672.64	5540.165
	100	34680.36	4159.002
	100	39343.75	3445.205
	100	49890.79	4526.787
Commercial unit at 128 L/min	10	8600	1191.694
	10	10637.53	1743.044
	10	6613.622	1260.638
	10	4199.206	682.191
	10	5586.167	682.191
	100	7490.253	716.4824
	100	7348.469	280.6068
	100	4091.516	572.5983
	100	10767.13	1024.329
	100	8272.607	1346.135
Influent	100	N/A	86000
	100	N/A	69302.65
	100	N/A	72795.82
	1000	581377.7	110292.7
	1000	537401.2	60485.84
	1000	406377.7	89004.92
Project prototype at 125 L/min with 6 lamps	10	3535.152	1015.524
	10	4063.777	594.0885
	10	3577.709	542.8967
	10	4647.58	433.8813
	10	4989.079	583.8742
	100	3964.125	1034.345
	100	4281.173	723.1961
	100	6731.251	572.5983
	100	5633.458	1034.345
	100	7183.811	425.1152
Project prototype at 497 L/min with 6 lamps	10	N/A	14546.48
	10	N/A	6930.265
	10	N/A	21019.04
	10	N/A	14546.48
	10	N/A	16979.4
	100	106375.3	18856.55
	100	69302.65	18754.84
	100	91706.05	18384.78
	100	116189.5	19820.62
	100	86000	21321.22
Project prototype at 257 L/min with 6 lamps	10	N/A	5374.012
	10	N/A	4989.079

	10	N/A	8104.432
	10	N/A	5175.492
	10	N/A	7279.582
	100	55861.67	6957.011
	100	36917.52	9601.136
	100	34680.36	7043.702
	100	55861.67	6282.809
	100	36917.52	5622.535
Project prototype at 494 L/min with 4 lamps	10	N/A	16979.4
	10	N/A	21019.04
	10	N/A	N/A
	10	N/A	30041.64
	10	N/A	16979.4
	100	128693.4	26016.82
	100	128693.4	29080.61
	100	145464.8	30740.85
	100	86000	25819.89
	20	17200	31607.35
Project prototype at 250 L/min with 4 lamps	10	N/A	9838.699
	10	N/A	9170.605
	10	N/A	10637.53
	10	N/A	8104.432
	10	N/A	6930.265
	100	48134.77	11029.27
	100	72795.82	13364.31
	100	76681.16	18856.55
	100	55861.67	19820.62
	100	91706.05	12217.07
Influent	100	N/A	81044.32
	100	N/A	69302.65
	100	N/A	46475.8
	1000	357770.9	88195.29
	1000	381051.2	104477.7
	1000	419920.6	86023.25
Project prototype at 250 L/min with 3 lamps	10	N/A	N/A
	10	N/A	21019.04
	10	N/A	30041.64
	10	N/A	30041.64
	10	N/A	N/A
	100	169794	29364.01
	100	300416.4	44904.34
	100	145464.8	31607.35
	100	N/A	44904.34
	100	210190.4	35777.09
Project prototype at 126	10	N/A	4813.477

L/min with 3 lamps	10	N/A	2908.061
	10	N/A	4341.216
	10	N/A	5175.492
	10	N/A	4989.079
	100	43412.16	4905.039
	100	31622.78	6262.946
	100	33624.22	1183.401
	100	40637.77	4461.441
	100	34680.36	4861.724
Project prototype at 126 L/min with 2 lamps	10	N/A	10637.53
	10	N/A	8600
	10	N/A	11618.95
	10	N/A	9170.605
	10	N/A	10637.53
	100	51754.92	18012.76
	100	60590.23	15029.38
	100	66136.22	13327.85
	100	91706.05	19820.62
	100	128693.4	13035.45
Project prototype at 247 L/min with 2 lamps	100	300416.4	63245.55
	100	300416.4	43412.16
	100	N/A	51754.92
	100	210190.4	41992.06
	100	N/A	43412.16
Project prototype at 130 L/min with 1 lamps	100	210190.4	46475.8
	100	300416.4	36917.52
	100	116189.5	38105.12
	100	300416.4	35777.09
	100	210190.4	38105.12
Project prototype at 496 L/min with 1 lamps	100	N/A	33371.19
	100	N/A	42029.18
	100	N/A	34239.24
	100	N/A	28312.67
	100	N/A	33429.79
Project prototype at 250 L/min with 1 lamps	100	N/A	44904.34
	100	N/A	49890.79
	100	N/A	43412.16
	100	N/A	46475.8
	100	N/A	39343.75
Influent	100	N/A	72795.82
	100	N/A	60590.23
	100	N/A	72795.82
	1000	481347.7	104349.8
	1000	517549.2	129748.9
	1000	498907.9	98994.95

Appendix 2, Patent review note

The appendix here shows all the patents that are reviewed. However, not all the patents are relevant to the thesis topic. Therefore, only the relevant patents are discussed in the main body of the thesis.

Two patent search engines were used; the Scopus patent search and google patent search. This two search engines use a different searching algorithm.

Scopus patent search

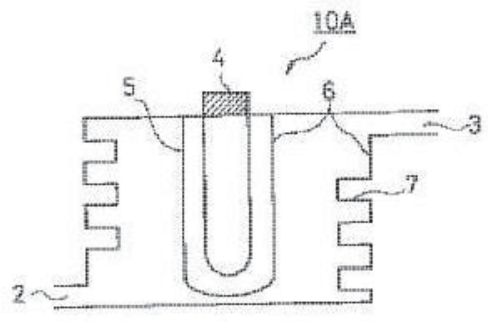
Scopus patent search is based on key words searching. Table A-1 shows the key word combinations that have been used, and only the results that are highlighted were reviewed.

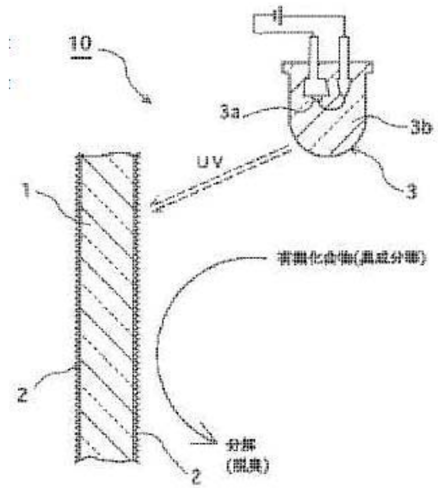
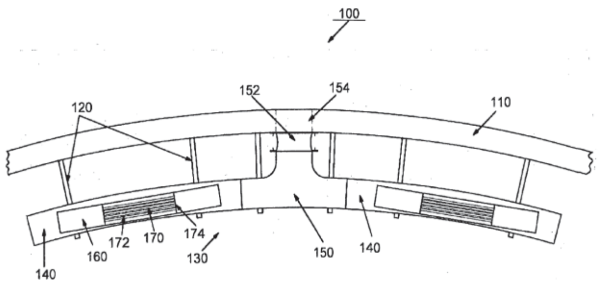
Table A-1, summary of key words search

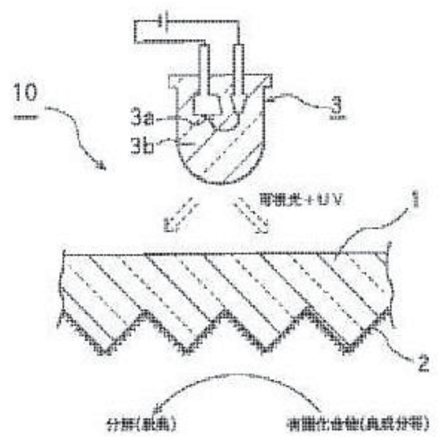
ID	key words search	results
A	UV disinfection	462
B	UV disinfection + wastewater Or contaminate	42
C	UV+ disinfect* OR sanitize* OR purify* + wastewater Or contaminate OR sewage OR water	1225
D	UV disinfection + wastewater Or contaminate OR sewage + thin film OR sheet	2
E	UV disinfection + wastewater Or contaminate OR sewage OR water + thin film OR sheet	10
F	UV disinfection + wastewater Or contaminate+ water*	228
G	UV+ disinfect* + wastewater Or contaminate OR sewage OR water + thin film OR sheet	13
H	UV+ disinfect* OR sanitize* + wastewater Or contaminate OR sewage OR water + thin film OR sheet	13
I	UV+ disinfect* OR sanitize* OR purify* + wastewater Or contaminate OR sewage OR water + thin film OR sheet	18

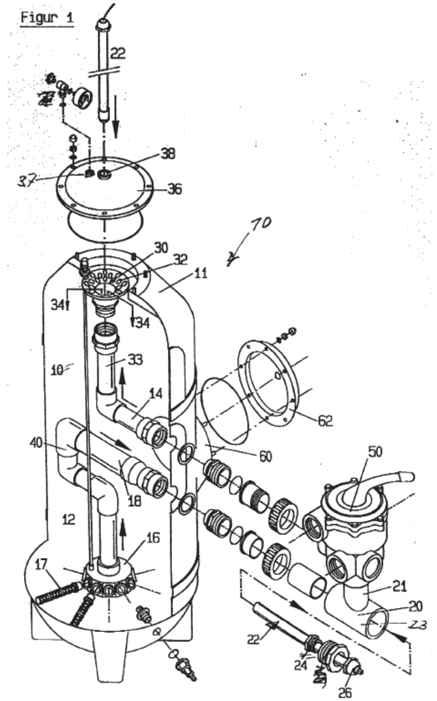
Note: the symbol "*" means in the key word can has some degree of variation, such as disinfect, disinfection, disinfector.

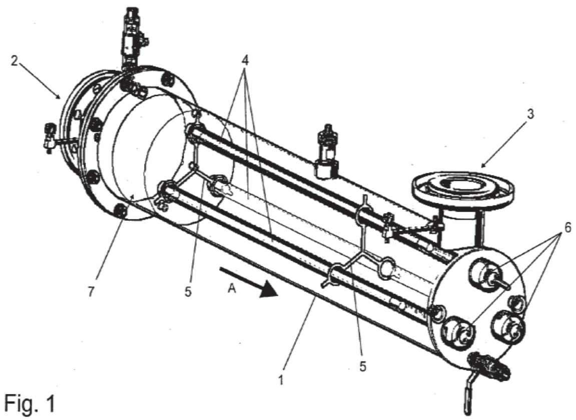
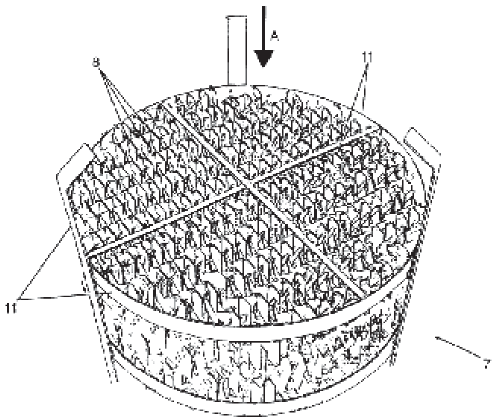
Table A-2, Scopus patent search summary

