UNDERSTANDING THE EFFECT OF PARTICLE-SIZE ON UV DISINFECTION:

KINETICS, MECHANISMS AND MODELING

by

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Abstract

This study aimed to better understand the impact of suspended particles on ultraviolet disinfection of municipal effluents. The results showed that particles of sizes greater than 45 μm accounted for more than 90 % of the surviving coliform in the tailing region of secondary effluent UV dose-response curve. Particles in larger size fractions also showed a greater tailing propensity – the probability of particle surviving UV doses beyond 30 mJ/cm^2. In modeling the disinfection performance of secondary effluents, this was found to be the summation of the disinfection of all its particulate constituents. It was therefore possible to predict UV dose-response curve based on measurements of effluent particle-size distribution and particle disinfection kinetics. Finally, the tailing propensity was found to greatly depend on treatment processes. Trickling filter particles exhibited ten times greater tailing propensity than activated sludge particles, owing to their greater UV resistance and percentage viability.

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Chapter 1 Introduction: Overview of Research

1.1 Background

Proper disinfection treatment is extremely vital for reducing the large amount of microorganisms present in wastewater, which when discharged untreated could pose a serious risk of waterborne diseases such as Cholera, Typhoid and Hepatitis; it is the primary mechanism in preventing microbial contamination of water resources (Farnood, 2004). In addition, the development of a thorough disinfection technique could also be crucial for providing relief to the ever-intensifying problem of freshwater scarcity. With proper disinfection, microorganism level in wastewater can be reduced to a safe level, allowing for wastewater to be reused in applications such as agricultural and urban irrigation without compromising on human health.

UV has long been established as an effective form of wastewater disinfection. It works by causing damage to cellular DNA, thereby inactivating the metabolism of microorganisms. UV is fast becoming a popular alternative to chlorine disinfection given its several advantages. It does not result in the formation of carcinogenic disinfection by-product such as trihalomethanes as in the case of chlorine disinfection. Furthermore, regulations established on the total residual chlorine limits on wastewater effluent meant that the use of chlorine often requires an additional dechlorination step, which utilizes yet another chemical – sulfur dioxide (Das, 2001). Hence, UV is comparatively a much cleaner technology and accomplishes microbial inactivation without any quantifiable adverse toxicological effects (Blatchley et al., 1997).

However, as in the case of using chlorine, tailing problem exists in UV disinfection. Rate of microbial inactivation in secondary effluents typically follows a first-order kinetic at low UV doses. At UV doses of approximately 30 mJ/cm^2 and beyond, this rate will often decrease drastically, resulting in a plateau region termed disinfection tailing. It is widely understood that tailing is caused by the presence of particle-associated coliform (PAC) bacteria (Emerick et al., 2000; Nieuwstad et al., 1993; Oliver et al., 1975; Qualls et al.,

1983). These are coliform bacteria that are embedded within wastewater floc. As a result of the shielding by the high UV-absorbing floc material, large UV doses are required for inactivation of PAC bacteria. In addition, wastewater particles could scatter or absorb UV irradiation, or shade free coliform bacteria from UV exposure (Darby et al., 1993), thereby reducing the transmittance of UV in wastewater.

Tailing problem could pose a threat to the economic viability of using UV for disinfection, especially when treating poor quality influent with a high amount of suspended solids. In cases of stringent disinfection criteria, such as those set forth in the California Wastewater Reclamation Criteria, where the 7-day median cannot exceed 2.2 total coliform/100 mL (Title 22, Division 4, Chapter 3 of the California Code of Regulations), the presence of tailing problem could also render UV disinfection inadequate. Nevertheless, it has been suggested and demonstrated in literature that the use of upstream processes such as ultrasound (Blume et al., 2004) and filtration (Braunstein et al., 1996; Darby et al., 1993 and 1999; Janex et al., 1998; Jolis et al., 2001; Loge et al., 2001; Lazarova et al., 1998; Ormeci et al., 2002; Qualls et al., 1983 and 1985) can help reduce the problem of tailing. The efficacy of implementing such an upstream treatment will hinge on a good understanding of the mechanisms by which PAC resist UV.

At present, there is still a lack of consensus over how the size of the wastewater particle could influence the degree of UV resistance of PAC. It was suggested earlier that beyond the size of 10 μm, this degree of resistance is independent of particle size. Yet, recently published works seem to point towards the fact that larger particles provide greater shielding effect on PAC. It is therefore the objective of this research to better comprehend this phenomenon, particularly to understand and quantify the UV disinfection kinetics of PAC according to the size of wastewater particle. This information can then be translated into knowing the effluent criteria necessary for achieving the desired level of disinfection, and consequently a better selection of upstream process in terms of operational performance and economics.

1.2 Objective and Hypothesis

Hypotheses of this research are:

1. The resistance of particle associated coliform increases significantly with the size of the particle.
2. Disinfection performance of an effluent is the sum of the disinfection of its particulate constituents.
3. UV dose response curve can be predicted from the knowledge of UV disinfection kinetics of individual particles and particle size distribution data.

Based on the above hypotheses, the entire research was broken down into 3 main phases as follow:

- The first part of this research will involve fractionating wastewater particles into various size fractions, and quantifying their UV disinfection kinetics. A unique fractionating technique involving the use of standard testing sieve-trays and nanopure water for washing will be employed. This technique has been shown to effective separate wastewater particles into narrow size fractions without altering their disinfection kinetics. The focus will be on particles greater than the size of 30 μm; base on previously published research, this appears to be the size range most critical to the problem of UV disinfection tailing.

- The work will then be extended to modeling the disinfection performance of a whole effluent. The objective is therefore to use the protocol established earlier for quantifying particle disinfection kinetics to obtain the kinetics data for the various size fractions, and to use these data to predict effluent disinfection performance based on its particle-size distribution.

- In the final phase of the research, trickling filter effluent will be tested. Effluents from trickling filter are known to produce poor UV disinfection performance. Yet, there has been no study on the disinfection kinetics of trickling filter particles. The objective of this phase is therefore to extend the protocols developed to quantifying

the disinfection kinetics of trickling filter particles of various size fractions, and comparing them with that of activated sludge particles. The comparison can potentially provide a better understanding of the cause of poor UV disinfection performance in trickling filter effluent.

1.3 Thesis Outline

The thesis consists of 6 chapters as follows:

- Chapter 2 will first discuss some of the fundamental in UV disinfection, such as the mechanisms and the applications. This will be followed by an in-depth discussion on the impact of wastewater particles on disinfection tailing, and the influence of particle size on the level of PAC resistance. In addition, the importance of modeling UV disinfection and the existing models developed for predicting disinfection performance will be discussed. Finally, the chapter will touch on the application of UV disinfection in trickling filter effluent. Overall, the entire chapter will provide the background and literature review for this research, particularly highlighting the motivation of each of the 3 phases of this research as discussed earlier.

- Chapter 3, 4 and 5 will focus on each of the 3 phases of this research respectively. In each chapter, the objective will be reiterated, followed by a discussion of the research methodology. Finally, the results will be presented along with discussions and conclusions.

- Chapter 6 will present the key conclusions as well as some of the recommendations on how the research in this thesis could be continued, and highlighting areas that would require more work to be done.

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Chapter 2 Literature Review

2.1 Background on UV Technology

2.1.1 Disinfection Mechanism

UV refers to the spectrum of electromagnetic radiation with wavelength ranging from 100 nm to 400 nm. In the context of disinfection, however, it is the region between 200 nm and 300 nm that possesses germicidal ability. UV light works by causing a permanent photochemical change, inducing the formation of new bonds between adjacent nucleotides in cellular DNA and RNA. Of all the nucleotides, thymine undergoes change the most readily and the chemical changes are very stable (Das, 2001). As a result of the dimerization, the affected microorganism loses its ability to produce enzymes. More importantly, the disruption to the DNA molecule prevents cells from producing a copy of its DNA when it wants to replicate. A microorganism that cannot reproduce is then considered to be dead (USEPA, 1999).

Exposure to UV irradiation therefore causes inactivation of microorganisms, and this ranges from bacteria, protozoa, viruses, molds to fungi and algae (Das, 2001). The kinetics of inactivation is a function of UV dose, expressed as the product of germicidal radiation intensity (I) and exposure time (t) (Cheremisinoff et al., 1981), and there are several mathematical relations developed to describe the inactivation kinetics (E.g. Collins and Selleck, 1972; Severin et al., 1983; Wolfe, 1990). The model that is used to describe inactivation of a single free microorganism is given by the Chick-Watson Kinetics (Zimmer, 1961), as follows:

$$\frac{N}{N_0} = e^{-kD} \qquad (2.1)$$

Where

N = number of viable coliform bacteria, CFU/100ml

N_0 = initial number of viable coliform bacteria, CFU/100ml

k = first-order inactivation constant, cm^2/mJ

D = UV dose, mJ/cm^2

2.1.2 Application of UV Technology

For the past 100 years, disinfection was predominantly achieved by chlorination. Yet in recent years, chlorination is no longer the indispensable choice for disinfection of either water or wastewater (Chiu et al., 1999) for concerns over the generation of toxic disinfection by-products. Ultraviolet (UV) radiation, on the other hand, is increasingly gaining widespread acceptance as the alternative to chlorine disinfection given its several advantages; to date, there are over 2,000 installations of this technology in wastewater treatment plants (Sakamoto et al., yet to be published). It is a physical disinfection process (Blatchley III et al., 1996) and can accomplish microbial inactivation without any quantifiable adverse toxicological effects (Blatchley III et al., 1997). On the other hand, chlorination is known to generate disinfection byproducts such as trihalomethanes (THMs) especially in effluents containing large amount of dissolve organic acids. THMs have been linked to increasing cancer risks and birth defects, and they are classified by the U.S. Environmental Protection Agency (EPA) as a probable or possible carcinogen (Swichtenberg, 2003). Furthermore, regulations established on the total residual chlorine limits on wastewater effluent meant that the use of chlorine often requires an additional dechlorination step, which utilizes yet another chemical – sulfur dioxide (Das, 2001). In addition, the use of UV disinfection also has the advantage of having a smaller spatial requirement than chlorination as its rapid disinfection mechanism ensures a shorter contact time of seconds rather than minutes (Chiu et al., 1999). UV disinfection has also been shown to be economically competitive with chlorination (Scheible et al., 1981), or even less expensive in some cases especially when the cost of dechlorination is factored in (Blatchley III et al., 1996).

Application of UV is done via the use of UV lamps, which operate on the same principle as fluorescent lamps. The most commonly employed lamp in existing UV disinfection systems are the low-pressure mercury arc lamps. These lamps emit approximately 85 % of their total radiant intensity at a wavelength of 253.7 nm (Chiu et al., 1999), which is extremely close to the wavelength of maximum germicidal effectiveness for *E. coli and Cryptosporidium* (Gates, 1930; Linden et al., 2001). In recent years, medium pressure UV lamps have also been used for their significantly higher germicidal UV power

per unit length (Bolton et al., 2003). These lamps emit most of its radiation in the visible range, and operate at an extremely high temperature of 600 – 800 °C (Trojan Technologies, 2000).

To estimate the dose required for achieving the desired disinfection performance in the final effluent, a bioassay procedure using bench-scale UV apparatus needs to be performed. The standardization of the procedure was proposed by Bolton et al., 2003. In this process, cell suspensions are separately exposed to various UV doses from a collimated beam UV device. The device typically consists of a low-pressure UV lamp and a collimator tube, to ensure that the UV irradiation is delivered perpendicularly onto the cell sample. Following the irradiation, the cell suspensions are then cultured to enumerate the number of surviving colony forming unit (CFU). The entire process will ultimately generate a Dose-Response Curve (DRC), which would indicate the UV doses necessary for achieving the various CFU levels. The detailed description can be found in chapter 3.2. Given the complexity in an actual UV system, the dose-response information needs to be integrated with dose-distribution information (Chiu et al., 1999). This information is derived based on the non-uniformities in hydrodynamics within the UV reactor, which can affect the contact time, and also the spatial variation of the UV intensities within the irradiated zone of the reactor.

2.2 Impact of Wastewater Particles on UV Disinfection

2.2.1 Problem of Disinfection Tailing

In UV disinfection, the performance and efficiency can be greatly affected by several water quality parameters, particular those that can impact on the UV transmittance. UV transmittance is the measure of the ease of UV transmission through a solution, i.e. the 'demand' for UV (Scheible, 1987). Dissolved chemicals such as iron and coloring agents can absorb UV irradiation, thereby reducing the effective amount of UV energy that reaches the target microorganisms. Consequently, a larger dose of UV is needed to accomplish the desired level of disinfection.

A more critical problem with the use of UV disinfection is the impact wastewater particles have on the disinfection kinetics. While the presence of UV-absorbing dissolved chemicals can increase the UV demand of the system, it does not reduce the microbial sensitivity towards UV irradiation. On the other hand, wastewater particles are known to harbor coliform bacteria (or any other type of microorganism, but in this discussion it will be referred to coliform bacteria, as it is commonly used as the principle indicators of disinfection performance (Braunstein et al., 1996)). The embedding of the coliform bacteria within the wastewater particle therefore significantly reduces their exposure to UV irradiation, especially when floc material is known to greatly absorb UV light (Loge et al., 1999). As a result, the particle-associated coliform bacteria (PAC) become considerably more 'resistant' to UV disinfection.