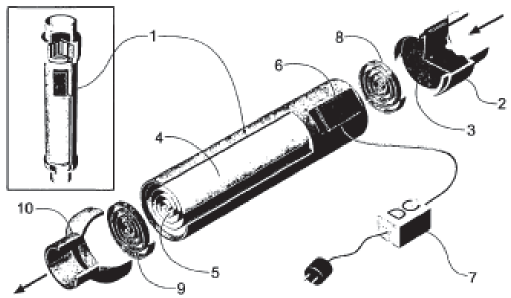
Key words: UV+ disinfect* OR sanitize* OR purify* + wastewater Or contaminate OR sewage OR water + thin film OR sheet			
Patent number [year of publish]	Picture	Description	Comment
JPH10263535(A) [1998]		The UV light, 4, is contained by a membrane, 5, which the UV light can penetrate through. The penetrated UV light would then disinfect the water in the reactor (Toru, 1998).	• Not for wastewater disinfection • Not thin film disinfection • Not supercritical flow disinfection
JP 2004167445 (A) [2004]	N/A	An apparatus and method for fluorescent microscope observation (Seiichi, 2004).	Out of interest
US 7,485,799 [2009]	N/A	An apparatus and method for solar cells (Guerra, 2009).	Out of interest

JPH09940 (A) [1997]		The base body, 1, is coated with a thin film of titanium dioxide, 2, which is a photo-catalysis. UV light is irradiated by the light source UV LED, 3, to illuminate the base. As a result, the surface of the base could purify the air, water or be an antimicrobial surface (Osamu, 1997b).	• Not thin film disinfection • Not supercritical flow disinfection
EP 2242559 (A2) [2010]	N/A	Air purifier (Kyung-Sook, 2010)	• Out of interest
US 20030228727 (A1) [2003]	N/A	An apparatus and method for solar cells (Guerra, 2003)	• Out of interest
EP 1403320 (A1) [2004]		It is used within a clarifier. The clarified effluent, 130, is flowed into the treatment chamber, 140, and passes through the UV apparatus, 170, to be disinfected. The treated wastewater is then flow out via outlet, 150 (Martin, 2004).	• Not thin film disinfection
WO 200909662	N/A	Air purifier (Kyung-Sook, 2010)	• Out of interest

[2009]			
JPH 09941 (A) [1997]		Similar patent as JPH09940 (A) – the same inventor, but different configuration (Osamu, 1997a).	• Not thin film disinfection • Not supercritical flow disinfection

EP 1092682 (A1) [2001]		The apparatus is used to filter the water. The UV lamp, 22, is optionally used to provide extra purification (ING, 2001).	• Not thin film disinfection

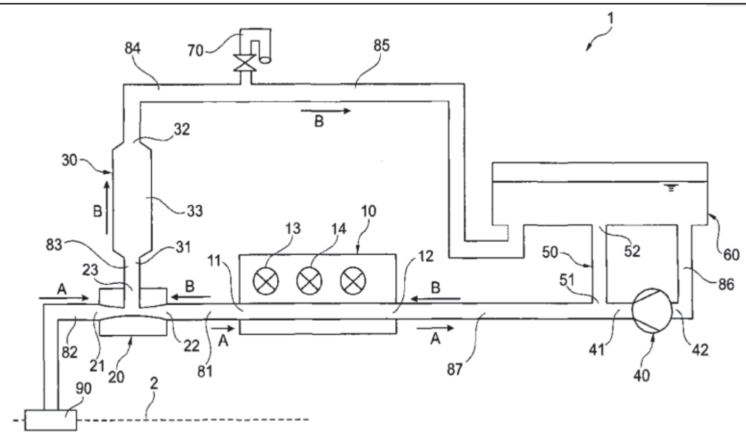
EP 1837309 (A1) [2007]	 Fig. 1  Fig. 2	The apparatus is similar to an ordinary cylindrical closed channel UV reactor, but with a specially design baffle (7) (Sief *et al.*, 2009)	• Not thin film disinfection
EP 1282450 (A1) [2003]	N/A	Air disinfection apparatus (Hurst, 2004)	• Out of interest
WO 9817394 (A1) [1998]	N/A	A process of using sustainable steam to sanitize the wastes (Akiyoshi *et al.*, 1997)	• Not UV disinfection

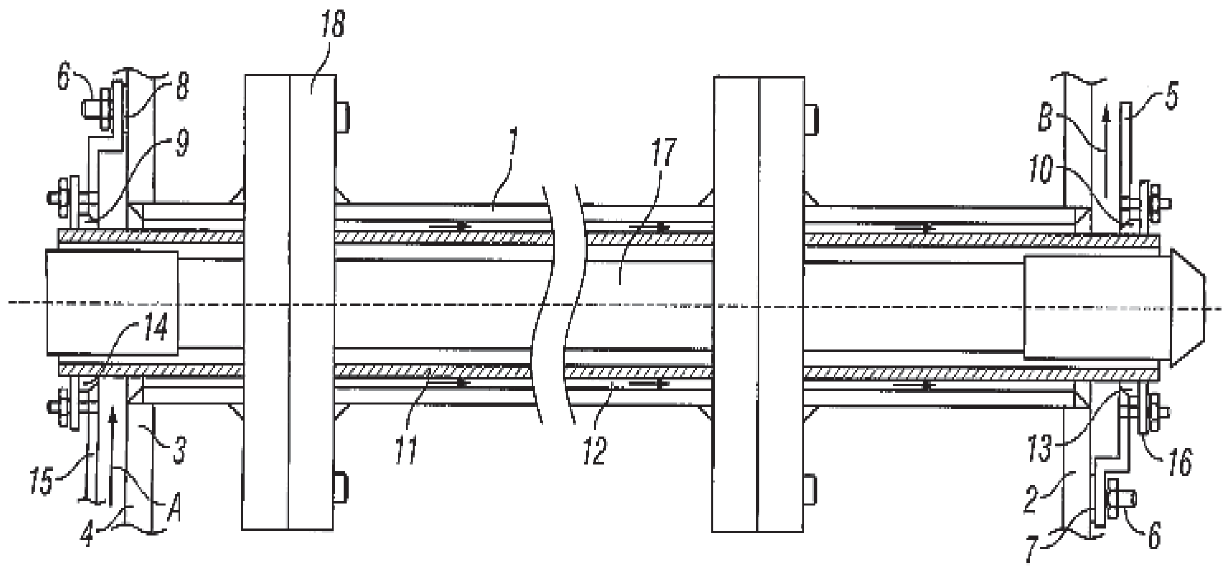
US 7226542 B2 [2007]		A micro array sealed with UV emitter, 4, is rolling up as picture shown. The water is entered the reactor from the inlet, 2, through the micro-discharge array to be disinfected, and then exit from the outlet, 10 (Zemel *et al.*, 2007).	• It is design for small scale drinking water treatment • The device could be thin film disinfection • The device can perform at flow rate larger than 1 litre per minute, and have lifetime 150 litre. • Not supercritical flow
US 7592607 B2	Refer to EP 1837309 (A1)		
JPH 11114048 (A) [1999]	N/A	Air purifying device (Shinya, 1999)	• Out of interest
JP 2003322370 (A) [2003]	N/A	Photo-catalyst air cleaning apparatus (Hiroo, 2003)	• Out of interest
JPH 01280460 (A) [1989]	N/A	Body part warming bath device (Yoshio, 1989)	• Out of interest

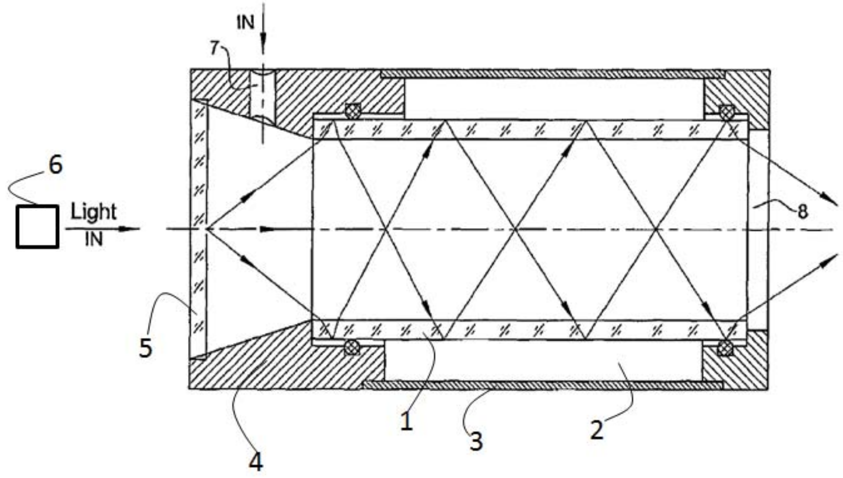
Google patent search results

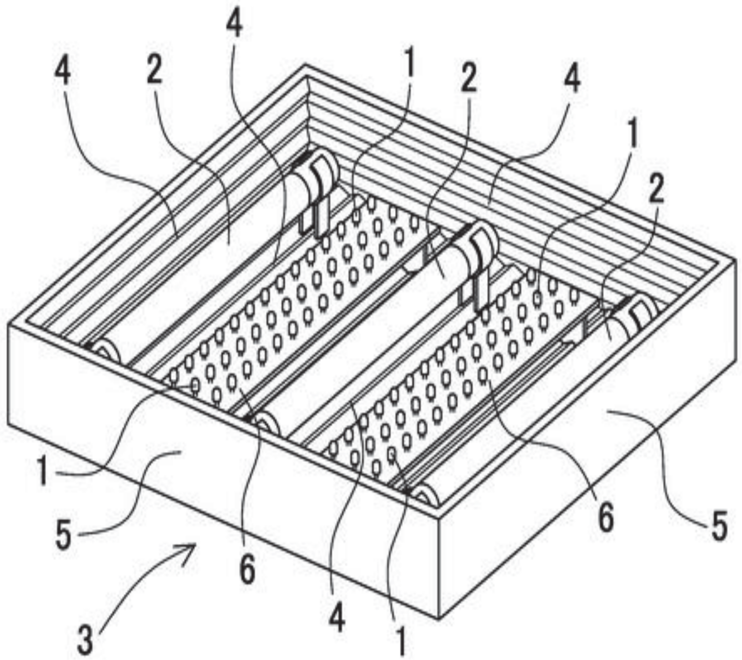
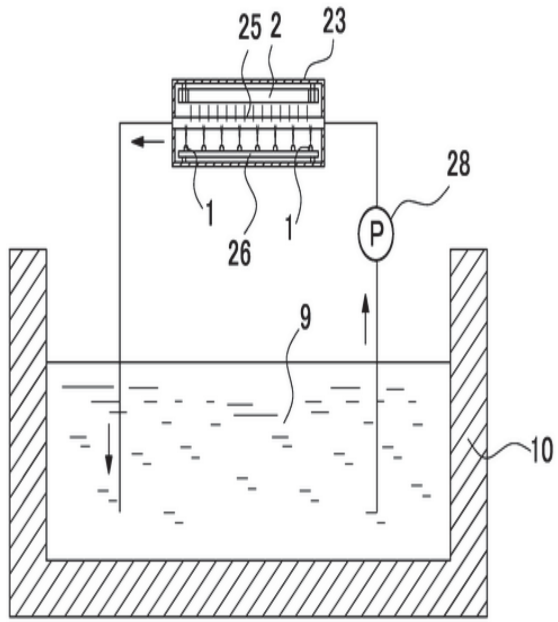
Google patent search is also used. Different from the Scopus patent search, the number of recommended patent will not decrease as the key word become more specific. So that only some of the patents are reviewed from the results. The key word for the google patent search was thin film and non-submergible UV lamp. In totally, 13 patents are reviewed, which are invented from 1993 to 2013.

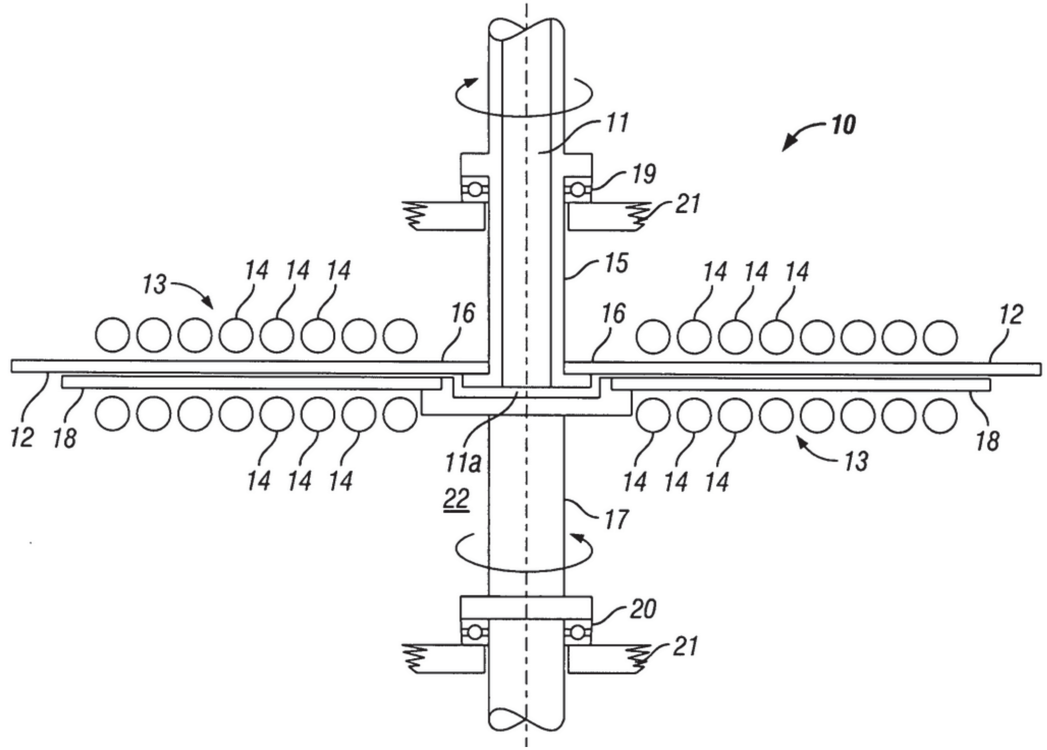
Table A-3, google patent search summary

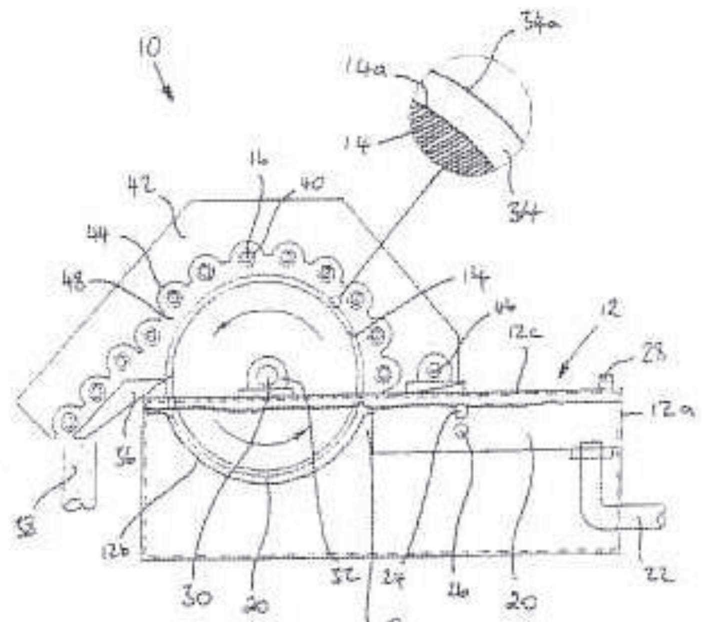
Patent ID:	WO 2013023771 A1 OR DE 102011110105 A1
Year	2013
Configuration	
Description	This device is designed for passenger transport vehicles use, in particular aircraft. The device can have two operation modes, which are filling (A) and discharging (B) mode. In filling mode, water from water source (90) flow through the UV device (10) and enter the water reservoir (60), via the pipes 82, 81, 87 and 50. The water will not flow into pipe 83 because of the venture effect. In discharge mode, water from the reservoir (60) is pumped (40) through the UV device (10) to the discharge tap (70), via pipes 86,87,81,83, and 84. Water will not flow into pipe 3 because at that time, the water source (90) is sealed, and water reach to a death end in pipe 82.
Discussion	• Not thin film disinfection
Source	Axel *et al.* (2013)

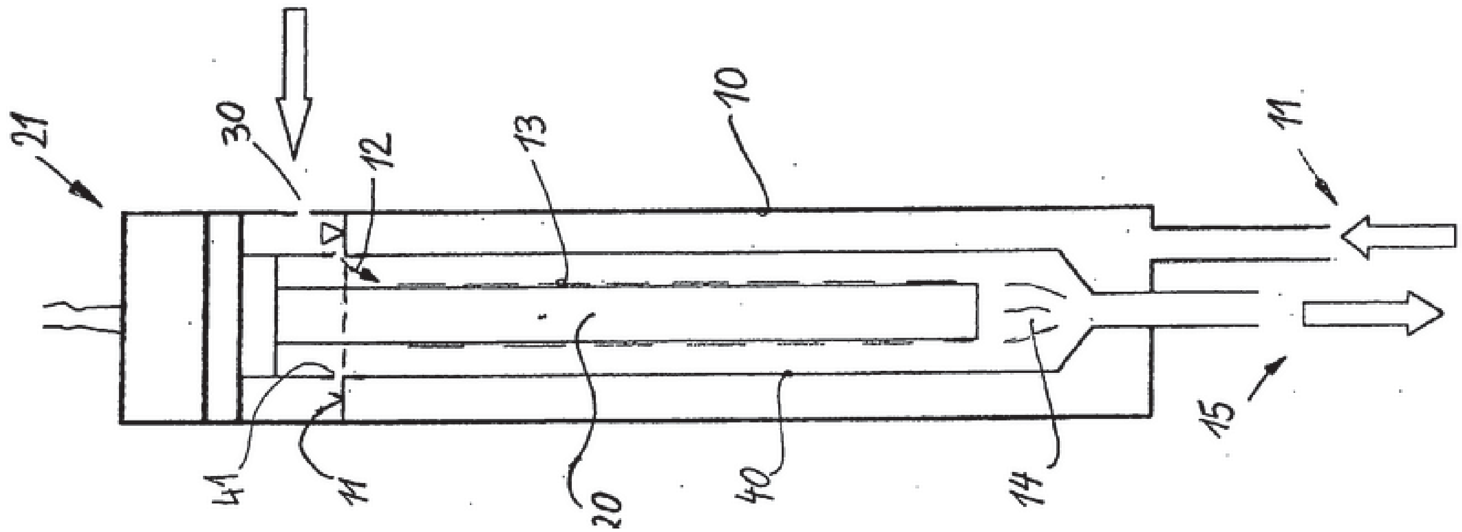
Patent ID:	US 20120097862 A1 OR (CA2759824A1, CN102427830A, EP2424576A1, WO2010125389A1)
Year	2012
Configuration	
Description **Discussion**	See section 2.7.2.6
Source	Snowball (2012)

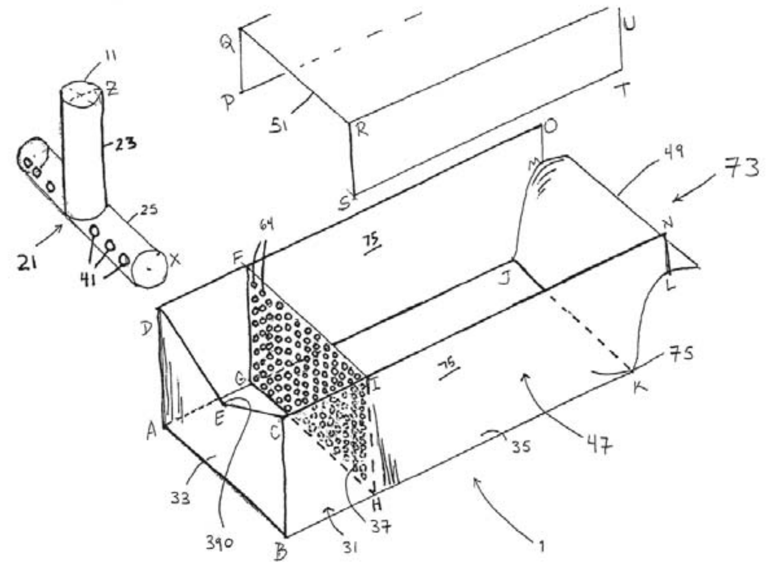
Patent ID:	US 7683344 B2 OR EP1654006A1, EP1654007A1, US20070272877, US20090000639, US20100178201, WO2005011753A1, WO2005011754A1
Year	2010
Configuration	
Description	Contaminated water enters the system from 7 and exit from 8. UV light from the source (6) enters the system through the transparent glass (5), and has contact with the contaminated water; hence inactivate the microorganisms. The pipe (1) is made of quartz sleeve. The quartz sleeve is protected by the metal sleeve (3) with air gaps (2) between the metal sleeve and the quart sleeve.
Discussion	• Not a thin film disinfection reactor
Source	Levy *et al.* (2010)

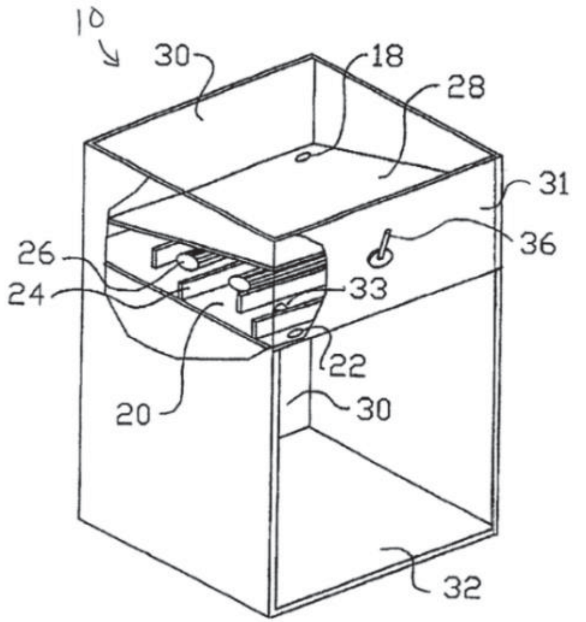
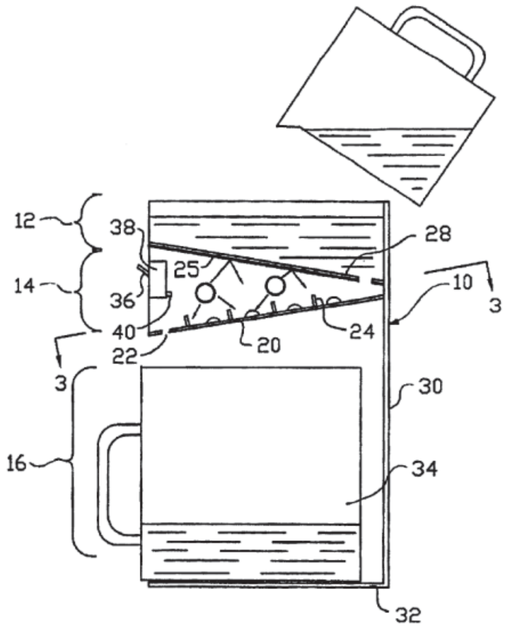
Patent ID:	US 8324595 B2 OR EP2394963A1, EP2394963A4, US20110226966, WO2010058607A1
Year	2009
Configuration	 
Description	The device uses combination of UV lamps (2) and UV LED (1) to disinfect contaminated water. It can be used as either submerged configuration or no submerged configuration (as the figure on right). The patent document also includes the supportive data of the device's treatment.
Discussion	• Not a thin film disinfection reactor
Source	Takahashi *et al.* (2009)