The problem pose by wastewater particles is best illustrated in Figure 2.1, which shows a DRC of a typical wastewater secondary effluent. The initial steep slope of the curve is the result of the inactivation of free microbes – coliform bacteria that are freely suspended in the wastewater, rather than being entrapped within particles. It should be noted that any reduction in UV transmittance would not change the slope of the curve; it will only lead to an increase in contact time to achieve the same UV dosage. Beyond the dose of 20 mJ/cm^2, a drastic decrease in the rate of inactivation of coliform bacteria can be observed.

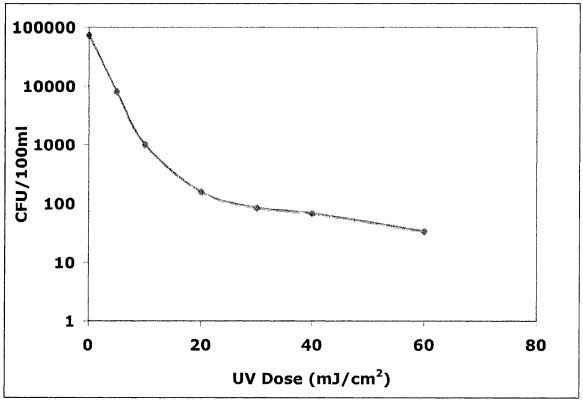

Figure 2.1 DRC of a typical secondary wastewater effluent, clearly illustrating the tailing problem in UV disinfection.

This is due to the fact that the majority of the free microbes are inactivated, and the remaining survivors are the highly resistant PAC bacteria. The plateau region in the UV DRC is termed the tailing region.

The problem of disinfection tailing is certainly no major impairment to the efficacy of UV disinfection; this is evident in the increasing popularity of the technology. Many times the problem could be avoided by not having to operate the disinfection system in the tailing region. The problem is also not unique to the use of UV technology. Due to the mass transfer limitation within wastewater particles, disinfection tailing is also encountered in chlorine disinfection (LeChevallier et al., 1984; Herson et al., 1987; Berman et al., 1988).

However, there are still situations whereby the occurrence of disinfection tailing could pose a concern to the economic viability of using UV disinfection. When an effluent contains a large amount of suspended solids, the tailing could be at a very high CFU level.

As such, the disinfection system may be forced to operate at the tailing region in order to meet the discharge regulations; large UV doses will be required to inactivate much of the PAC bacteria. One example of such a situation is in coastal wastewater treatment plant, whereby the discharge into deep waters with large tide and current permits the use of only primary treatment.

Disinfecting processed wastewater for reuse could also pose a challenge to the use of UV disinfection. At present, agricultural irrigation represents the largest reuse of processed wastewater, accounting for about 60 % of the total (Viessman & Hammer, 1998, pp. 769). Such application often requires the most stringent water quality standards. For instance, the California Wastewater Reclamation Criteria states that for higher-quality reclaimed water, the 7-day median cannot exceed 2.2 total coliform/100 ml and the maximum concentration cannot exceed 23 total coliform per 100 ml (Title 22, Division 4, Chapter 3 of the California Code of Regulations). Table 2.1 shows a summary of the suggested guidelines for water reuse based on water reclamation and reuse practices in the United States. The presence of PAC bacteria could make it difficult or impossible to meet the disinfection criterion at economically viable UV doses. Upstream processes such as filtration would be necessary to remove the PAC bacteria prior to UV disinfection. More will be discussed in the next section.

Table 2.1. Suggested guidelines for water reuse based on water reclamation and reuse practices in the United States (Source: Manual of Guidelines for Water Reuse, EPA/625/R-92/004

Types of Reuse	Treatment	Reclaimed Water Quality
Agricultural Reuse – Nonfood Crops Pasture for milking animals; fodder, fiber and seed crops	• Secondary • Disinfection	• pH = 6 – 9 • ≤ 30 mg/l BOD • ≤ 30 mg/l SS • ≤ 200 fecal coli/100 ml • 1 mg/l Cl_2 residual (min)
Agricultural Reuse – Food Crops commercially processed; surface irrigation of orchards and vineyards	• Secondary • Disinfection	• pH = 6 – 9 • ≤ 30 mg/l BOD • ≤ 30 mg/l SS • ≤ 200 fecal coli/100 ml • 1 mg/l Cl_2 residual (min)
Restricted Access Area Irrigation Sod farms, silviculture sites, and other areas where public access is prohibited, restricted, or infrequent	• Secondary • Disinfection	• pH = 6 – 9 • ≤ 30 mg/l BOD • ≤ 30 mg/l SS • ≤ 200 fecal coli/100 ml • 1 mg/l Cl_2 residual (min)
Agricultural Reuse Food Crops Not Commercially Processed Surface or spray irrigation of any food crop, including crops eaten raw	• Secondary • Filtration • Disinfection	• pH = 6 – 9 • ≤ 10 mg/l BOD • ≤ 2 NTU • No detectable fecal coli/100 ml • 1 mg/l Cl_2 residual (min)
Urban Reuse All types of landscape irrigation (e.g. golf courses, parks, cemeteries). Also vehicle washing, toilet flushing, use in fire protection systems and commercial air conditioners, and other uses with similar access or exposure to the water	• Secondary • Filtration • Disinfection	• pH = 6 – 9 • ≤ 10 mg/l BOD • ≤ 2 NTU • No detectable fecal coli/100 ml • 1 mg/l Cl_2 residual (min)

Table 2.1 (con't)

Types of Reuse	Treatment	Reclaimed Water Quality
Indirect Potable Reuse Groundwater recharge by spreading into potable aquifers	• Site specific • Secondary and disinfection (min.). May also need filtration and/or advanced wastewater treatment	• Site specific • Meet drinking water standards after percolation through vadose zone
Groundwater recharge by injection into potable aquifers	• Secondary • Filtration • Disinfection • Advanced wastewater treatment	Includes, but not limited to, the following: • pH = 6.5 – 8.5 • ≤ 2 NTU • No detectable fecal coli/100 ml • 1 mg/l Cl_2 residual (min) • Meet drinking water standards

2.2.2 Solution to Disinfection Tailing: Implementation of Upstream Processes

It is well understood that PAC bacteria is the cause of disinfection tailing. It is also well demonstrated that the problem can be eradicated by filtering away the PAC prior to UV disinfection. Qualls et al. (1985) showed that by filtering effluent samples with a 10 μm filter, the DRC would diverge at the tailing region; the survival rate was much lower in the filtered effluent. Similar results were also obtained in other researches published (Janex et al., 1998; Jolis et al., 2001). Omerci et al. (2002) also demonstrated the importance of removing PAC by comparing the disinfection performance of naturally occurring PAC and non-particle associated coliform bacteria (NPAC) in wastewater using a single wastewater source. The NPAC was obtained via 3 different processes – EGTA extraction, filtration and blending followed by filtration. In the first method, wastewater samples were blended with 1 mM of EGTA for 1 minute at 3500 rpm. The use of EGTA has been previously reported to aid in the desorption of bacteria, by altering the bonding mechanisms in particles (Camper et al., 1984). Coupled with the blending, the process has been shown to be effective in eluting coliform

bacteria from soil (Bakken, 1985; Lindahl et al., 1994; Ramsay, 1983) and wastewater particles (Parker et al., 1995). The second method of obtaining NPAC was similar to that of Qualls et al. (1985), except that 5 μm filter was used to remove the PAC. In the third method, the filtrate from the 5 μm filtration was blended at 3500 rpm for 1 minute, to further de-clump any possible PAC that might have passed through the filter. Overall, the results showed that for PAC, complete inactivation could not be achieved even after relatively high UV doses. On the contrary, NPAC prepared by all 3 methods were rapidly inactivated to beyond detection limits.

Several pilot plant studies have also shown that by implementing an upstream filtration process, UV disinfection can perform well enough to meet the stringent California Wastewater Reclamation Criteria. Darby et al. (1993) showed that by sending the secondary effluent through a continuous-backwash deep-bed granular medium upflow filter (DynaSand filter, Parkson Corporation, Fort Lauderdale, Fla.) prior to disinfection, the most stringent criteria, that the 7-day median not exceed 2.2 total coliform/100 ml and that the total coliforn not exceed 23/100 ml in more than one sample in a 30-day period, could be met consistently, with an average UV dose of at least 97 mJ/cm^2. This was in spite of the fact that UV system was unable to achieve the same criteria with the same effluent without filtration even at UV doses as high as 239 mJ/cm^2. In a similar study conducted over a period of 22 weeks, it was found that the same reuse criteria could be met at an average UV dose of 168 mJ/cm^2 and 112 mJ/cm^2 for total and fecal coliform respectively (Braunstein et al., 1996). Other filtration techniques were also demonstrated to work effectively in eliminating the tailing problem. Loge et al. (2001) showed that by integrating a disc filtration into the treatment train upstream of the UV disinfection, the discharge requirement of 23 MPN /100 ml based on a 30-day running median could be met 99.9 % of the time, at an average UV dose of 150 mJ/cm^2. Likewise, Jolis et al. (2001) showed that the Title 22 standard of 2.2 total coliform / 100ml could be met at an UV dose of 80 mJ/cm^2, by first filtering the effluent with a gravity monomedia filter. The filter media used was a bed containing 1.22 m of anthracite with an effective size of 1.5 mm and a uniformity coefficient of 1.7.

A different approach in handling PAC would be to disintegrate the particles into smaller pieces by the use of ultrasound. The cavitations generated are effective in breaking up PAC, such that the resulting smaller particle fragments would provide little or no shielding to the embedded coliform bacteria. The efficacy of this technique was demonstrated by Oliver et al. (1975), who found that the coliform survival rate could be reduced by sonicating a 1000 ml sample of secondary effluent with a 20 kHz, 300 W ultrasound probe prior to UV disinfection. More recently, it was shown by Blume et al. (2004), that by having a 10s sonication process ahead of the UV disinfection, the EU Bathing Water Directive Guide Value of 100 fecal coliform / 100 ml could be met at a much lower UV dose. Overall, despite the energy input to the ultrasound process, it was concluded and demonstrated that the technology could still bring about a significant energy saving as compared to just using UV disinfection alone for attaining the same disinfection level.

2.2.3 Effect of Particle Size on Disinfection Tailing

While it is clear that upstream processes could eliminate or at least alleviate the problem of disinfection, the works published so far have primarily focused on demonstrating the efficacy of such an implementation. There is still a lack of understanding on how the process could be optimized. It is no doubt that having a membrane to remove all the PAC will lead to a far superior disinfection performance. Yet, the susceptibility to fouling of the membrane as a result of interactions between the membrane and the mixed liquor (Bouhabila et al., 1998) will inevitably be a tremendous strain on the economics of the operations. This is especially true if the system is applied to a primary effluent, whereby the discharge criteria are also less stringent. The optimization of upstream processes implementation will therefore require a better understanding of the extent of UV resistance that PAC exhibit, and whether the resistance is a function of particle size and/or treatment processes. This will then translate into knowing what type of wastewater particles to focus the upstream processes on, and the degree of treatment that would suffice according to the discharge criteria. Finally, the most optimal upstream process could then be chosen based on the performance requirement and operating economics.

Presently, several works had been published in the literature regarding the effect of particle size on the extent of microbial shielding. Earlier works established that wastewater particles harboring coliform bacteria only account for about 1% of the total coliform bacteria count, yet they become the limiting factor especially when meeting stringent disinfection standards (Qualls et al., 1983). It was also shown that with a 10 μm filtration, the number of surviving coliform bacteria at a dose of 26 mJ/cm^2 was reduced to less than 20% (Qualls et al., 1985). Based on this, it was concluded that suspended solids smaller than 10 μm do not exhibit significant UV resistance. This concept was subsequently accepted and applied in some other research works (Emerick et al., 2000; Jolis et al., 2001), and it was suggested that upstream processes should be designed to remove all suspended solids greater than 10 μm to improve the performance of a UV disinfection system (Loge et al., 2001).

Emerick et al. (2000) took a step further by integrating the concept of the 10 μm threshold size with that of particle-associated coliform bacteria (PAC). PAC was defined to be coliform bacteria embedded in particles greater than the critical size of 10 μm and were therefore shielded to some degree from UV irradiation. Fluorescence in-situ hybridization was used to stain PAC in order to determine the fraction of wastewater particles that contain viable coliform bacteria, and based on the particle concentration measurement the number of PAC could then be calculated. By compiling results on the number of PAC and UV disinfection performance of effluents taken from various treatment processes, it was shown that the amount of PAC correlated well with the residual coliform bacteria number at high UV doses of greater than 100 mJ/cm^2 (Emerick et al., 1999). The correlation ($R^2 = 0.90$) was also much better than previous effort by Scheible (1987), whose use of suspended solids level could only account for approximately 50 % of the fluctuations in the residual coliform concentration. The effluent PAC level was therefore deemed as the wastewater parameter most critical to UV disinfection performance (Loge et al., 2001).

It was further hypothesized that beyond the suggested threshold level of 10 μm, particle size does not have any effect on the degree of shielding towards UV irradiation (Emerick et al., 2000). This was based on the observation that coliform bacteria were located at random positions within a wastewater particle, such that a coliform bacterium embedded

deep within a larger particle could be located on an unobstructed light pathway, whereas another coliform bacterium embedded within a smaller particle could be completely shielded from incident UV light (Loge et al., 1999). It was therefore concluded that neither the size of a particle nor the distance an embedded coliform is located from the surface of the particle could decide the ease of inactivating a target organism. In order words, in any wastewater particles, the likelihood of inactivating the most shielded coliform bacteria is independent of the size of the harboring particle. This concept was further proven experimentally and it formed the basis of an equation developed for modeling the UV Dose-Response Curve (DRC) of typical wastewater effluents, which will be discussed in greater depth in the subsequent section. The equation proved adequate in modeling the shape of the DRC of several effluent samples from various treatment systems within error tolerable for Multiple-Tube Fermentation method.

However, the concept of particle size having no effect on the degree of UV shielding remained questionable. The work did not isolate particles of different sizes and show the similarity in their UV inactivation kinetics. Instead, it was only shown that the percentage distribution of viable PAC across different size classes remained statistically similar before and after exposure to a relatively high UV dose. Through this, it was concluded that the likelihood of UV survival for PAC in the different size classes was the same. However, it should be noted that the methodologies used in determining the PAC size distributions for both before and after UV exposure were different, making the cross-comparison questionable. Particularly, the distribution for post-UV exposure was determined by serial filtration, which is disputable given that filtration could never result in good separation of particles greater and smaller than the filter pore size. Yet, it was assumed that the particle-size distribution (PSD) of the samples obtained from the serial filtration was within the pore sizes of the filters.

In fact, contradicting opinions can be found published in the literature, stating that larger particles lead to a greater tendency for tailing to occur (Cairns et al., 1993; Farnood, 2004; Madge et al., 2006; Qualls et al., 1985). Qualls et al. first found that the number of coliform bacteria surviving a UV dose of 26 mJ/cm^2 correlated better with the number of

larger particles; correlation with particles greater than 20 μm and 40 μm both resulted in r^2 value of 0.55, while that with particles greater than 10 μm and initial coliform bacteria count resulted in r^2 values of 0.41 and 0.28 respectively. Hence, it was concluded that larger particles provided more or better coliform protection and have dominant effect on coliform survival at high UV doses despite the much greater number of particles in lower size classes. Madge et al. separated wastewater particles into 3 size fractions by serial filtration using nylon filters – small (< 5 μm), medium (5 – 20 μm) and large (> 20 μm), and showed that the large fractions consistently exhibited greater tendency for tailing. The disinfection kinetic constant of the overall wastewater sample was also shown to correlate with the percentage of total coliform bacteria located in the large fraction.

While the work brought about new understanding to the problem of UV disinfection tailing, it focused on extremely low UV doses of less than 15 mJ/cm^2. Typically, UV disinfection tailing occur at an UV dose of approximately 30 mJ/cm^2 (Farnood, 2004; Loge et al., 2001; Ormeci et al., 2002). Hence, the results could show no more than the tendency for tailing; the UV dose was too low for the UV DRC's to evidently display the level of tailing. Moreover, the DRC did not seem to represent that of typical wastewater samples – 2-log reduction were observed in most of the whole effluent samples at an extremely low UV dose of around 5 mJ/cm^2, and the same occurred for the large-particle fraction at around 10 mJ/cm^2. In one of the sample, disinfection level below the detection limit was even achieved at a dose of less than 10mJ/cm^2. This is unusual given that the typical rate of disinfection for free microbe is known to be around 3-log reduction at 15 mJ/cm^2 (Das, 2001); Ho et al. (1998) reported that an UV dose of 65 mJ/cm^2 was required to bring the coliform level down to 240 CFU/100ml in a secondary effluent. In addition, the work done by Madge et al. had lumped together particles greater than 20 μm as a whole. However, there is reason to believe that particles greater than the size of 20 μm are most responsible for tailing based on the work by Qualls et al.. (For simplicity of discussion, the group of particles most responsible for tailing will be termed as the Tailing Particle Fraction (TPF).) Hence, the work lack resolution within the TPF and therefore shed light on the effect of particle size within the more critical size range. The work by Farnood (2004), on the other hand, had conclusively shown that for particles greater than 40 μm, UV disinfection resistant increases with particle

size. The mechanisms behind were not investigated and the work focused on activated sludge effluent only.

Overall, it can be seen that based on the existing work published in the literature, there is still room for a better understanding of how the size of wastewater particles can influence the UV resistance of PAC. It would be useful to also model and quantify the UV disinfection kinetics of PAC. Together, these will form one of the main focuses of this research, and will be discussed in greater detail in Chapter 3. The aim is to eventually arrive at a better understanding of how the choice of upstream processes could be made based on the effluent characteristics and discharge criteria.

2.3 Modeling of UV Disinfection Performance

2.3.1 Factors Affecting UV Disinfection Performance

Modeling UV disinfection performance of an effluent is especially useful when designing a full-scale disinfection facility. A reliable model can facilitate the sizing of the UV system based on the effluent conditions and disinfection criteria. It also facilitates the selection of appropriate effluent quality criteria necessary for meeting the disinfection objectives, so that upstream processes can be designed accordingly. In addition, it can help in monitoring the performance of the system. At present, UV disinfection performance is estimated by bioassay – a cumbersome process that requires at least one day for results to be obtained. A model can potentially allow the disinfection performance to be estimated based on simple measurements of wastewater parameters. In order for such a model to be developed, it is important to first understand the factors that can affect the disinfection performance of an UV system.

The efficiency of UV disinfection is strongly influenced by several effluent quality characteristics. One of the most important parameters is UV transmittance, which is the most commonly used parameter in predicting UV disinfection efficiency (Severin, 1980). UV transmittance is the measure of the ease of UV transmission through a solution, i.e. the wastewater 'demand' for UV (Scheible, 1987). It is measured by a spectrophotometer

operated at the same UV wavelength of 254 nm. UV transmittance is expressed as a percentage relative to distilled water, which is set at 100 % (Sakamoto et al., yet to be published). A lower UV transmittance implies that a smaller amount of UV irradiation would reach the target organisms, and hence resulting in lower disinfection efficiency. In general, UV transmittance for effluent from suspended growth treatment processes ranges from 60 to 65 %, while that for fixed film processes varies from 50 to 55 % (Das, 2001).

UV transmittance can be adversely affected by the presence of UV absorbing soluble compound. These chemicals may include phenolic compounds, humic acids, lignin sulfonates, iron, and coloring agents (Huff et al., 1965; Yip et al., 1972). The presence of dissolved iron compounds is of particular concern given that these compounds are commonly added during treatment processes such as coagulation and the precipitation of phosphate. The concern over dissolved iron has also made the UV industry to implement a maximum allowable iron of 0.3 ppm above which the use of UV disinfection would be deemed inappropriate (Das, 2001). Dissolve iron can affect UV disinfection in a number of ways. First, when present at high enough concentration, dissolved iron can significantly absorb UV irradiation, thereby lowering the UV transmittance. Dissolved iron can also be adsorbed onto wastewater particles and increase the UV shielding on particle-associated coliform bacteria. In addition, it has been hypothesized that the use of iron could reduce the porosity of wastewater floc, thereby reducing the availability of pathways for UV light to reach embedded coliform bacteria (Emerick et al., 1999).

Besides dissolved chemicals capable of absorbing UV irradiation, the presence of suspended solids can also adversely affect the transmittance of UV through wastewater. In addition to increasing the UV resistance of PAC as previously discussed, suspended solids can also absorb UV rays, or scatter or block them from target organisms. As such, wastewater with high turbidity would require a significantly longer exposure time to achieve the same UV dose.

UV transmittance has been previously correlated with some wastewater parameters, particularly those that relate to the level of dissolved chemicals and the amount of particulate

matter. In an attempt to find surrogate measurements for UV absorbance, Qualls et al. (1985) found a correlation between UV absorbance and measurements of COD and turbidity. The COD level was mostly associated with dissolved component while the turbidity was from the particulates. Harris et al. (1987) also attempted to correlate several water quality parameters with UV absorbance, and found significant relationship between UV absorbance and turbidity, total suspended solids (TSS), total organic carbon (TOC) and total biological oxygen demand (BOD).

2.3.2 Correlations Between Disinfection Performance and Wastewater Parameters

There have been several efforts to correlate UV disinfection performance with some of the wastewater characteristics parameters, in an attempt to develop a system of predicting the performance. Qualls et al. (1985) found significant correlations between the number of coliform survival at UV dose of 26 mJ/cm^2 and suspended solids (SS) of the unfiltered samples, as well as SS and UV absorbance caused by particles over 10 μm diameter. It was therefore concluded that UV disinfection could be a relatively predictable process (Qualls et al., 1985). Although the accuracy of predicting the concentration of surviving coliforms for each sample may be low, the correlations could still generate a reasonable range of values to be expected, especially considering that several orders of magnitude inactivation were involved (Qualls et al., 1985). Similarly, Harris et al. (1987) also found significant relationships between some water quality parameters and log fecal coliform survival – turbidity, TSS, VSS, TOC and total BOD.

On the other hand, contradicting results were published by some other researches. Blatchley III et al. (1996) attempted to correlate fecal coliform log kill with relative UV intensity, transmittance and turbidity and found no correlation. It was concluded that no single parameter would control the behavior of UV systems. However, this could also be attributed to the fact that the results were obtained from a pilot test; during normal daily operations the controlling parameters will vary on a somewhat independent basis (Blatchley III et al., 1996). Similarly, Janex et al. (1998) observed high variability in disinfection

performances between effluents from different sites and of the same site but at various times. It was concluded that no correlation exists between UV disinfection kinetics and water quality parameters like UV transmittance, COD or particle concentration and PSD. With TSS level, inactivation coefficient did show an inverse trend up to a level of 5 mg/L beyond which the effect became negligible.

2.3.3 Existing Models For UV Disinfection

There are several models developed to describe the UV disinfection performance of effluent. Generally, the models can be classified into 2 types – equations that model the UV response of effluent base on the disinfection kinetics, and equations that predict the disinfection performance base on wastewater qualities. Table 2.2 shows a summary of all the models developed.

Table 2.2. Summary of all the models developed for describing and predicting UV disinfection performance

Model	Equation	Reference
One-hit	$\frac{N}{N_0} = e^{-kD}$	Zimmer (1961)
Multi-target	$\frac{N}{N_0} = 1-\left(1-e^{-kD}\right)^m$	Zimmer (1961)
Multi-hit	$\frac{N}{N_0} = e^{-kD}\sum_{i=0}^{m-1}\frac{(kD)^i}{i!}$	Zimmer (1961)
Double-exponential	$\frac{N}{N_0} = (1-\beta)e^{-k_1 D} + \beta e^{-k_2 D}$	Jagger (1977)
Modified two population	$\frac{N}{N_0} = (1-\beta)\left(1-\left(1-e^{-kD}\right)^m\right) + \beta e^{-k_2 D}$	Jagger (1977)
Cairns et al.	$\frac{N}{N_0} = (1-\beta)e^{-k_1 D} + \sum \beta_i e^{-kT_\mu^* D}$	Cairns et al. (1993)
Emerick et al.	$\frac{N}{N_0} = (1-\beta)e^{-kD} + \frac{\beta}{kD}\left(1-e^{-kD}\right)$	Emerick et al. (2000)

Table 2.2 (con't)

Model	Equation	Reference
Scheible	$N = N_0 \exp\left[\frac{ux}{2E}\left(1-\left(1+\frac{4(aI)^b E}{u^2}\right)^{1/2}\right)\right] + c(SS)^m$	Scheible (1987)
Loge et al.	$N = A(SS)^a (UFT)^b (N_0)^c (I \times t)^n$	Loge et al. (1996)

In spite of the efforts in correlating UV disinfection performance with water quality parameters, there are still few equations developed for predicting the level of disinfection base on measurable wastewater parameters. This could be due to the fact that there can be many plant parameters that could potentially affect UV inactivation kinetics, making the model complicated to develop. It is also not easy to isolate the effect of a single parameter; effect from one parameter could be offset by changes in another parameter. For this reason, it is difficult to have a generalized model; the models developed in the past were mainly empirical and site specific (Loge et al., 1996; Scheible, 1987). More importantly, the parameters involved in the models had to be bulk parameters such as total suspended solid and unfiltered UV transmittance, that lump together several factors that could individually influence disinfection performance. For instance, although the measure of TSS reflects the amount of solids present, the parameter does not capture the effect of particle size distributions on UV disinfection performance. This could explain the observations made by Sakamoto et al. (2001), in which the disinfection performance of 3 different effluent samples were different despite having same TSS level. Thus, bulk parameters do not seem to adequately describe the variations in disinfection performance. Reliance on bulk parameters also prevents generalizations from being made on the relationship between treatment process type and UV performance (Emerick et al., 1999).

More recently, a model that focused on UV disinfection at the particle level was developed. The model relied on empirically determined value of free microbe inactivation constant under UV to predict effluent disinfection performance based on the number of particle-associated coliform bacteria (N_p) present (Emerick et al., 2000). The model was demonstrated to reasonably fit actual UV dose-response curves, and N_p could be regressed

from the fit. However, the accuracy of the model relied heavily on the determination of N_p, which could not be easily measured. As a result, the functionality of this model is compromised. Moreover, there is no parameter that could correlate to and predict N_p. The model therefore cannot be used to predict and monitor the effect of changes in influent characteristics on UV disinfection. In addition, the model is based on the assumption that particle size does not have an impact on disinfection kinetics, which is questionable.