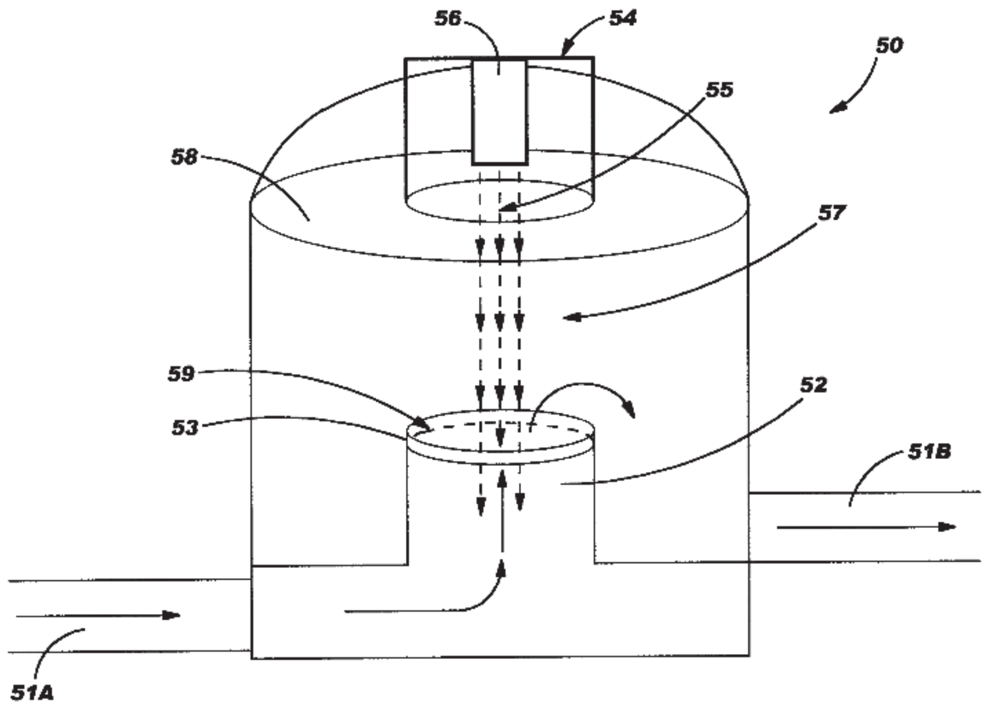
Patent ID:	US 20090004050 A1 OR CA 2635164 A1, EP2055317 A2, EP 2055317 A3
Year	2009
Configuration	
Description	See section 2.7.2.7
Discussion	
Source	Snowball (2009)

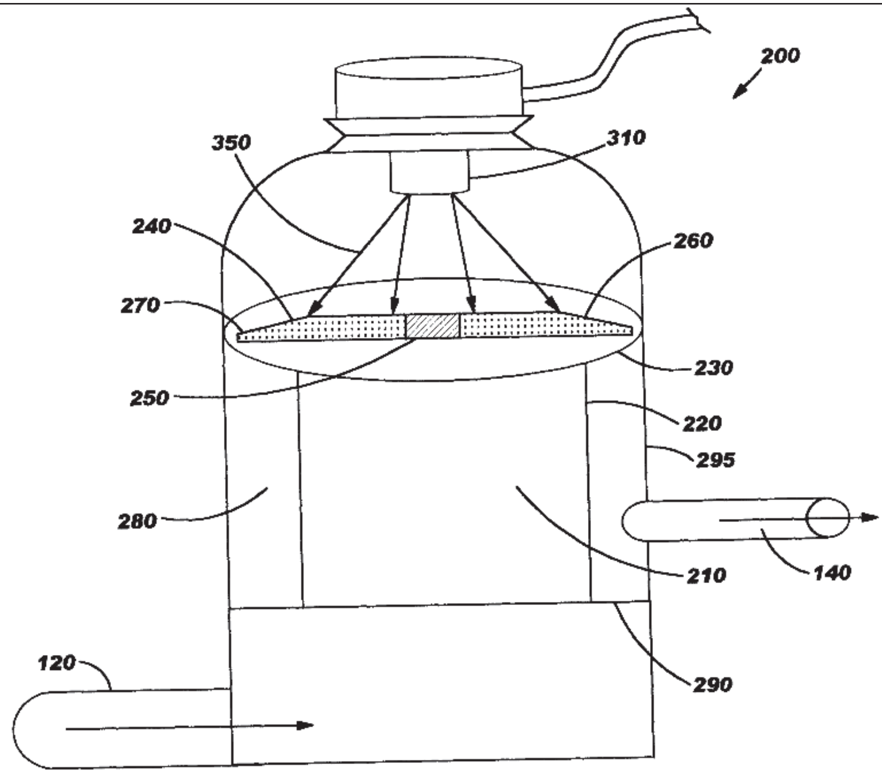
Patent ID:	EP 1865997 A1 OR GB 2424877, WO 2006106363 A2, WO 2006106363 A3, CA 2604141 A1
Year	2007
Configuration	 Fig. 1
Description / Discussion	See section 2.7.2.8
Source	Snowball (2007)

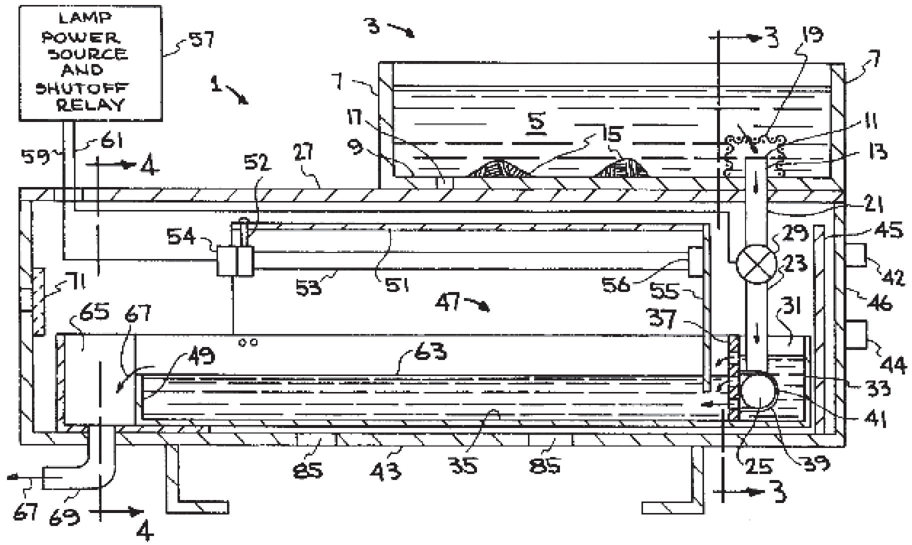
Patent ID:	US 20050061743 A1 OR DE10151488A1, DE50209679D1, EP1436025A1, EP1436025B1, WO2003035145A1
Year	2005
Configuration	
Description	The device is designed for treating waste fluid, particularly for medical waste. Two chambers are used in this reactor, one outer chamber (10) and one inner chamber (40). Contaminated water enters the outer chamber from the inlet (11) as the arrow shown. The contaminated water is then up flow and pass the opening (41). After the contaminated water pass the opening (41), it will fall into the inner chamber (40). In the inner chamber, there is a UV irradiator (20), and the spacing between the inner chamber wall and the irradiator (20) is relatively thin. So a uniform falling thin film is treated by the irradiator (20). Finally, the treated fluid is discharged to the outlet (15).
Discussion	• Not thin film disinfection • Not supercritical flow
Source	Buttner (2005)

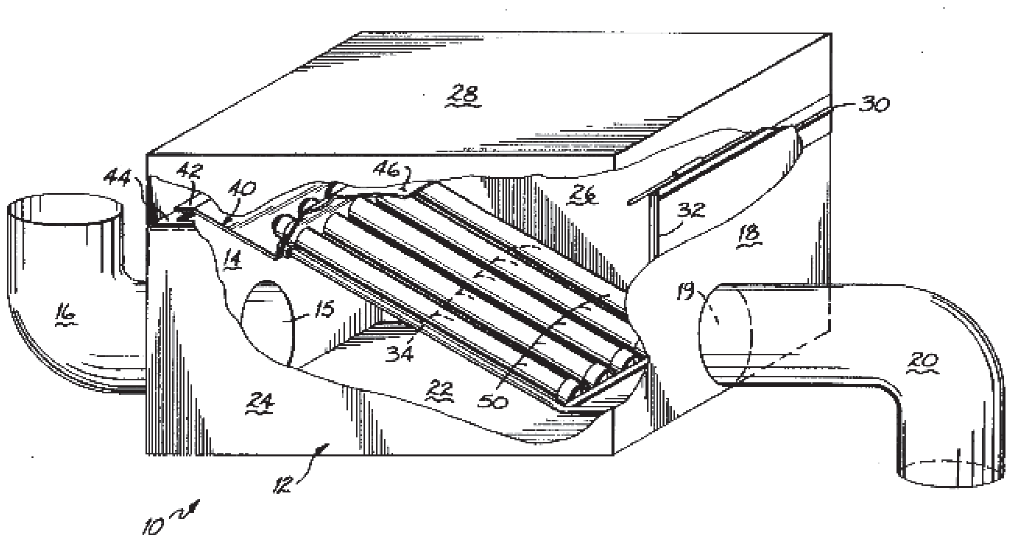
Patent ID:	US 6803587 B2 OR US6974958, US7217933, US20020117631, US20050092931, US20060192136
Year	2004
Configuration	
Description	The device is designed for drinking water treatment in household. Water enters the inlet chamber (31) from the inlet manifold (21). As the contaminated water fills up the inlet chamber (31), the water slowly disperse into the treatment chamber (47), through the baffle plate (37). The water in the treatment chamber (47) is treated by the UV irradiation from the UV device (51), which placed on top of the treatment chamber (47). As the water in treatment chamber (37) is slowly filled up, the water will overflow through the baffle dam (49).
Discussion	• Not thin film disinfection
Source	Gadgil *et al.* (2004)

Patent ID:	US 6773608 B1 OR DE69922950D1, DE69922950T2, EP1082268A1, EP1082268B1
Year	2004
Configuration	 
Description	The fluid slowly drains into the reaction chamber, and then is UV disinfected as it flows through the reaction chamber. The flow of the fluid is regulated by the zigzag orientated baffles and the protrusions.
Discussion	• Not thin film disinfection
Source	Hallett and Hallett (2004)

Patent ID:	US 6447720 B1 OR EP 1322341 A1, WO2002009774 A1
Year	2002
Configuration	
Description	See section 2.7.2.9
Discussion	
Source	Horton *et al.* (2002)

Patent ID:	US 6403030 B1 OR CA2430057A1, CN1254277C, CN1487842A, EP1365814A2, EP1365814A4, WO2002055438A2, WO2002055438A3
Year	2002
Configuration	
Description / **Discussion**	See section 2.7.2.10
Source	Horton (2002)

Patent ID:	US 5780860 OR CA2262678A1, CA2262678C, CN1131714C, CN1231615A, DE69728674D1, EP0921823A1, EP0921823A4, EP0921823B1, WO1998005367A1
Year	1998
Configuration	
Description	This device is designed for developed countries water or wastewater treatment use. Water in the upper chamber will naturally settle the suspended solid (15) on the tray floor (9), and then enters the manifold inlet (21) through the screen (19). The water from the manifold inlet (21) will pass through a baffles plate (31) and flow on the main tray floor (35). While it is flowing on the floor (35), UV light is irradiated on the water from the UV lamps (53). The treated water will overflow the baffle weir (49) and into the outlet (67). The movement of the flow is driven by gravitational force.
Discussion	• Not a thin film disinfection reactor
Source	Gadgil and Garud (1998)

Patent ID:	US 5208461 A OR WO 1993007091A1
Year	1993
Configuration	
Description	The device is designed for wastewater treatment. Contaminated water enters the system through the pipe (16) and then flow pass the semi-submerged UV lamps (34) to be disinfected. The treated water will be discharged by the outlet pipe (20).
Discussion	• Not a thin film disinfection reactor
Source	Tipton (1993)

Appendix 3, Froude number calculations

In the experiments, the project prototype and 2nd generation was tested at sluice gate of 2, 4 and 6 mm, and process flow rate of 500, 250 and 130 L/min. Table A-4 shows the Found number of the project prototype at each setting.