It is therefore another major objective of this research to establish a model that could effectively predict the UV disinfection performance of secondary effluent base on some measurable effluent parameters. Like Emerick et al. (2000), the fundamental of the model will be the understanding of UV disinfection kinetics at the particle level, and influence of particle size will also be taken into account. More will be discussed in Chapter 4.

2.4 Application of UV Disinfection in Trickling Filter Effluent

2.4.1 Problem of Poor Disinfection Performance

Trickling filters are attached-growth biological beds, with filter media supporting microbial growths on their surfaces. The media is usually crushed rock, plastic-sheet packing formed into modules, or plastic packing of random shapes (Viessman and Hammer, 1998, pp. 542). Wastewater is spread onto the bed following the settling process in the primary clarifiers. There are several advantages in using trickling filter over activated sludge process. The operation is generally simpler, and cheaper to maintain, and the waste sludge generated is also easier to handle (Viessman and Hammer, 1998, pp. 542). In addition, trickling filter is reported to be able to efficiently and consistently remove total chemical oxygen demand and suspended solids despite the fluctuations in the influent quality and flow rate (Boltz et al., 2006). The process could also support the growth of a wider range of microorganisms at various locations within the biofilm. This permits the formation of biological niche, in which different groups of microorganisms could degrade different organic substrates (Bishop, 1997). In an activated sludge system, the slow growing microorganisms would have been washed out due to the complete mixing.

However, the effluent from trickling filter has often been reported to produce poor UV disinfection performance. In comparing the UV disinfection of secondary effluents, Sakamoto et al. concluded that effluents from fixed film processes generally required a higher UV dose than suspended growth system to achieve the same level of disinfection performance. This was despite the fact that the quality of the effluent from all the different treatment processes tested was similar. The UV transmittance ranged from 65 to 67 %, and the total suspended solids (TSS) levels were between 15 to 25 mg/L, with a mean of 20 mg/L. Similar result was also obtained by Emerick et al. (1999), who found that the average number of coliform bacteria surviving UV doses in excess of 100 mJ/cm2 in trickling filter effluent was approximately double that in the activated sludge process. However, the TSS level was in the trickling filter effluent was more than 3 times that of the activated sludge effluent.

2.4.2 Cause of Poor UV Disinfection Performance

In terms of the UV absorbance, trickling filter particles have been reported to have a lower absorbance than the activated sludge particles. Loge et al. (1999) found that the UV absorbance in trickling filter wastewater solids was 3300 cm^{-1}, as compared to the range of 10700 to 74200 cm^{-1} in activated sludge process solids. Hence, the cause of the poorer disinfection performance is largely attributed to the poorer effluent quality in terms of the level of suspended solids – a problem often associated with the trickling filter process. In a survey of the performance of conventional trickling filters employing modular plastic media, Parker et al. (2005) found that seven of the eight plants surveyed failed to meet the USEPAs monthly average effluent requirements. Even at low total organic loading (TOL) level (TOL has been shown to correlate with the effluent suspended solids level for high-rate plastic media trickling filters (Sarner, 1986)), there was still a 12 % probability of exceeding the requirement in any given month.

It has been said that due to the absence of a sedimentation step, fixed film process tend to produce effluent with larger particles than suspended growth process (Metcalf and Eddy, 1991). The inferior effluent quality has also been attributed to the poorer settling

characteristics of trickling filter particles (Banks et al., 1976; Sarner, 1986). In fact, Schubert et al. (2001) found that settling tanks are unable to provide sufficient hydraulic retention time for the settling of particles with diameters smaller than 100 μm, and concluded that in terms of sedimentation behavior, there are hardly any advantages in using the trickling filter process as compared to the activated sludge process. Zahid et al. (1989) also found that the settling velocities measured for trickling filter particles smaller than 100 μm were too small for proper settling to occur without flocculation, and concluded that the turbidity in trickling filter final effluent is attributed to particles smaller than 100 μm.

On the whole, it is clear that trickling filter effluent tend to have a higher level of suspended solids. Given that wastewater particles are the main cause of UV disinfection resistance, it is logical to attribute the poorer disinfection performance in trickling filter effluent to its higher suspended solid level. However, at this point, there is still a lack of actual understanding of the UV disinfection characteristics of trickling filter particles. Neither is there a comparison between the UV disinfection kinetics of trickling filter and activated sludge particles. The final phase of this research was therefore devoted to quantifying the disinfection kinetics of trickling filter particles. It is an extension of the work in the earlier part of the research, applying the protocols developed earlier. Ultimately, the results obtained would facilitate the comparison between the disinfection kinetics of particles from the 2 wastewater treatment processes, and possibly provide a better understanding into the cause of poor disinfection performance in trickling filter effluent. More will be discussed in Chapter 5.

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Chapter 3 Propensity of Tailing in UV Disinfection

3.1 Introduction

Wastewater particles are widely recognized as the contributor to UV disinfection tailing. Naturally, filtration has been identified to help eradicate the tailing problem. Although the efficacy of the technology has been widely demonstrated in the literature, there is still a lack of study on how its implementation can be optimized. Targeting filtration at the removal of all particles will inevitably lead to a superior disinfection performance. Yet, the economic viability of such an operation is questionable.

At the same time, there is reason to believe that particle size can have significant influence on the UV resistance of particle-associated coliform bacteria; larger wastewater particles can provide more obstructions to the path of UV irradiation, and thus greater shielding effect. One way of optimizing filtration implementation will then be to identify if a threshold particle-size exists, when targeting particle removal to achieve the desired disinfection performance. It is no doubt that other factors such as particle composition and density can have significant impact on disinfection kinetics, but in the context of optimizing filtration, the understanding of the effect of particle size appears most critical.

However, to date this understanding is still lacking. It has been suggested that particles greater than the size of 10 μm possess equal UV shielding ability (Emerick et al., 1999, 2000; Jolis et al., 2001; Loge et al., 1999, 2001; Qualls et al., 1983), and should therefore be removed for better UV disinfection performance. Yet, contradicting conclusions were made based on the work by Qualls et al., Madge et al. and Farnood.

The objective of this chapter was thus to better understand the effect of particle size on UV resistance. It was hypothesized that larger particles are more resistant to UV disinfection and are the main contributors to the problem of tailing. Unlike previous works, a unique methodology of concentrating wastewater particles into narrow size fractions will be

employed, and this will allow for a direct measurement and comparison of particle UV disinfection kinetics with respect to particle size.

3.2 Materials and Methods

3.2.1 Sample Collection

Wastewater samples were collected from Ashbridges' Bay WWTP located at the eastern end of the city of Toronto. The plant has a capacity of 818,000 cubic metres per day and utilizes an activated sludge biological system for secondary treatment along with primary and secondary sedimentation. Treated effluent is disinfected with chlorine prior to its discharge into Lake Ontario. Mixed liquor samples were collected from the aeration tank at the point before discharge into the secondary clarifier, while secondary effluents were sampled at the end of the clarifier, right before the effluent is channeled for disinfection. The collected samples were stored at 4°C before testing. To ensure that the storage does not alter the sample characteristics and hence the experimental results, the samples were analyzed within 12 hours of the collection.

3.2.2 Sample Filtration and Sieving

To establish the significance of large particles in UV disinfection tailing, part of the secondary effluent sample was sieved using a No.450 standard sieve with 32μm opening. Bioassay was then performed on both the filtered and unfiltered effluent samples to examine how the removal of large particles would affect the disinfection tailing level.

The second set of experiments was aimed to better quantify the effect of particle size on UV disinfection kinetics. This was done by fractionating mixed liquor sample into narrow size fractions using various sieve trays (U.S.A. Standard Testing Sieve). To obtain a fractionated sample, two sieve trays were stacked with the tray having a larger opening on top. Mixed liquor was then poured through and wastewater particles were collected on the bottom sieve. This fraction was then gently washed under nano-pure water for 15 min to

remove the smaller particles trapped in the sieve The sample was then back-washed from the sieve tray and collected into a container. The fractionated samples were subsequently diluted with nano-pure water to the appropriate particle concentration and analyzed for its PSD and particle concentration. Based on the PSD of the samples, five fractions were chosen for bioassay testing: 20 – 25 μm, 32 – 45 μm, 53 – 63 μm, 90 – 106 μm, and 125 – 150 μm. These size ranges were selected to minimize the overlap in PSD between the fractionated samples. More importantly, the samples will collectively encompass the size range of particles occurring in typical secondary effluents that are most responsible for UV disinfection tailing.

One concern arising from the sieving process is the use of Nano-pure water to wash and re-suspend the fractionated particles. Control experiments showed that using nano-pure water for dilution had no statistically significant effect on disinfection kinetics (Appendix A).

3.2.3 PSD Analysis

Particle size distribution (PSD) analysis was carried out using a Multisizer 3.0 particle analyzer (Beckman Coulter Canada, Mississauga, Ontario, Canada). Fractionated samples were diluted with a 10.7 g/L solution of NaCl to the appropriate concentration and analyzed to obtain the size distribution and number concentration of particles. It should be noted that since Multisizer operates based on Coulter principal, it underestimates the actual size of porous particles such as those found in wastewater. In this paper, the particle sizes quoted were estimated based on the comparison between actual sieve sizes and the corresponding measurement from the Multisizer.

3.2.4 UV Bioassay

The UV system used was a low-pressure mercury vapor lamps (Trojan Technologies, London, Ontario, Canada), which emits roughly 85% of their output at a wavelength of 253.7 nm (Chiu et al., 1999). The system consisted of two lamps housed in a horizontal stainless

steel casing, and a black-painted collimating tube (22 cm length, 9 cm internal diameter) that extended vertically downward to achieve a region of uniform UV irradiation. 20 ml of samples were placed in a Petri dish 4.8 cm in diameter and stirred with a magnetic stirrer throughout the irradiation. The UV doses that the samples received ranged from 10 to 70 mJ/cm^2. The intensity of the UV applied was measured using an IL1700 radiometer equipped with a SED240 sensor and NS 254 filter (International Light, Newburyport, MA, USA). A spreadsheet developed by Bolton et al. (2003) was then used to calculate the exposure time needed based on the measured intensity while accounting for several correction factors, to ensure that the sample was exposed to the desired average fluence rate. The correction factors included the Reflection Factor, Petri Factor, Water Factor, and Divergence Factor (Bolton et al. 2003). All factors remained relatively constant for the same experimental set up except for Water Factor, also known as Morowitz factor (Morowitz, 1950), which is given by the following equation:

$$\text{Water Factor} = \frac{1-10^{-a\,l}}{a\,l\ln(10)}$$

Where

a = decadic absorption coefficient (cm^{-1})

l = vertical path length (cm) of the water in the Petri dish.

Absorption coefficients of samples were measured at UV wavelength of 254nm by Lambda 35 UV/Vis Spectrometer (Perkin Elmer), which featured a double-beam, all-reflecting system, installed with an Integrating Sphere device (Labsphere RSA-PE-20).

Samples were irradiated at a designated UV dose and the extent of disinfection was assessed using the number of surviving fecal coliform as indicator. The surviving fecal coliform was enumerated by using the membrane filtration method as described in the Standard Methods (APHA, 1998). m-FC Agar (VWR, Mississauga, Ontario) was used as the culturing media and the buffer solution used for rinsing was 13.6g/L KH_2PO_4 at pH 7.2. Samples were incubated at a temperature of 45 °C for 24 ± 3 hours, and the number of colony forming units (CFU) were counted by image analysis.

3.3 Results and Discussions

3.3.1 Significance of Large Particles in Disinfection Tailing

Figure 3.1 shows the DRC of a secondary effluent pre-filtered with 32 μm and 75 μm sieve trays, and the corresponding un-filtered original effluent sample. The results show that by removing large particles, UV disinfection performance at the tailing region could be lowered drastically. The tailing level for 32 μm pre-filtered sample was reduced by 90 % from 150 CFU/100ml to a coliform level of 15 CFU/100 ml at a UV dose of 30 mJ/cm^2. Eventually, at the maximum dose of 60 mJ/cm^2 applied in the experiment, the tailing level was only at 5 % (4 CFU per 100 ml) of the unfiltered sample at the same UV dose. For the 75 μm pre-filtered sample, at both UV doses of 30 and 60 mJ/cm^2, tailing level was reduced by 60 % (50 CFU per 100 ml) and 80 % (13 CFU per 100 ml), respectively when compared to the unfiltered sample. Therefore, the results support the hypothesis that larger particles are most critical to UV disinfection tailing, such that up to 95 % reduction in the tailing level could be achieved by filtering particles greater than 32 μm.

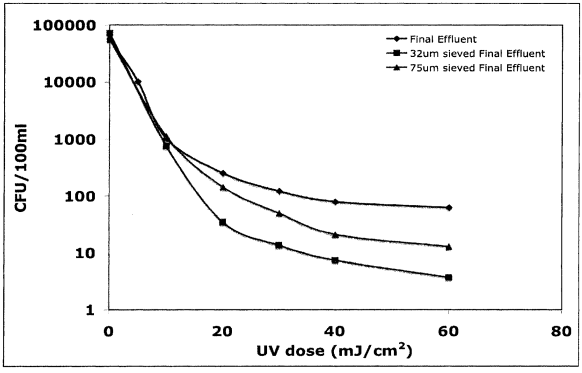

Figure 3.1 Comparison of DRC for secondary effluent sample with and without pre-filtration with 32 μm and 75 μm sieve trays.

A look into the detailed PSD of the samples further accentuates this point (Figure 3.2 and 3.3). In both filtered samples, only a small amount of small particles in the size range of 10 μm to 45 μm (termed small particle fraction or SPF in this discussion) were removed – 15 % in the 32 μm pre-filtered sample and a negligible amount in the 75 μm pre-filtered sample. Yet, more than 80 % reduction in tailing level was still achieved in both samples.

In fact, the percentage reduction in the tailing level appeared to correspond better with the percentage removal of larger particles – 70 % and 50 % of all particles greater than the size range of 45-53 μm (termed Large Particle Fraction, LPF) were removed in the 32 μm and 75 μm pre-filtered samples, respectively. The results show that the LPF is significantly more critical to the problem of UV disinfection tailing. Thus, this proves that the previously established concept that all particles greater than 10 μm equally shield embedded coliform bacteria from UV irradiation and that the extent of shielding is independent of particle size (Emerick et al., 1999, 2000; Jolis et al., 2001; Loge et al., 1999) is at best questionable. If this were true, the percentage reduction in tailing would have corresponded better with the percentage removal of SPF. A similar result has been reported in a recent work carried out by Yong. The implication of the above finding is that upstream processes should target the removal of LPF in effluent, as compared to all particles greater than around 8 μm as previously postulated (Jolis et al., 2001; Loge et al., 2001).

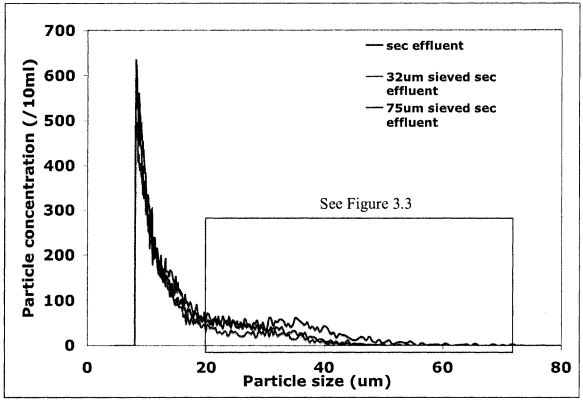

Figure 3.2 PSD comparison of secondary effluent before and after pre-filtration

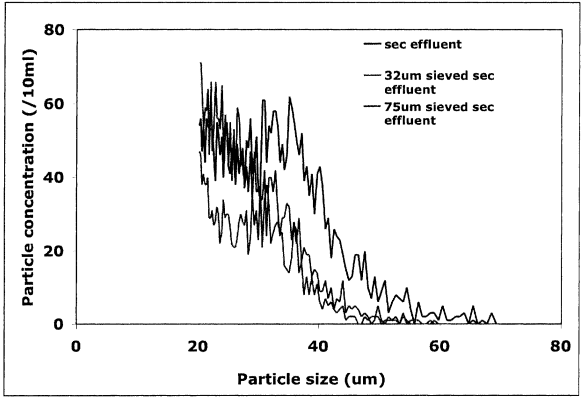

Figure 3.3 Close-up of PSD from 20μm onwards.

From Figure 3.1, it can also be seen that UV resistance appeared to increase with particle size. To better illustrate this point, the DRC's from Figure 3.1 were used to calculate the coliform survival for the <32 μm, 32-75μm, and >75 μm size fractions, respectively (Figure 3.4). The coliform counts for all the size fractions were then expressed as percentage of the total coliform level, i.e. that of the initial unfiltered sample. The graph shows that at low UV doses, the coliform count in the unfiltered effluent sample was made up of mainly the <32 μm fraction, which agrees with findings published by Madge et al.. However, the contribution by the <32 μm fraction was observed to decrease rapidly with increasing UV dose, and they were mostly inactivated by the dose of 20 mJ/cm^2. This is only possible if the smaller particles required a smaller UV dose for inactivation than the larger ones. At the onset of the tailing region, i.e. at UV dose of 30 mJ/cm^2, the 32-75μm fraction was the main contributor to the coliform survival. As the dose continued to increase, the contribution by the >75 μm fraction increased and reached to about 80% at the dose of 60 mJ/cm^2. It is important to note that >75 μm fraction constituted only about 5% of total particles count. Overall, the shift in the distribution of coliform survival towards the larger particle size fractions at higher UV doses highlights the inverse relationship between UV disinfectability and particle size.

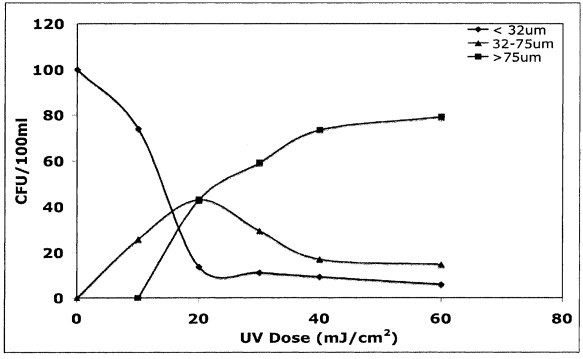

Figure 3.4 Percentage distribution of surviving coliform bacteria across various size ranges.

3.3.2 Effect of Particle Size on UV Resistance

a) Modeling of Dose-Response Curves

As mentioned earlier, wastewater particles were concentrated into narrow size fractions and DRCs were constructed from these samples to study their disinfection kinetics. Data was collected over a 10-month period, and the averaged DRC for each size fractions is presented in Figure 3.5. The inactivation rate for free microbe is also presented in the figure for comparison; this was obtained experimentally by filtering the secondary effluent using a 8um Whatman filter paper and performing UV assay on the filtrate.

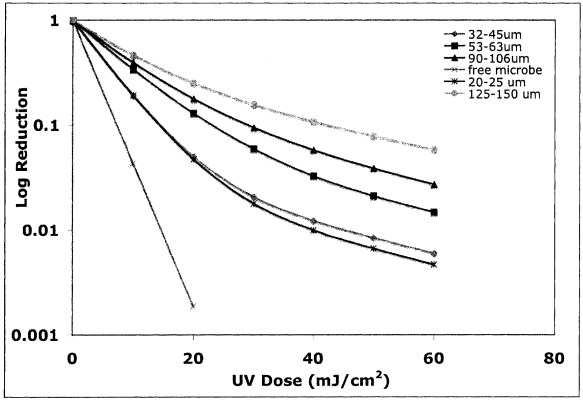

Figure 3.5 Average DRC for the different size fractions and free microbes.

From figure 3.5, it is clear that UV resistance of particle-associated coliform bacteria increases with the size of the harboring particle. This can be seen from the gentler initial slope and the higher tailing level in the DRC as the size of the particles increased. The initial slopes of all the curves were also significantly gentler than that of the free microbes, indicating that the degree of shielding on particle-associated coliform bacteria was significant

in all size fractions. Also, all the slope of DRCs seemed to be similar at the tailing region (UV dose of 40 mJ/cm^2 and above).

The presence of two distinct gradients; i.e. a steeper initial slope followed by a tailing region, in all the DRCs indicates variability in the UV response among the particles within each size fraction. Three possible explanations for this phenomenon were postulated: 1) the steeper initial slope is due to the presence of large amount of free microbes in the samples, 2) large particles were present in the smaller size-fraction samples, creating the tailing of the DRC, or 3) there is an inherent variation in the UV resistance of particles for any given size fraction.

To examine the first hypothesis, a UV assay was performed such that 2 sets of the same sample were separately irradiated. One was cultured as per normal, while the other irradiated sample was first filtered with a 5 μm membrane filter before the filtrate was cultured. The latter step was carried out in order to approximate the amount of free microbes present in the samples during UV bioassay. From the results, it was found that free microbes accounted for less than 3 % of the CFU at zero UV dose in all size fractions, and their contribution became negligible at doses beyond 10 mJ/cm^2. Consequently, it was concluded that the presence of free microbe had negligible impact on the shape of the DRC of the samples. Concerning the second hypothesis, the PSD of a 32 – 45 μm sample reviewed that large particles (greater than 90μm) were only present at less than 0.5% of the total particle count in the sample, insufficient to account for the tailing observed.

Therefore, the only reasonable explanation for the distinct shape of DRC could be that the particles in the fractionated samples were not homogeneous. Instead, it may be assumed that two groups of particles existed within each size fractions – a small fraction of UV resistant particles mainly responsible for the tailing, and the more UV susceptible particles whose inactivation kinetics were given by the initial slope of the DRC. Therefore, a double-exponential model may be used to model the UV inactivation kinetics of wastewater particles:

$$\frac{N}{N_0} = (1-\beta)e^{-k_1 D} + \beta e^{-k_2 D} \qquad (3.1)$$

where N is the residual number of viable particles after UV irradiation, in CFU/100ml, N_0 is the initial number of viable particles, in CFU/100ml, and D is the delivered UV dose, in mJ/cm^2. In this equation, β represents the fraction of UV-resistant particles. Finally, k_1 and k_2 are the first-order inactivation rate constant for the UV-susceptible and UV-resistant particles, respectively. To obtain the values of the parameters, a nonlinear regression was performed and Figure 3.6 shows an example of the fit of the experimental DRC data using Equation (3.1).

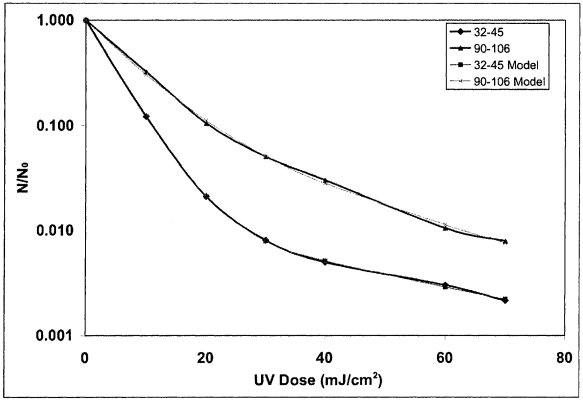

Figure 3.6 DRCs plotted from experimental data and by fitting the double-exponent model to the same set of experimental data.

b) Analysis of Model Parameters

Based on Equation (3.1), the key parameters that affect the UV disinfection performance are β, k_1 and k_2 and their impact on the shape of the DRC is illustrated in Figure 3.7. The figure separately plots out the first and second exponential term of Equation 3.1 along with the combined equation. It clearly shows that the magnitude of k_1 describes the initial slope of a DRC while k_2 and β describe the slope and height of the tailing region, respectively.

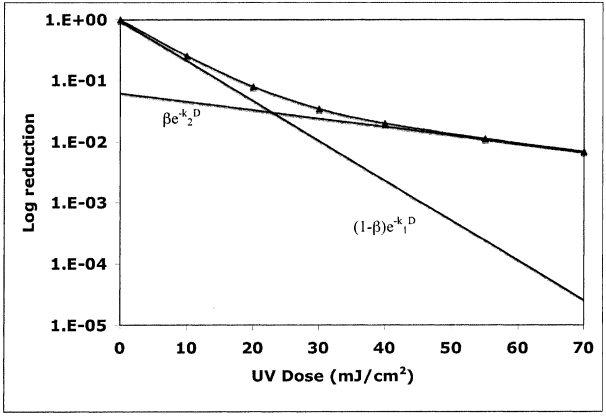

Figure 3.7 Effect of model parameters on DRC.

The values of k_1, k_2 and β were regressed from all the experimental DRC results for the various size fractions collected over the 10-month period. Figure 3.8 and 3.9 show the summary of their average values for all the size fractions.

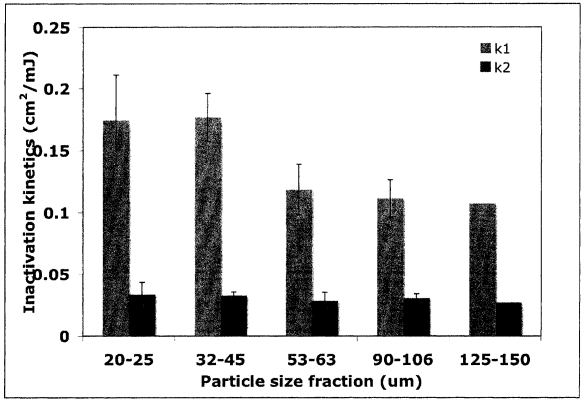

Figure 3.8 Summary of the average of k_1 and k_2 for all size fractions obtained over 10-month period.

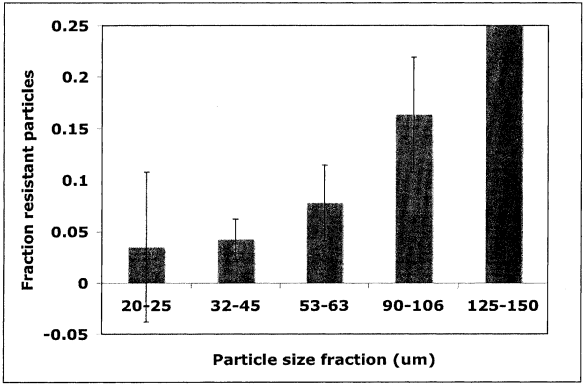

Figure 3.9. Summary of the average of β for all size fractions obtained over 10-month period.