Table A-4, Found number at each setting

	500 L/min	250 L/min	130 L/min
2 mm	37.18341	18.591707	9.6676878
4 mm	13.14632	6.5731612	3.4180438
6 mm	7.155951	3.5779757	1.8605474

Sample calculation

The project prototype at sluice gate of 6 mm (the thickest gap) and operated flow rate of 130 L/min

The reaction chambers of both devices are 80 cm wide and the fluid thickness is 6 mm.

$$v = \frac{Q}{A} = \frac{130\ lpm}{(0.8m \times 0.006m)} = \frac{0.0021\ m^3\ per\ s}{0.0016} = 0.45\frac{m}{s}$$

$$Fr = \frac{0.45}{\sqrt{9.81 \times 0.006}} = 1.86 \gg 1$$

Therefore, it is supercritical flow UV reactor

Appendix 4, Reflector designs

Signal unit of parabola shaped reflector

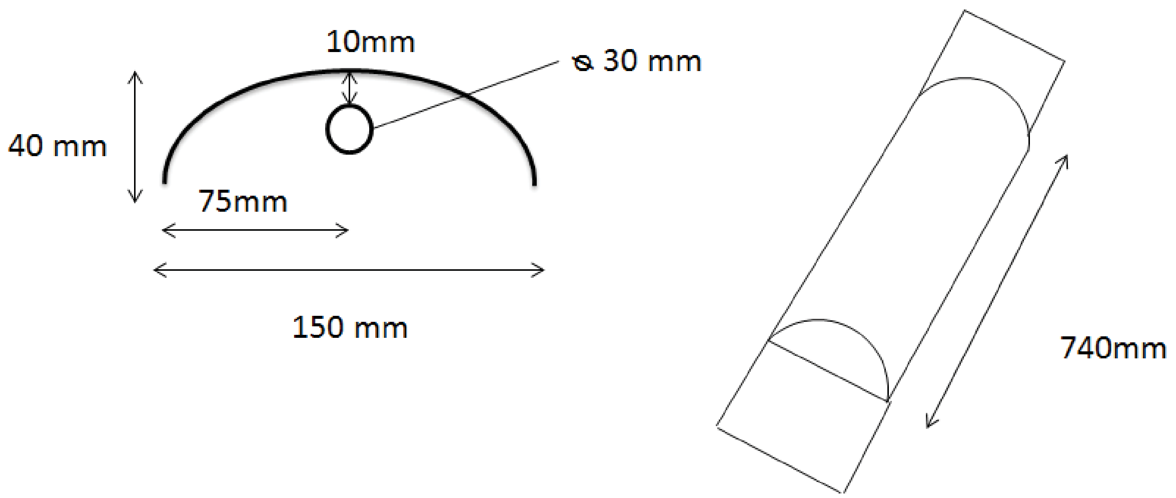


Figure A-7-1, design of parabola shaped reflector

Sketch of square shaped reflector

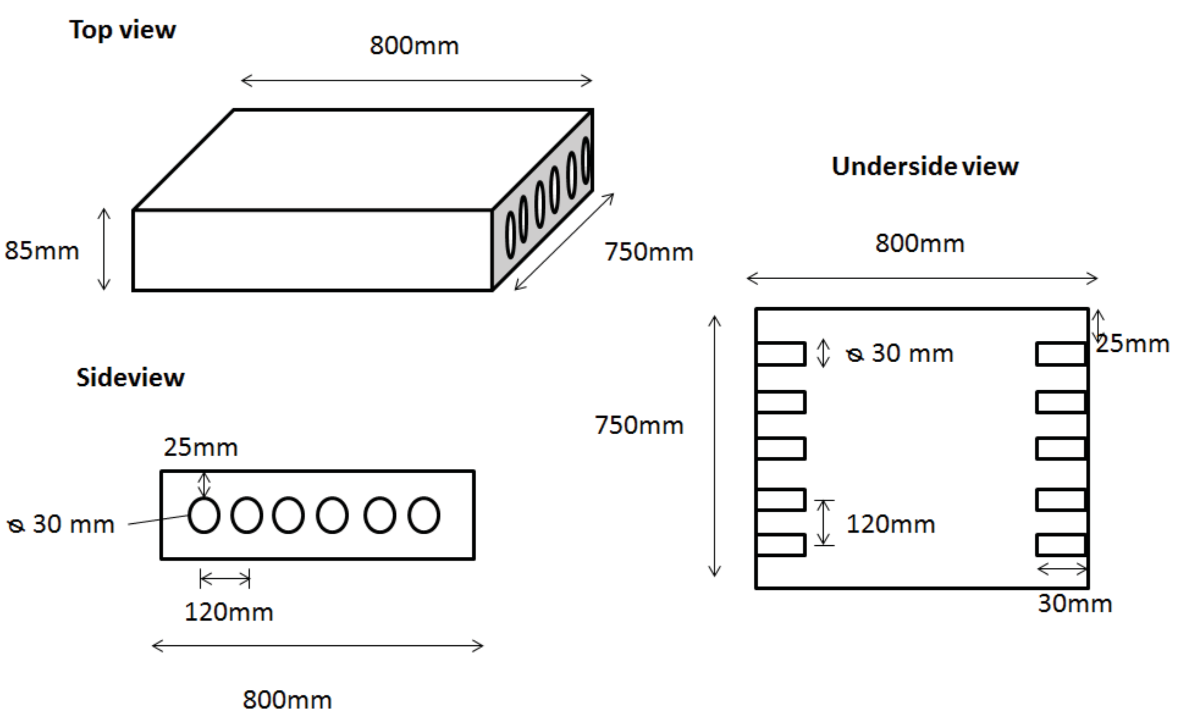


Figure A-7-2, design of square shaped reflector

Appendix 5, Commercial unit design

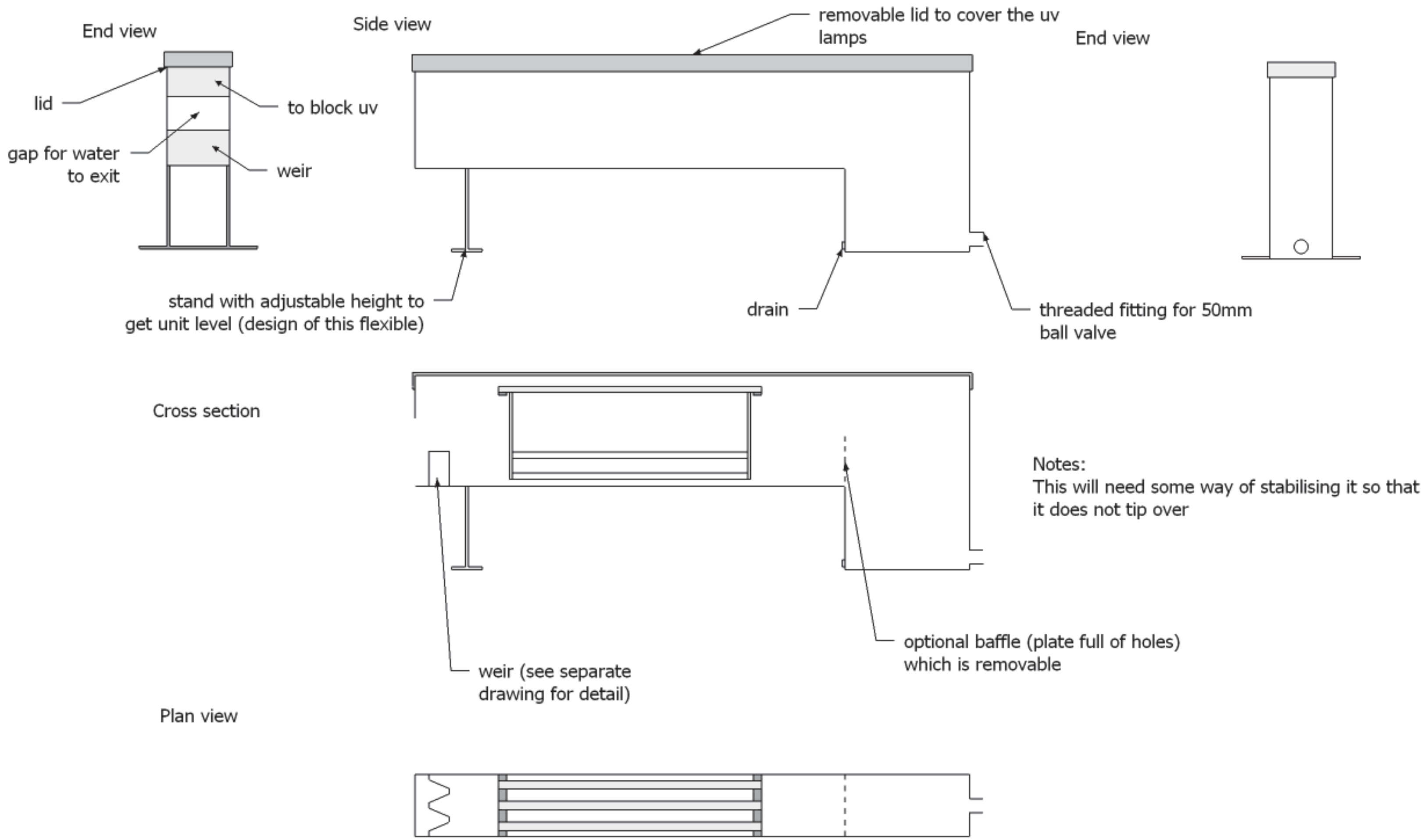


Figure A-7-3, commercial unit design (a)