Figure 3.8 shows that the initial slope of DRC, k_1, decreased from 0.18 to 0.11 with increasing particle size from 20 to 150 μm. On the other hand, k_2 was found to be independent of particle size and remained constant at about 0.03 for all the size fractions. Both inactivation constants were also greatly smaller than that of free microbes, which was found to be 0.3, highlighting the significance of UV shielding on particle-associated coliform bacteria.

While the inactivation constants at the tailing region were independent of particle size, this did not imply that particle size had no effect on the tailing region. Figure 3.9 shows the effect of particle size on β. The results showed that particle size had a strong influence on the level of tailing – β for the largest size fraction was almost 10 times that of the smallest size fraction. In fact, the variation in this parameter accounted for much of the differences in the DRCs between size fractions at the tailing region, indicating that the effect of particle size on UV disinfection is largely due to the presence of a greater UV-resistant fraction in larger size fractions.

The trend in the values of k_1 clearly supports earlier hypothesis that larger particles can provide more obstruction to the path of UV irradiation. Yet, the occurrence of the UV-resistant particles with the same disinfection kinetics of k_2 in all size fractions also suggest the presence of factor other than particle size that is affecting UV disinfection kinetics. This seems to point to the existence of critical regions of high UV shielding within wastewater particles of all sizes. The observed trend in the β values could be due to a greater tendency for these critical regions to occur within larger particles. In addition, the use of blending technique to disperse all coliform bacteria entrapped within wastewater particles has shown that larger particles could contain up to 3 times more coliform bacteria per particle (refer Appendix G) than particles in the smaller size fraction. This could also potentially increase the probability of having at least one coliform bacterium to be located within the critical region, resulting in a higher β value.

One possible hypothesis for the identity of the critical regions is that these are regions of dense floc structure. Such heterogeneous floc had already been suggested to exist by

recent publications. Through the use of fluorescence staining, McSwain et al. (2005) found that flocs were comprised of a small center of extracellular polymeric substances (EPS) and cells surrounded by a network of filamentous bacteria and fungi. EPS are polymer matrix containing variable proportions of proteins, carbohydrates and nucleic acids (Jorand et al., 1995; Pavoni et al., 1972; Urbain et al., 1993), and they originate from cell lysis and metabolic excretion (Jorand et al., 1998). They have widely been considered to be essential to bacterial flocculation in activated sludge flocs (Pavoni et al., 1972; Snidaro et al., 1997; Wingender et al., 1999). Hence, the concentration of EPS in small center could suggest the existence of dense cores in activated sludge floc. Liao et al. (2002) also suggested a conceptual model that described the structure of activated sludge floc to be consisted of two physically distinct regions defined by the arrangement of EPS. The core was postulated to be a dense hydrophobic region surrounded by a loose outer structure kept together by relatively weak interactions.

More recently, Yuan et al. (private communication) showed that by shearing off the outer layer of flocs using Couette Flow technique, the remaining portion of the flocs exhibited higher shear strength, indicating the existence of a physically strong and dense inner core. It is conceivable that the dense core of flocs could harbor indicator organisms and result in a small k_2 values observed in this study.

In addition, by associating hydrophobicity with the formation of dense cores, the concept of a 2-level floc structure could also explain the fact that β value increased with particle size. Due to the interaction with the surrounding hydrated environment, it is reasonable to believe that the core of the activated sludge floc may be more hydrophobic than the outer layer (Liao et al., 2002). Besides, spectroscopic evidence also showed that highly pronounced hydrophobic regions existed inside activated sludge flocs (Ganaye et al., 1997). Larger particles can have a greater tendency of encountering limitations in the diffusion of oxygen and nutrients from the bulk solution to the core, resulting in a lower growth rate. Lower growth in turn can lead to a more hydrophobic surface (Liao et al., 2001) and hence a greater likelihood of dense cores formation.

Finally, it was also observed that samples collected on days whereby the treatment plant operated at higher SRT showed higher β values across all size fractions. Based on the same theory of a 2-layer structure, higher SRTs had been associated with greater hydrophobicity and more pronounced cores (Liao et al., 2002). In summary, the concept of the existence of a small dense core in activated sludge flocs appears to explain the existence of 2 inactivation rate constants in each size fraction, and higher β values for larger size fractions. However, more experiments are needed to prove the validity of this hypothesis.

c) Percentage Viability and Tailing Propensity

In assessing UV disinfection performance of wastewater, the number of particle-associated coliform bacteria plays a critical role (Emerick et al., 1999; Loge et al., 2001, 2001). Hence, it is important to quantify the percentage of viable particles, p, that contain at least one viable coliform bacterium. Values of p were determined experimentally by dividing the concentration of viable particles by the total particle concentration in the sample. The former was obtained from bioassay, i.e. by culturing the sample without any UV exposure and enumerating the CFU, while the latter was measured using Coulter particle size analyzer. Figure 3.10 shows that the average value of p obtained for each size fractions over the 10-month period varies from about 5% to 22%. This is within the range published by other researchers (Emerick et al., 1999; Farnood, 2004). Using the same methodology, Farnood obtained values of percentage viability to be within the range of 7.0 to 11.0%. In the work by Emerick et al., wastewater particles were fixed onto membrane filter by filtration. Fluorescence In-situ Hybridization was then used to identify particles containing coliform bacteria. Through image analysis, the percentage of particles containing at least one embedded coliform bacteria was found to be from 3.8 to 31.1% for a wide range of activated sludge systems.

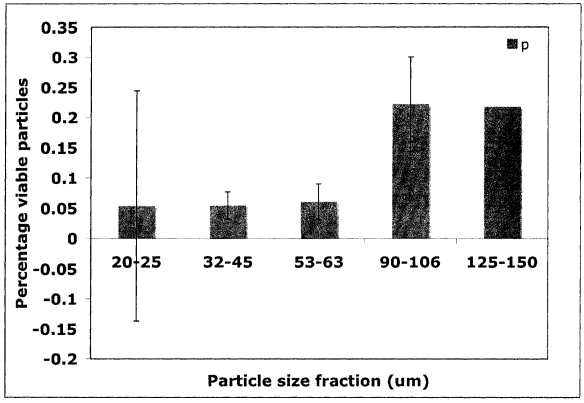

Figure 3.10 Average results of percentage viability for all size fractions over the 10-month period.

Given the small value of p, it can be concluded that the majority of the suspended particles in the activated sludge samples were not viable. This is in agreement with the observation made by Qualls et al. (1985) that many of the large particles did not contain coliform bacteria. More importantly, it can be seen that particle size had a strong influence over the viability of wastewater particles: the percentage viability of the largest size fraction was almost 4-5 times that of the smallest one. This is expected given that larger particles have a larger number of microorganisms and are therefore more likely to be viable.

From Equation 3.1 and Figure 3.7, it can be seen that the UV-susceptible fraction becomes insignificant at UV doses of 40 and beyond. Therefore, at the tailing region, for each size fraction, Equation 3.1 can be simplified to as follow:

$$N = N_p p \beta e^{-k_2 D} \qquad (3.2)$$

where N_p is the number of particles within the size fraction, and p is the percentage viability of particles within the size fraction. Given that the rate of inactivation at the tailing region, k_2, is independent of particle size, by normalizing Equation 3.2 by the number of particle, N_p, a new parameter termed the tailing propensity (TP) is introduced and defined as follows:

$$\text{Tailing Propensity} = p\beta \qquad (3.3)$$

where p is the fraction of viable particles and β is the fraction of UV-resistant particles.

TP describes the number of UV-resistant coliform bacteria per particle occurring in a sample. Values of TP for the various size fractions are shown in Figure 3.11. TP for the smallest size fraction was about 0.0012, while that for the largest size fraction was about 0.087. Hence, particles larger than 125 μm are about 90 times more likely to have high UV resistance than particles in the 20 – 25 μm size fraction. The small TP values show that most of the wastewater particles are either not viable or are not highly UV resistant.

Also, given that k_2 is extremely small and independent of particle size, TP value provides an approximation of the probability that a particle will contain at least one viable coliform bacterium and that this particle will survive UV disinfection at the tailing region. It therefore allows for a direct comparison of the propensity of particles in different size fractions to contribute to disinfection tailing.

On the whole, TP value serves as a summary of the overall effect of particle size on the UV disinfection kinetics. It can be seen that coupling higher percentage viability with a higher fraction of UV-resistance particle, the detrimental effect of larger particles on UV disinfection tailing is greatly magnified. Also, by combining information of TP values with that of the effluent particle-size distribution, it is possible to generate a size distribution for the surviving coliform count at the tailing region.

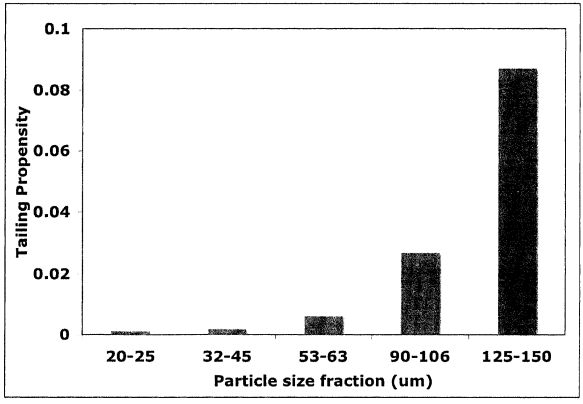

Figure 3.11 TP for the various size fractions tested.

3.4 Conclusion

Upstream processes such as filtration are widely accepted as promising solutions to the problem of UV disinfection tailing. The motivation of this research was therefore to gain a detailed understanding on the tailing phenomenon, particularly how particle size can influence the UV inactivation kinetics and the tailing propensity of wastewater particles. Knowledge on this can inevitably assist in optimizing the implementation of upstream processes.

The results showed that the particles mainly responsible for tailing of UV dose response curve were those larger than 45-53 μm sieve fraction. The disinfection of various particle fractions followed the double-exponential inactivation kinetics – a steeper initial slope of inactivation followed by a much gentler tailing region. Particle size was found to strongly influence the UV inactivation kinetics of wastewater particles. Larger particles had a

gentler initial slope of inactivation and a higher tailing level, although the inactivation rate constant at the tailing region appeared to be independent of particle size. Larger particles also showed greater tendency of harboring coliform bacteria, with much higher percentage viability. A new parameter termed tailing propensity was defined that describes the likelihood that a particle in an effluent sample is highly UV-resistant and remains viable at UV dose of 30 mJ/cm^2 and above. Particles larger than 100 μm exhibited as much as 90 times greater tailing propensity than smaller particles in the range of 20-30 μm – a consequence of the combination of having a greater tendency of harboring coliform bacteria and greater fraction of UV resistant particles. Values of tailing propensity could allow for the prediction of the distribution of UV tailing across the particle size range, thereby facilitating the design and optimization of upstream processes for improving UV disinfection. However, further research is required to better understand how disinfection kinetics and percentage viability could be affected by plant operating condition.

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Chapter 4 Prediction of UV Disinfection Performance

4.1 Introduction

Despite the importance of UV disinfection kinetics for the effective design and operation of ultraviolet reactors, there is still a lack of a comprehensive prediction model that relates effluent quality to the UV disinfection performance. Previously developed models, were mainly based on bulk effluent parameters such as TSS (Loge et al., 1996; Scheible, 1987) and as a result, they did not capture the actual disinfection characteristics of the wastewater. Consequently, the model coefficients were no more than values obtained from mathematical regression. These models tended to be site specific and the differences in their values between different sites could be more than six orders of magnitude (Emerick et al., 1999). There was also no meaningfully way of accounting for these differences and relating them to plant operating conditions, as the coefficients were merely values mathematically obtained from calibrating the plant disinfection performances with the bulk parameters.

Therefore, the objective of this research was to develop a mathematical model to predict UV disinfection performances based on the mechanistic understanding of UV disinfection of particles. It is also important that such a model involves a minimal number of parameters (Farnood, 2004).

Size distribution and concentration of wastewater particle has been shown to be an important indicator of effluent UV disinfection performance (Cairns et al., 1993; Farnood, 2004; Madge et al., 2006; Qualls et al., 1983, 1985). It was therefore hypothesized that the disinfection performance of an effluent could be predicted by summing the disinfection of all the individual particle size fractions present in the sample. In other words, the UV DRC of an effluent could be predicted simply based on the particle-size distribution (PSD) data. To prove these hypotheses, the DRC of a synthetic mixture was compared to the summation of the DRC of its constituents. This 'additivity rule' was then extended to secondary effluents from an activated sludge system, to test its applicability under realistic conditions. Ultimately, the aim was to demonstrate that using average particle inactivation kinetics

collected over a sufficiently long period of time, it is possible to predict the effluent disinfection performance from PSD data with reasonable accuracy.

4.2 Materials and Methods

4.2.1 Sample Collection

Wastewater samples from activated sludge process were collected from Ashbridges' Bay WWTP located at the eastern end of the city of Toronto. The detailed description of the plant was presented in chapter 3. The collected samples were stored at 4°C. To ensure that the storage does not alter the sample characteristics and hence the experimental results, the samples were analyzed within 12 hours of the collection.