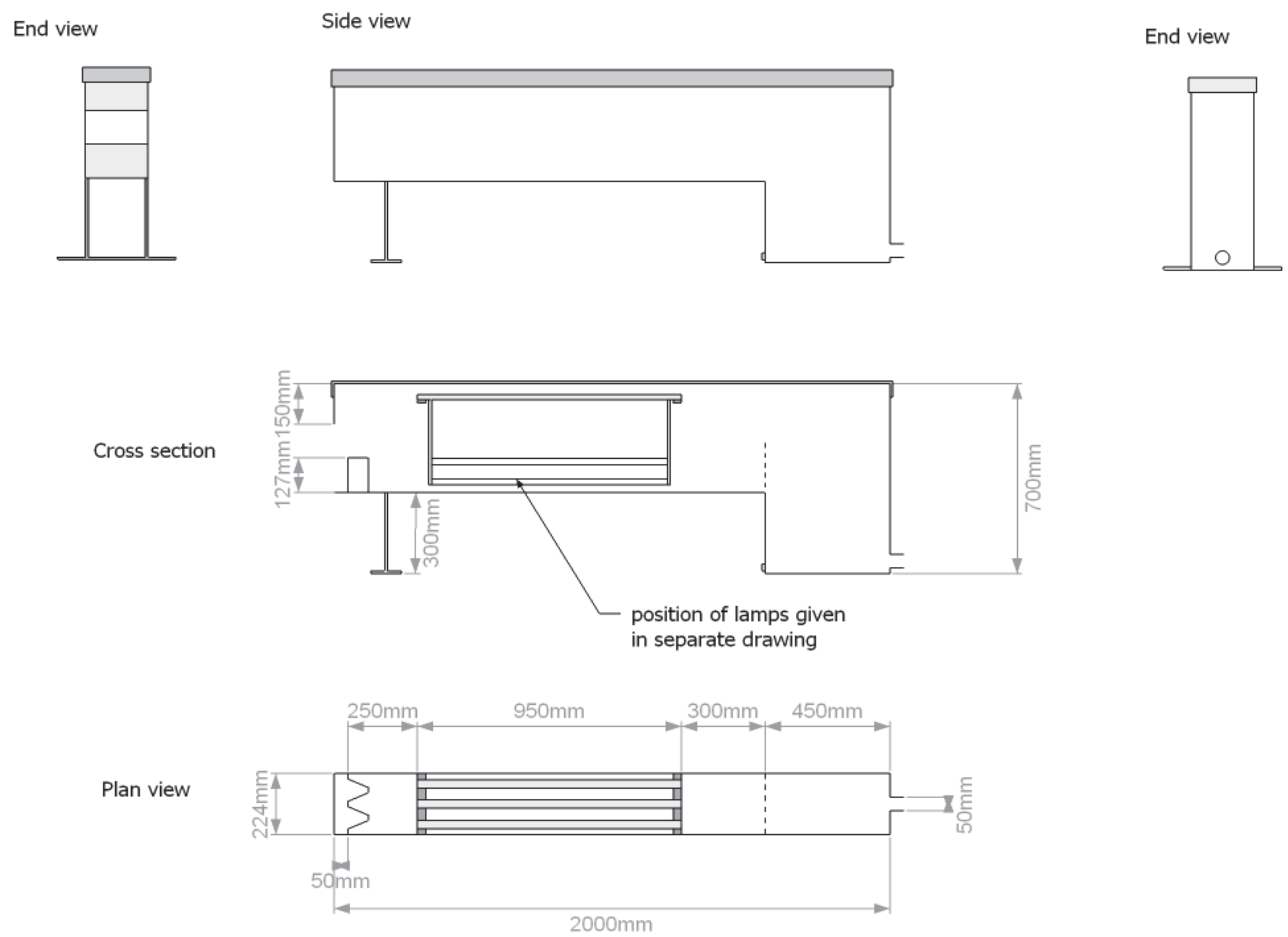


Figure A-7-4, commercial unit design (b)

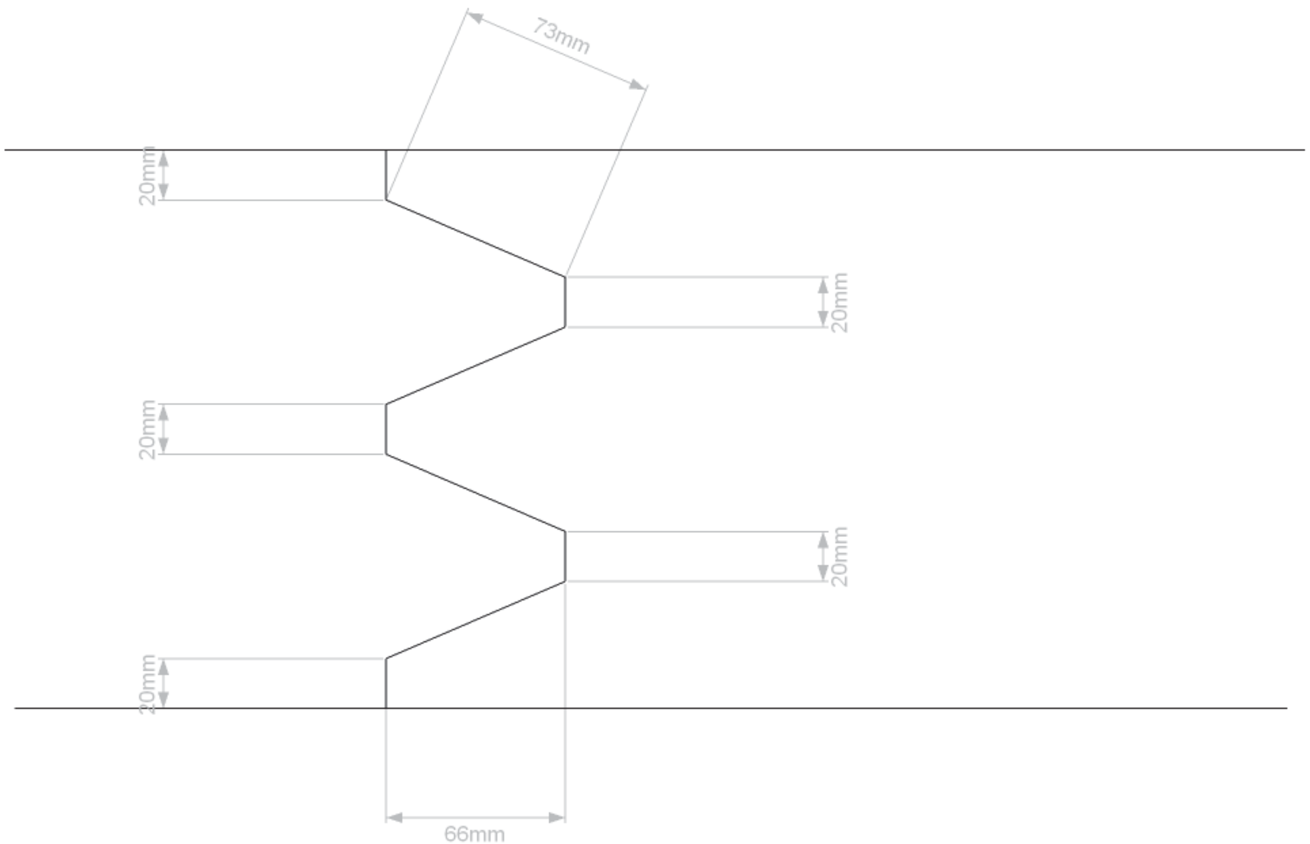


Figure A-7-5, weir design of the commercial unit

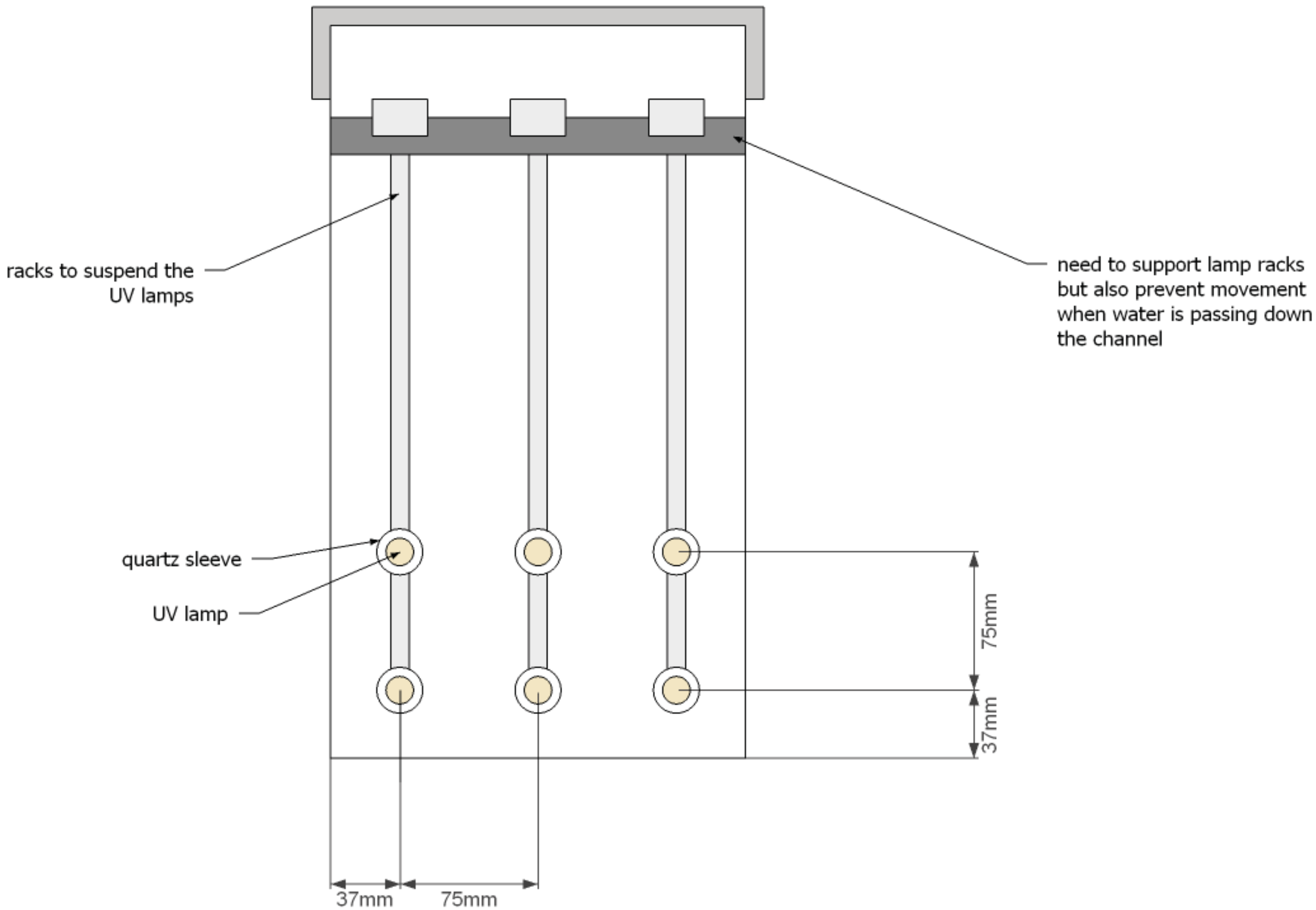


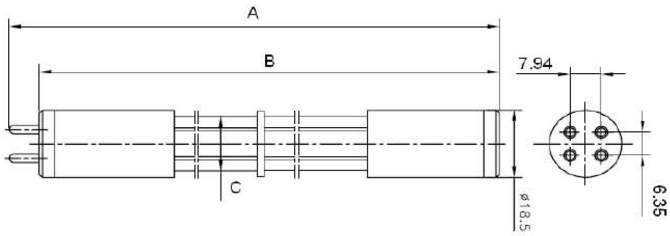
Figure A-7-6, lamp positions of the commercial unit

Appendix 6, UV lamp- GPH840N2/S

	Germicidal Lamp Data Sheet **GHO36T5L/4 LL**	**LightTech Lamp Technology Ltd.** H-2120 Dunakeszi Hegyrejáró u.1. Tel:+36 /27/541-800 Fax:+36 /27/390-099 info@lighttech.hu www.lighttech.hu

Dimensions

A - Base face to opposite pin length	**850 mm**
B - Base face to base face length	**842 mm**
C - Diameter	**15 mm**



Electrical Data *(nominal values)*

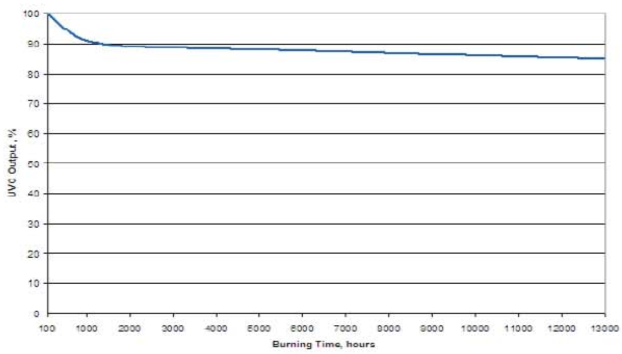
Lamp Wattage	**87 W**
Lamp Current	**800 mA**
Lamp Voltage at High Frequency	**110 V**

Physical Data

UV Output 253.7nm (100hr)	**28 W**
Intensity @ 1m	**260 µW/cm2**
Rated Average Life	**13000 hrs**

Maintenance curve

The useful life is determined on the operation condition of the lamp (for example type of ballast, ignitor used, cooling conditions, on/off cycle, etc.)



Note: Performance data are valid under laboratory conditions.

LightTech, Inc. Confidential 2010.09.03

Note: GHO36T5L/4LL is the same lamp as GPH840N2/S. The difference is due to different company series number (information provided by Davey Water Product LTD.)

Figure A-7-7, information of the UV lamps used in the project

Appendix 7, Ballast Information Sheet

Figure A-7-8, information of the ballast used in the project

Appendix 8, Flow meter information

GPI® **Economy Electronic Digital Meters**

TM Series Water Meter

Display Model

"Look for the Blue Label!"

Shown with 90° Adapter (sold separately)

Pulse Model

TM SERIES - SPECIFICATIONS		
Design Type:	Turbine	
Fitting Size:	1/2" 3/4" 1" 1-1/2" 2"	
Fitting Type:	Schedule 80 Spigot (pipe) end or NPT (female)	
Flow Range:		
1/2 " TM050	1-10 GPM (3.8 - 38 LPM)	
3/4 " TM075	2-20 GPM (7.6 - 76 LPM)	
1 " TM100	5-50 GPM (19-190 LPM)	
1-1/2" TM150	10-100 GPM (38-380 LPM)	
2" TM200	20-200 GPM (76-760 LPM)	
Accuracy:	+/- 3.0 % of reading	
Pressure Rating:	225 PSIG at 73°F	
Operating Temperature:	+32°F to +140°F (0° to +60°C)	
Battery Life:	5 Years	
Wetted Materials		
Housing:	PVC	
Bearings:	Ceramic	
Shaft:	Tungsten Carbide	
Rotor:	PVDF	
Rings:	316 Stainless Steel	
Shipping Weight(approx.)	Spigot	NPT
1/2 " TM050	.38 lbs (.172 kg)	.55 lbs (.249 kg)
3/4 " TM075	.43 lbs (.304 kg)	.67 lbs (.304 kg)
1 " TM100	.49 lbs (.222 kg)	.49 lbs (.381 kg)
1-1/2" TM150	.66 lbs (.299 kg)	1.38 lbs (.626 kg)
2" TM200	.78 lbs (.354 kg)	1.78 lbs (.807 kg)
Display Features:	Rate of Flow, Batch and Cumulative Totals.Field Calibration available.	
Pulse Output:	Open Collector (NPN)	

APPROVALS

CE

SAMPLE MODEL

TM100-N- P

Model Size | Fitting Type | Electronic Choice

SPIGOT VERSATILITY

Flange | Union | Male NPT | Coupler

Spigot models include a male end that allows you to glue on any PVC fitting.

Features and Benefits:

- easy to install
- available in NPT or Spigot fittings
- meets Schedule 80 specifications
- displays in Gallons, Litres, and Cubic Feet
- 5 year Lithium batteries
- indicates batch, cumulative totals and rate of flow
- non-volatile totalizers

Applications:

- OEM water treatment equipment/skids
- sub-metering of facility water usage
- small waste water treatment equipment
- water based cooling systems - chillers

GPI®

ML-2037-01

Figure A-7-9, information of the flow meter used in the project

Appendix 9, Wastewater consistency check

In order to check the consistency of a WWTP effluent, secondary treated wastewater from PNWWTP was collected and analysed. The wastewater was collected every 15 minute until the 45 minute. The variation of *E. coli* concentration with in these 45 minutes is shown as Figure A-7-10. Figure A-7-10 shows that the *E. coli* concentration is not significantly varied, which suggests that the wastewater quality was not significantly changed within those 45 minutes.

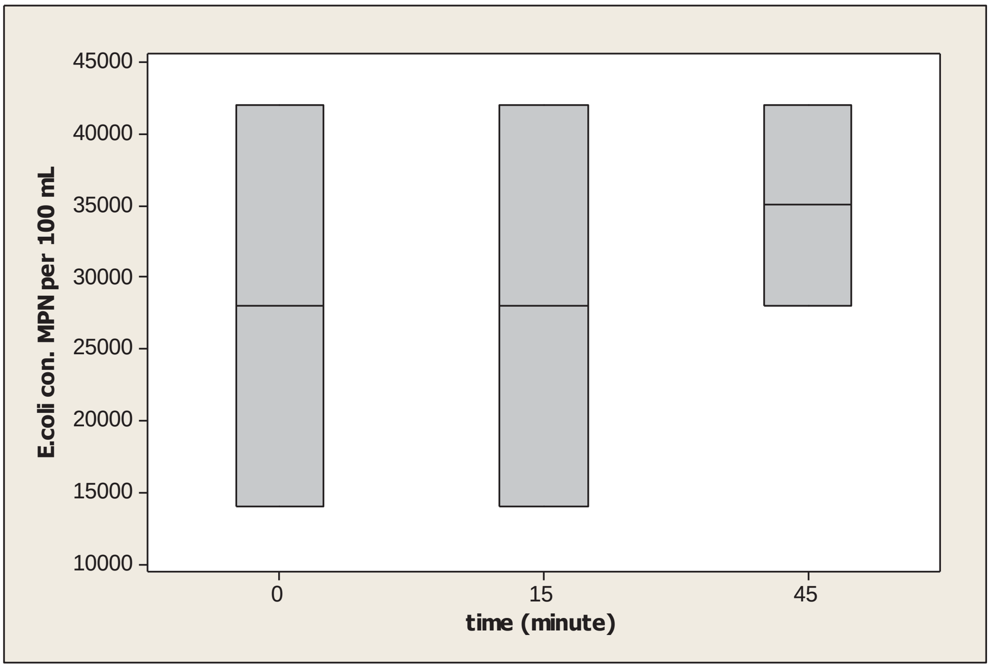
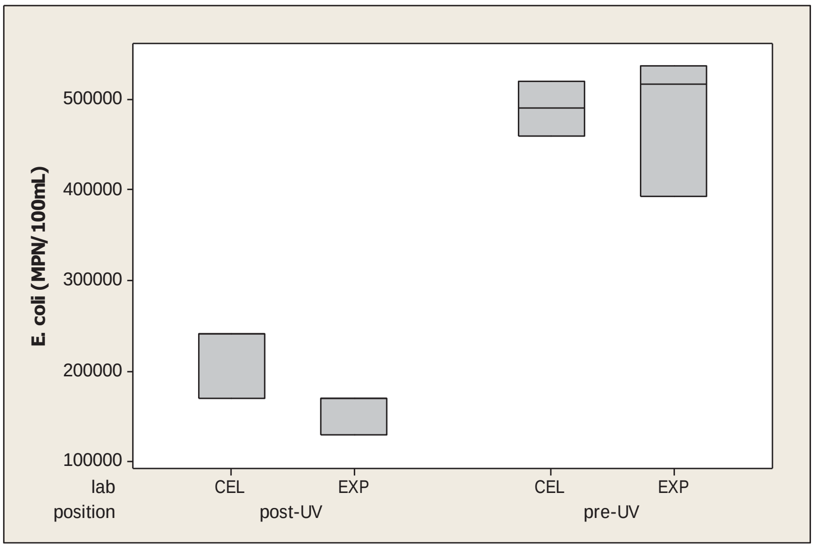


Figure A-7-10, *E. coli* concentration of the secondary treated wastewater from PNWWTP in a period of 45 minute

Appendix 10, Reliability of the sample analysis

The reliability of the experimental method was assessed by comparing to the parallel results from an independent laboratory, called Central Environmental Laboratory (CEL). Additional samples were collected in some of the experiments, and sent to CEL for analysis. Two comparisons were conducted, of which one was in a pre-experiment and one was in the Shannon UV test.

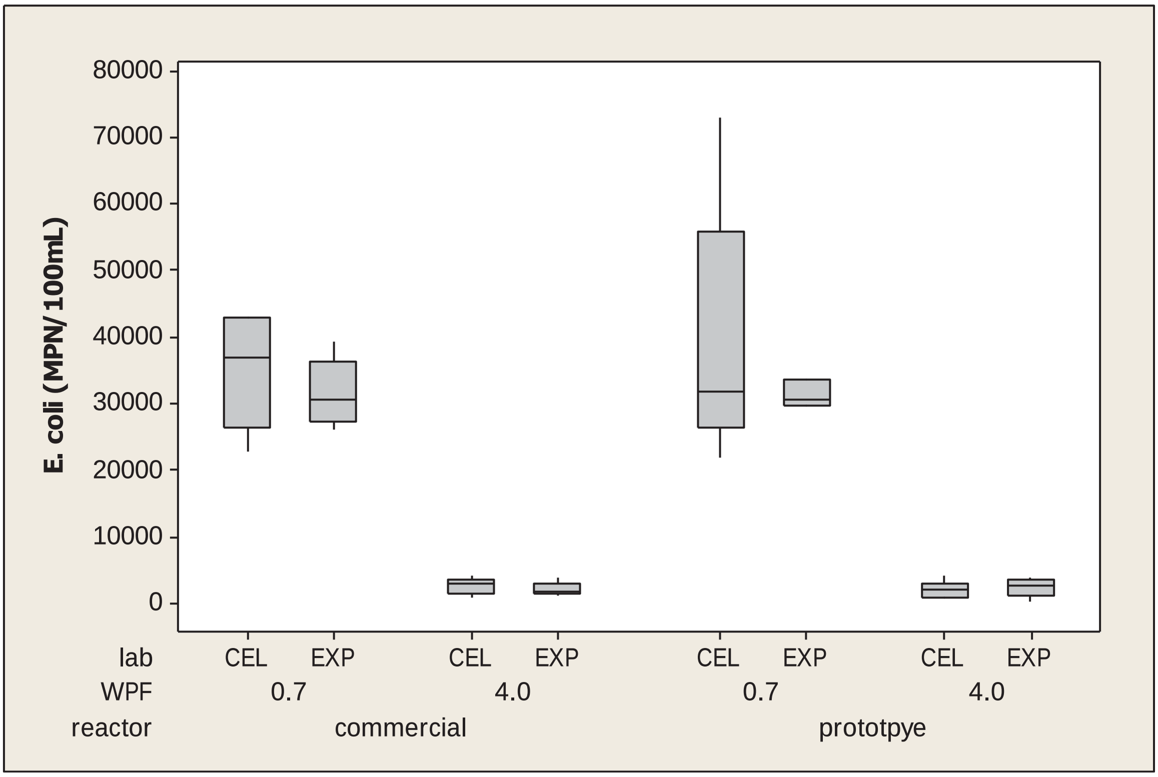
Before the project experiments had started, a pre-experiment was conducted. Wastewater samples from the PNWWTP at the pre and post UV treatment points were collected for enumeration analyses. Some of the sample replicates were sent to CEL, allowing a parallel comparison of the results. The comparison of the pre-experiment's results is shown in Figure A-7-11, which shows that the results from CEL are similar to the experimental results. Also, the t-test suggests that the results are statistically the same (p-value of 0.9 and 0.08). These suggest that the experimental analysis is reliable.