4.2.2 Sample Sieving

Quantifying the disinfection kinetics of wastewater particles according to their size will require sieving the particles into narrow size fractions and performing bioassay on the sieved samples. This was done using various sieve trays (U.S.A. Standard Testing Sieve) as outlined in chapter 3.

4.2.3 PSD Analysis

PSD analysis was carried out using a Multisizer 3.0 particle analyzer (Beckman Coulter Canada, Mississauga, Ontario, Canada). 10.7 g/L of NaCl (VWR, Mississauga, Ontario) solution was used as the electrolyte. The procedures for obtaining the PSD and particle concentration were the same as that mentioned in chapter 3.

4.2.4 UV Bioassay

The UV system used was a low-pressure mercury vapor lamps (Trojan Technologies, London, Ontario, Canada), which emits roughly 85% of their output at a wavelength of 253.7 nm (Chiu et al., 1999). The set-up and the detailed description of the procedures were given in chapter 3.

4.3 Results and Discussions

4.3.1 Demonstrating 'Additivity Rule' in UV DRC

As mentioned earlier, it was hypothesized that the DRC of effluent is the summation of the disinfection of all particles in the sample. To proof this hypothesis, referred to as the 'additivity rule', a mass balance experiment was carried out. A mixed liquor sample was sieved into 3 size fractions: 32 – 45 μm, 53 – 63 μm and 90 – 106 μm. DRC for these fractions were constructed separately through bioassay. Concurrently, a portion of each of the 3 samples were mixed in known proportions to create a synthetic effluent sample, and its DRC was also constructed. If the 'additivity rule' is applicable to UV DRC, it would be possible to calculate and re-construct the DRC of the synthetic effluent by summing the DRC for each of the 3 sieved samples according to the mixing proportions.

The calculated DRC and the actual DRC of the synthetic effluent obtained from bioassay are shown in Figure 4.1. Statistical analysis of results showed that the differences between the calculated and experimental DRC of the synthetic effluent were within the experimental errors of UV bioassay, and therefore were not significant. These results verified the validity of the 'additivity rule' for UV disinfection kinetics.

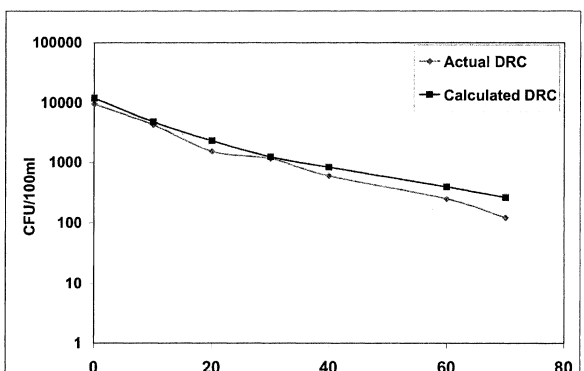

Figure 4.1 Comparison between actual DRC obtained from bioassay and calculated DRC for the synthetic effluent to demonstrate the validity of 'Additivity Rule' in UV DRC.

The similarity between the 2 DRC shows that the disinfection kinetics of the particles remained the same in the synthetic effluent as they were in their respective sieved samples. This suggests that the disinfection kinetics of a particle is only a function of its own size and not the particle concentration and size distribution of the solution it is in. On the other hand, it is widely understood that particles can increase UV resistance by the shading and scattering effect they have on the target microorganisms (Darby et al., 1993), and the level of shading and scattering should be influenced by the particle concentration and size distribution in the sample. Hence, the disinfection kinetics of the synthetic effluent should account for the possible synergistic or antagonistic effects on the particle disinfection kinetics arising from the changes in the particle concentration and size distribution, and the overall disinfection would therefore not be a direct summation of the individual constituents. A possible explanation for the observation could be that the samples were irradiated under a continuously stirred environment, thereby reducing the potential of particle shading and scattering. It is also likely that the particle concentration of the samples were not sufficiently

concentrated, such that the detrimental effect on the disinfection kinetics arising from particle shading and scattering was negligible when compared to the extremely high absorption of UV by the floc material surrounding particle-associated coliform bacteria (Loge, et al., 1999).

4.3.2 Application of 'Additivity Rule' to DRC of Secondary Effluent

To examine the applicability of 'additivity rule' under realistic conditions, mixed liquor samples were sieved into various size fractions: < 20 μm, 20 – 25 μm, 32 – 45 μm, 53 – 63 μm and 90 – 106 μm, and their DRC were obtained from bioassay. The DRC were then fitted to a double exponent kinetic model (Equation 3.1) by performing non-linear regression analysis using Mathematica, and the results are shown in Figure 4.2.

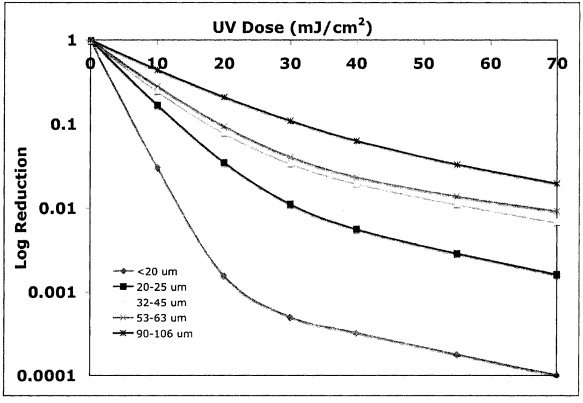

Figure 4.2. Results of DRC obtained for all size fractions.

In addition to UV DRC, the percentage of viable particle, p, was determined for each fraction using the procedure described in Chapter 3. Table 4.1 summarizes the results for the disinfection parameters of various size fractions. Note that the < 20 μm fraction showed an exceptionally high p value even though there was a general trend towards decreasing p value with decreasing particle size. This could be due to the fact that the < 20 μm sample was obtained by filtering the secondary effluent with a 20 μm sieve. As such, a large amount of free microbe was present in the sample.

Table 4.1. Summary of disinfection kinetics for all size fractions.

Size fraction (μm)	Multisizer Size (μm)	β	k_1 (cm^2/mJ)	k_2 (cm^2/mJ)	p (CFU/particle)
<20	5-12	0.00156	-0.353	-0.0391	0.0678
20-25	12-18	0.0230	-0.185	-0.0379	0.00734
32-45	18-28	0.0617	-0.150	-0.0313	0.0221
53-63	28-45	0.0515	-0.136	-0.0248	0.0353
90-106	>45	0.121	-0.0921	-0.0272	0.208

The PSD for the effluent sample is given in Figure 4.3. The PSD was divided into five ranges corresponding to sieving size fractions listed in Table 4.1. It should be noted that the measurements given by the Multisizer tend to underestimate the actual particle size due to its measuring principles. Hence, the PSD generated by the Multisizer for the sieved samples had to be corrected for this artifact. The Multisizer size ranges corresponding to the various sieve size ranges are listed in Table 4.1. After dividing the particle size distribution to appropriate size ranges, the total number of particles for each range, N_{pi}, was determined. Using the respective disinfection kinetics for size range "i", the coliform survival rate within each ranges, and therefore the DRC for the secondary effluent sample was estimated based on:

$$N = \sum_{i}^{n} p_i N_{pi} \left[(1-\beta_i) e^{-k_{1i} D} + \beta_i e^{-k_{2i} D} \right] \qquad (4.2)$$

where N is number of coliform at UV dose D, in CFU/100ml, p_i is the fractional particle viability of the i^{th} size range, β_i is the fraction of UV-resistant particles in the i^{th} size range, k_{1i} is the inactivation constant for the UV-susceptible fraction in the i^{th} size range, and k_{2i} is inactivation constant for the UV-resistant fraction in the i^{th} size range.

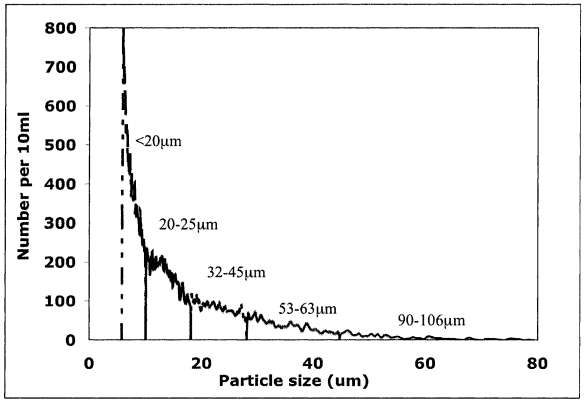

Figure 4.3. PSD of effluent sample being broken down into the various size ranges

Figure 4.4 shows the comparison between predicted and actual DRC of the secondary effluent. Using statistical analysis, the paired-t-test showed that the point-to-point differences between the re-constructed and actual DRC were within the level of errors expected of UV bioassay tests. This therefore suggests that the 'additivity rule' in DRC could be applied to a secondary effluent sample. This result further demonstrates that it may be possible to predict disinfection performance of secondary effluents in real time by online particle size measurement.

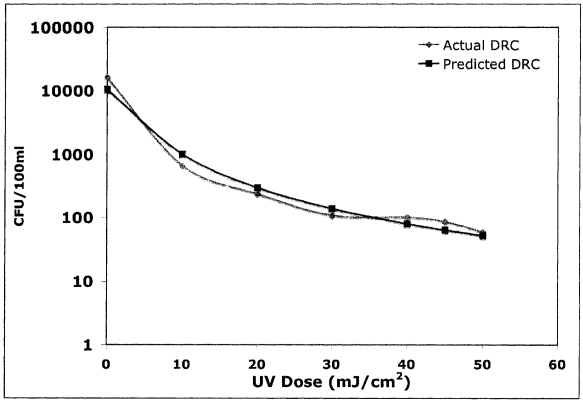

Figure 4.4. Comparison between actual and calculated DRC for a secondary effluent sample

The model developed here has the advantage of taking a more mechanistic approach, by focusing on the particle disinfection kinetics. It therefore involves a set of more fundamental parameters such as particle size distribution and particle UV inactivation constants. Although empirical and site specific, the values of these parameters have physical meaning and their differences and fluctuations could be related to treatment plant operating processes and conditions. The implication is that the fluctuations in the model parameters will be smaller, unlike in previous models, unless drastic changes to the treatment train are made. Furthermore, the disinfection kinetics could potentially be predicted based on the treatment plant's operating conditions, and in turn be used to provide a more accurate prediction of the effluent disinfection performance. However, further research is required to establish this link.

In addition, the proposed model provides quantitative insight regarding the contribution of various particle size fractions to the tailing of DRC, and this information could be useful in optimizing upstream treatment processes. For example, from the prediction

results obtained earlier, it was found that about 50 % of the coliform survival at the UV dose of 50 mJ/cm^2 was caused by particles in the 90 – 106 μm size range. This prediction agrees with the conclusion made by Qualls et al. (1983 et al.) indicating that there was a strong correlation between coliform survival at high UV dose and the amount of particles greater than 40 μm.

4.3.3 Prediction of UV Disinfection Performance Based on Effluent PSD

Here, the potential of using the proposed model as a practical way for predicting the disinfection performance of effluents based on their PSD is demonstrated. For this purpose, data collection for the disinfection kinetics was conducted over a 10-month period – samples were regularly collected from the Ashbridges' Bay Wastewater Treatment Plant and the disinfection kinetics for the various size fractions were obtained via the protocol established earlier. The mean values and confidence intervals for the model parameters – k_1, k_2, β and p, were compiled for each size fractions. These values were then used to predict the secondary effluent disinfection performance on several randomly selected occasions. In general, the predictions were reasonably close to the actual bioassay results; the errors in the predictions were statistically insignificant with respect to the errors expected of a bioassay process. Examples of some of the predictions generated are shown in Figure 4.5 and 4.6.

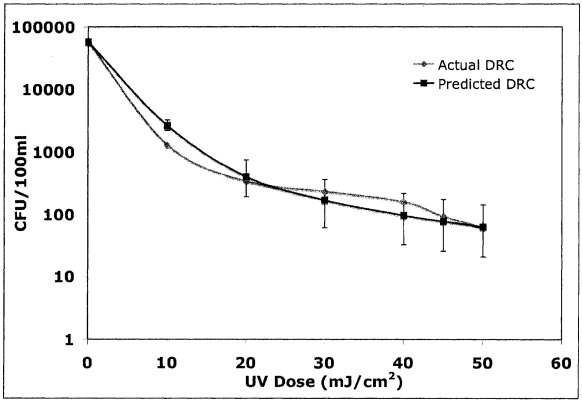

Figure 4.5. Comparison between actual DRC of a secondary effluent sample and that predicted from compiled data of disinfection kinetics.

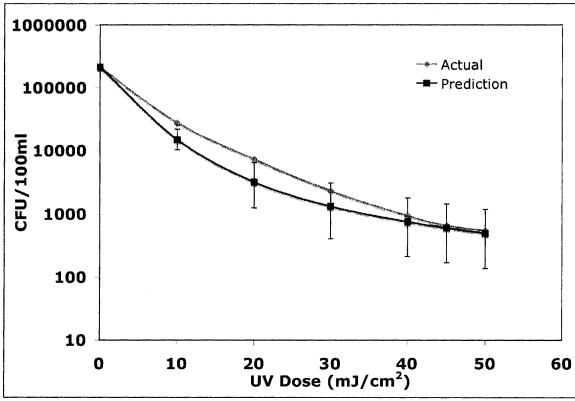

Figure 4.6. Comparison between actual DRC of a secondary effluent sample spiked with mixed liquor and that predicted from compiled data of disinfection kinetics.