Note: EXP = experimental results

Figure A-7-11, CEL vs experimental results

Additional analyses comparison was conducted in the first Shannon UV test. Extra replicates of the commercial unit effluent at process flow rate of 700 and 131 L/min were collected. Also, the replicates of the effluent from the project prototype at process flow rate of 354 and 131 L/min, with 3 and 6 UV lamps on, respectively, were collected. These extra replicates were sent to CEL for *E. coli* analyses. The results are shown in Figure A-7-12, which are similar. Also, the t-tests suggest that the results are statistically the same, which the p-values are greater than 0.05, as shown in Table A-5. These further confirm the reliability of the analysis result.



Note: EXP = experimental results; WPF = watt per flow.

Figure A-7-12, comparison of CEL, second comparison

Table A-5, p-value of Figure A-7-12 results

Comparisons	p-values
t-test of commercial unit at process flow rate of 700 L/min	0.45
t-test of commercial unit at process flow rate of 131 L/min	0.48
t-test of project prototype at process flow rate of 354 L/min with 3 UV lamps	0.40
t-test of project prototype at process flow rate of 131 L/min with 6 UV lamps	0.34

Appendix 11, Statistical analysis of the results

P-value of 2nd generation prototype vs. project prototype

Table A-6, P-values of 2nd generation vs. project prototype at different sluice gate gaps at low UVT wastewater condition (Figure 4-1)

2nd generation vs project prototype at 2 mm	0.02
2nd generation vs project prototype at 4 mm	0.66
2nd generation vs project prototype at 6 mm	0.10

Table A-7, p-values of reactors performance at different sluice gate gaps at low UVT wastewater conditions (Figure 4-1)

	2 mm vs 4 mm	2 mm vs 6 mm	4mm vs 6 mm
Project prototype	0.32	0.01	0.14
2nd generation prototype	0.03	0.30	0.24

Table A-8, p-values of 2nd generation vs. project prototype at different UVT wastewater conditions (Figure 4-2)

2nd generation vs project prototype in high UVT	0.01

Table A-9, p-values of reactors performance at different UVT wastewater conditions

	2nd generation prototype	Project prototype
Reactors' performance in high UVT vs low UVT	0.08	0.01

P-value for the project prototype variable test

Sluice gate gap thickness experiment

Table A-10, p-values of the project prototype performance at different sluice gate gaps at both UVT wastewater conditions (Figure 4-3)

	2 mm vs 4 mm	2 mm vs 6 mm	4 mm vs 6 mm
Low UVT	0.31	0.01	0.14
High UVT	0.09	0.00	0.11

Table A-11, p-values of the project prototype performance at different UVT wastewater conditions (Figure 4-3)

	2 mm	4 mm	6 mm
Low UVT vs. High UVT	0.42	0.14	0.00

Flow angle tuning experiment

Table A-12, p-values of the project prototype performance at different reaction chamber slopes at both UVT wastewater conditions (Figure 4-4)

P-values of t-test			
	0 vs. 30	0 vs. 60	30 vs. 60
Low UVT	0.00	0.00	0.77
High UVT	0.53	0.17	0.35

Table A-13, p-value of the project prototype performance at different UVT wastewater conditions (Figure 4-4)

P-values of t-test			
	0	30	60
Low UVT vs. High UVT	0.28	0.25	0.54

Reflector shape experiments

Table A-14, p-values of the project prototype with different reflector at both UVT wastewater conditions (Figure 4-5)

	parabola reflector vs. square reflector
Low UVT	0.00
High UVT	0.00

Table A-15, p-values of the project prototype performance at different UVT wastewater conditions (Figure 4-5)

P-values of t-test		
	Parabola reflector	square reflector
Low UVT vs. High UVT	0.08	0.33

Regression analyses of the project prototype vs. commercial unit

Regression analyses for primary treated wastewater tests

PNWWTP

Table A-16, Regression analyses of PNWWTP primary treated wastewater test (Figure 4-6)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.21	0.35	-0.12	0.06	86.4%
prototype at 500 L/min	0.50	0.72	-0.13	0.02	83.0%
prototype at 250 L/min	0.40	0.76	-0.27	0.31	71.6%
prototype at 130 L/min	0.47	0.69	0.37	0.87	87.6%
overall Prototype	0.54	0.69	-0.13	0.03	87.02%

Levin PNWWTP

Table A-17, Regression analyses of Levin primary treated wastewater test (Figure 4-7)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.00	0.06	0.05	0.18	11.7%
prototype at 500 L/min	0.24	0.49	0.00	0.16	66.5%
prototype at 250 L/min	0.42	0.54	0.24	0.40	91.5%
prototype at 130 L/min	0.59	0.68	0.08	0.27	98.3%
overall Prototype	0.61	0.70	0.00	0.13	92.9%

Regression analyses for secondary treated wastewater tests

PNWWTP

Table A-18, Regression analyses of PNWWTP secondary treated wastewater test (Figure 4-9)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.21	0.35	-0.12	0.06	86.4%
prototype at 500 L/min	0.50	0.72	-0.13	0.02	83.0%
prototype at 250 L/min	0.40	0.76	-0.27	0.31	71.6%
overall Prototype	0.54	0.69	-0.13	0.03	87.02%

Levin WWTP

Table A-19, Regression analyses of Levin WWTP secondary treated wastewater test (Figure 4-10)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.31	0.50	0.27	0.53	82.2%
prototype at 500 L/min	0.43	0.94	0.23	0.67	83.0%
prototype at 250 L/min	0.29	0.61	0.02	0.49	60.0%
overall Prototype	0.15	0.43	0.39	0.75	33.3%

Paraparaumu WWTP

Table A-20, Regression analyses of Paraparaumu WWTP secondary treated wastewater test (Figure 4-11)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	1.47	1.71	-0.72	-0.32	98.4%
prototype at 500 L/min	1.14	1.50	-0.16	0.09	88.9%
prototype at 250 L/min	0.46	0.69	0.17	0.50	87.2%
overall Prototype	0.51	0.72	0.28	0.49	74.4%

Regression analyses for tertiary treated wastewater tests

PNWWTP

Table A-21, Regression analyses of PNWWTP tertiary treated wastewater test (Figure 4-13)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.61	0.91	-0.11	0.28	87.9%
prototype at 500 L/min	0.54	0.79	-0.34	-0.06	81.0%
prototype at 250 L/min	0.49	0.93	-0.16	0.13	71.3%
overall Prototype	0.50	0.69	-0.13	0.08	76.73%

Fielding WWTP

Table A-22, Regression analyses of Fielding WWTP tertiary treated wastewater test (Figure 4-14)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.83	1.59	-0.73	0.06	81.4%
prototype at 500 L/min	1.49	1.86	-0.63	-0.40	95.2%
prototype at 250 L/min	1.29	1.57	-0.84	-0.54	95.9%
prototype at 130 L/min	0.75	1.42	-0.59	0.26	83.7%
overall Prototype	0.83	1.59	-0.73	0.06	87.5%

Regression analyses for stabilization pond treated wastewater tests

Rongotea stabilization pond

1st test

Table A-23, Regression analyses of the first Rongotea stabilization pond treated wastewater test (Figure 4-16)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.46	0.61	-0.38	-0.17	94.4%
prototype at 500 L/min	0.41	0.85	-0.19	0.09	56.6%
prototype at 250 L/min	0.58	0.79	-0.23	0.03	87.7%
overall Prototype	0.59	0.74	-0.15	0.00	85.1%

2nd test

Table A-24, Regression analyses of the second Rongotea stabilization pond treated wastewater test (Figure 4-17)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.06	0.12	0.11	0.24	62.3%
prototype at 500 L/min	0.30	0.85	-0.21	0.14	52.1%
prototype at 250 L/min	0.43	0.64	-0.26	-0.01	83.9%
prototype at 130 L/min	0.60	0.80	-0.29	0.11	94.1%
overall Prototype	0.59	0.73	-0.23	-0.05	86.9%

Shannon stabilization pond

1st test

Table A-25, Regression analyses of the first Shannon stabilization pond treated wastewater test (Figure 4-18)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.32	0.42	-0.13	0.09	90.5%
prototype at 500 L/min	0.92	1.14	-0.25	-0.10	96.9%
prototype at 250 L/min	0.57	0.73	-0.26	-0.06	91.9%
prototype at 130 L/min	0.32	0.41	-0.19	0.02	94.6%
Prototype overall	0.30	0.42	0.01	0.19	71.3%

2nd test

Table A-26, Regression analyses of the first Shannon stabilization pond treated wastewater test (Figure 4-19)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	1.16	1.59	-0.64	-0.02	90.6%
prototype at 500 L/min	1.77	2.42	-0.46	-0.05	91.2%
prototype at 250 L/min	1.40	2.10	-0.51	0.15	86.0%
prototype at 130 L/min	1.27	2.03	-0.82	0.23	89.1%
Prototype overall	1.46	1.80	-0.26	0.07	87.9%

Foxton Beach stabilization pond

Table A-27, Regression analyses of the first Shannon stabilization pond treated wastewater test (Figure 4-20)

	Slope (95 % CI)		intercept (95 % CI)		
	lower	upper	lower	upper	R - Sq
commercial unit	0.41	0.51	-0.15	0.08	93.7%
prototype at 500 L/min	0.25	0.41	0.18	0.29	85.5%
prototype at 250 L/min	0.50	0.65	-0.17	0.01	91.8%
prototype at 130 L/min	0.44	0.55	0.01	0.27	95.5%

Prototype overall	0.48	0.55	0.00	0.11	94.2%

Wastewater characteristics that affect the UV disinfection

Table A-28, p-values of the tests comparison for the commercial unit

Comparisons	1 vs. 2	1 vs. 3	1 vs. 4	2 vs.3	2 vs. 4	3 vs. 4
	0.99	0.01	0.00	0.00	0.00	0.26

Table A-29, p-values of the tests comparison for the project prototype

Comparisons	1 vs. 2	1 vs. 3	1 vs. 4	2 vs. 3	2 vs. 4	3 vs. 4
	0.72	0.00	0.00	0.00	0.00	0.93