Note that in Figure 4.6 the coliform survival level in the effluent sample was much higher than the typical effluents collected from the same site as it was spiked with a small amount of mixed liquor. This was done to test the effectiveness of the model in predicting effluent with a vastly different PSD conditions. It should be noted that Equation 4.2 is focused on the predicting the tailing region of the dose response curve and does not account for the free microbes in the effluent. Therefore, the difference in CFU count before UV irradiation between the actual and predicted DRC's was assumed to be due to the presence of free microbes. This amount of CFU was then added to the predicted DRC to compensate for this effect and an inactivation constant of 3-log reduction per 20 mJ/cm^2 of UV dose was assumed for the free microbes. The limitation of the model in predicting the free microbe level should not be of a concern because free microbes are highly susceptible to UV inactivation and have negligible effect on the CFU count at doses above 20 mJ/cm^2. In other words, under regular disinfection conditions, free microbes have negligible contributions to the overall coliform survival.

In all cases, the error between predicted and actual CFU was within half-log, and the actual DRC's were within or close to the 90% confidence interval of the predicted values. The goodness of the model predictions using averaged disinfection kinetics data is further examined by comparing the predicted versus actual CFU for all effluent samples (Figure 4.7). The graph obtained shows a gradient of one, with a high r-square value of 0.86, highlighting the fact that the predictions agreed with the actual results for majority of the time. The maximum difference between the data point and the unity line is also around half a log. This result also proves the previously mentioned point, that in a wastewater treatment plant, unless drastic changes are made to the treatment train, the effects of the day-to-day fluctuations in operating conditions on the particle disinfection kinetics generally is not significant. Rather, it is the changes to the effluent particle count and PSD that has the most significant impact on the effluent disinfection performance. Hence, by establishing a data of disinfection kinetics for the various size fractions, it is possible to predict effluent disinfection performance online, requiring only measurements of effluent PSD.

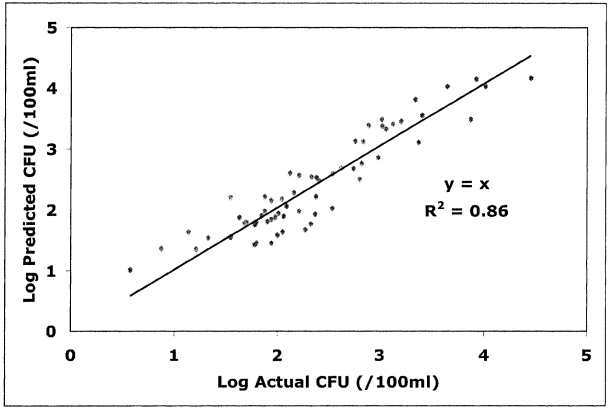

Figure 4.7. Plot of Log predicted versus Log actual CFU, illustrating the goodness of the model prediction.

4.4 Conclusion

The objective of this paper was to develop a mechanistic model to describe the UV DRC of secondary effluents. The hypothesis behind this approach was that UV DRC follows an 'additivity rule', i.e. the overall disinfection performance of the effluent is the sum of the disinfection of all its particulate constituents. The aim was to create a procedure that allows for a quick and real time prediction of UV disinfection performance. The results showed that the 'additivity rule' holds for UV disinfection; i.e. DRC constructed from the summation of the disinfection of all the particles was found to be similar to the actual DRC obtained from bioassay. This showed that for a given wastewater treatment plant, the disinfection characteristic of wastewater particles was only a function of particle size and not the particle concentration and size distribution of the solution it was in. Data of particle inactivation kinetics were also collected over a 10-month period and were used to predict the UV disinfection performances of secondary effluents based on their PSD with high accuracy. This result suggested that changes in effluent PSD and particle count were mainly responsible for the day-to-day fluctuations in effluent UV disinfection performance. It is the aim of future work to further improve the prediction methodology, by establishing the correlation between the disinfection kinetics and plant operating parameters.

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Chapter 5 Comparison of UV Disinfection Kinetics Between Treatment Processes

5.1 Introduction

The application of UV disinfection in trickling filter effluent has often been limited due to the high UV dose demand of such effluents. It is generally believed that the unsatisfactory UV disinfectability of trickling filter is due to the poor settleability of trickling filter particles, which could result in a high level of UV-resistant suspended particles. The objective of this paper was therefore to provide a better understanding of the disinfection kinetics of trickling filter effluent particles. The work first attempted to establish the critical size range, above which trickling filter particles would have a significant tendency to cause tailing of UV dose response curve (DRC). Using the protocols developed in chapter 3, the disinfection kinetics of particles of various size fractions were then quantified. The disinfection kinetic parameters for trickling filter particles were compared with those of activated sludge particles to develop a better insight into the origin of the high UV dose demand of trickling filter effluents.

5.2 Materials and Methods

Trickling filter samples were collected from Harmony Creek Water Pollution Control Plant, located in the Durham Region east of the city of Toronto. The plant has a capacity of 68,200 cubic meters per day and half of the secondary treatment processes comprise of trickling filtration facilities commissioned in 1962. The samples were transported to the laboratory and stored at 4 °C. For analysis of particle disinfection kinetics, part of the sample was sieved into three size fractions: 32 – 45 μm, 53 – 63 μm and 90 – 106 μm. In addition, the disinfection performance of the whole effluent was also tested. The prepared samples were analyzed for their PSD, and bioassays were performed to construct the DRC. Details of the sieving, PSD measurement and bioassay processes can be found in chapter 3.

5.3 Results and Discussions

5.3.1 Significance of Large Particles in UV Disinfection Tailing

To understand the contribution of large particles to tailing of UV DRC in tricking filter effluents, a portion of the final effluent sample was pre-filtered with a 32 μm sieve tray. The DRC of the filtered sample was then constructed and compared with that of the original effluent. The result is shown in Figure 5.1. The differences between the two DRC's highlight the importance of large particles to the tailing level of DRC. The removal of particles greater than 32 μm brought about a significant reduction in the tailing level. For the UV dose of 30 mJ/cm^2 and beyond, the average reduction in coliform count was about 90%. Moreover, the percentage of reduction in coliform count was higher at higher UV doses. This result suggests that larger particles were more UV resistant and therefore had a greater tendency to survive higher UV doses. This trend is in agreement with the earlier results obtained for the activated sludge particles, in which positive correlations between particle size and its UV resistance was reported. At this point, however, this hypothesis about trickling filter particles needed to be further examined.

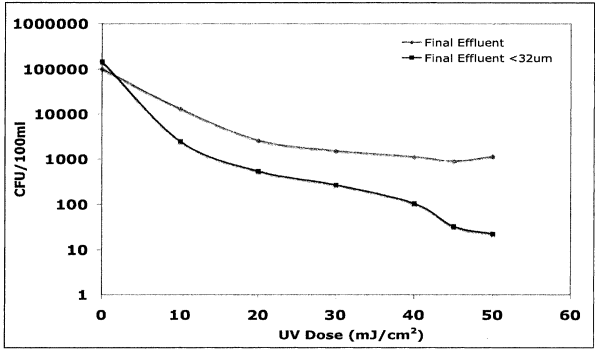

Figure 5.1. Comparison of DRC for trickling filter final effluent sample with and without pre-filtration with 32 μm sieve trays.

Figure 5.2 shows the percentage removal of the cumulative total number of particles by the pre-filtration process. The graph clearly shows that most of the large particles were removed from the effluent by pre-filtration while much of the smaller particles still remained. Considering all particles of size greater or equal to 10 μm, the percentage removal is only approximately 30 %. Yet the percentage reduction in the tailing level was 90 % as previously mentioned. This is only possible if the small particles had insignificant contribution to the tailing level of DRC.

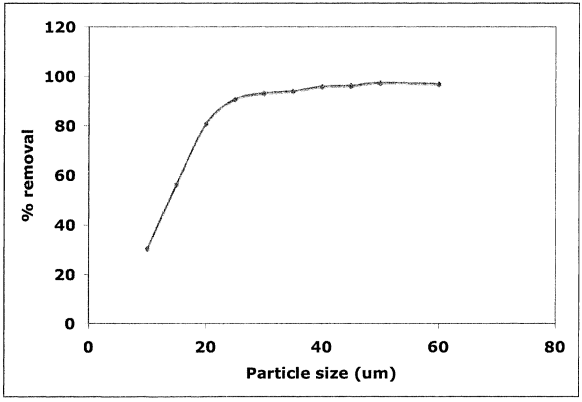

Figure 5.2. Percentage removal of the cumulative total number of particles greater than a certain size by the pre-filtration.

Based on Figure 5.2, particles that mainly contribute to the tailing of trickling filter DRC appears to lay between 25 to 30 μm (approximately 45 to 53 μm in terms of sieve size). The percentage removal of particles greater than both 25 μm and 30 μm (91 % and 93 % respectively) by the pre-filtration process corresponded well to the percentage reduction in tailing level (91%).

In addition, by compiling the results of all the DRC's for the same trickling filter effluent collected on several different days, it was found that the average number of surviving CFU at the tailing level correlated well (r^2=0.97) with the number of particles greater than 30 μm as shown in Figure 5.3. The gradient of the regression line was 0.036, showing that approximately 4 percent of the total number of particle greater than 30 μm would contribute to a CFU count at the disinfection tailing region. On the other hand, a much poorer correlation was observed when the same average number of surviving CFU was plotted against the total number of particles greater than 10 μm; the r-square value was only 0.55.

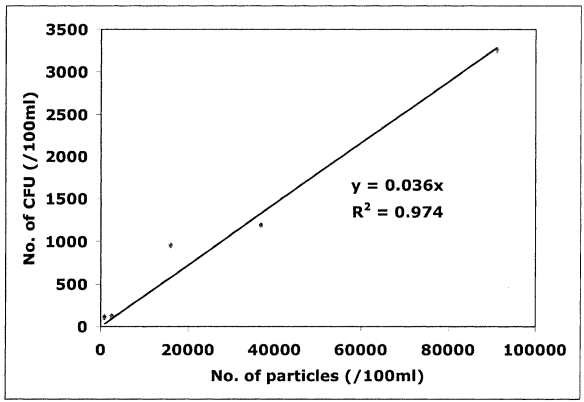

Figure 5.3. Correlation between the average number of CFU at tailing level and the number of particles greater than 30 μm.

It should be emphasized that, the concept of a threshold size does not imply particles smaller than this size would not contribute to disinfection tailing; it only serves to identify the particle size range that has most effect on the tailing of DRC.

Overall, the trends observed for trickling filter particles are similar to that of activated sludge particles reported in Chapter 3. The pre-filtration process with 32 μm sieve tray resulted in an average of 90 % reduction in tailing level in all the trickling filter samples tested, as compared to 94 % for activated sludge samples. 45 - 53 μm fraction appeared to be the critical size range for both activated sludge and trickling filter particles, above which the particles would have a significant tendency of contributing to disinfection tailing. This observation is also in agreement with that published by Yong, who observed a strong correlation between the percentage tailing improvement and percentage removal of particles greater than 45 μm to 53 μm for various effluent samples tested.

5.3.2 Effect of Particle Size on UV Resistance

a) Modeling of Dose-Response Curves

Based on the protocols developed in Chapter 3, wastewater particles in trickling filter effluent were fractionated into three narrow size fractions; namely 32 – 45 μm 53 – 63 μm, and 90 – 106 μm, through a sieving process. Bioassays were performed separately on each of the fractionated samples to obtain their individual UV dose response curves. This process was repeated several times over a two-month period and the average DRC obtained for each of the three size fractions are given in Figure 5.4. The inactivation rate for free microbe was also obtained experimentally and presented in the figure for comparison.

The results clearly show that larger particles exhibited a greater resistance towards UV disinfection; they were able to provide greater shielding effect on the embedded coliform bacteria. It can be seen that as the particle size increased, the initial slope of the DRC decreased, and the tailing level significantly increased.

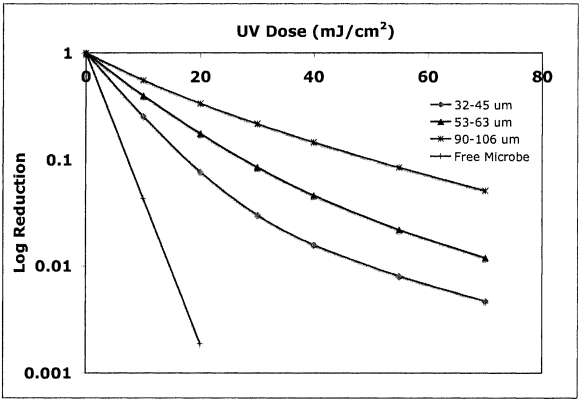

Figure 5.4 The DRC for each of the size fractions tested obtained from averaging all the data collected over a 2-month period.

Similar to the activated sludge particles, the DRC of trickling filter particles demonstrated a steeper initial slope followed by a significant reduction in rate of inactivation beyond the dose of 40 mJ/cm^2. As such, the double-exponential model introduced in Chapter 3 (Equation 3.1) was used here to describe the inactivation kinetics of trickling filter particles, and model parameters were determined using non-linear regression analysis.

As in the case of activated sludge particles, the change in the slope of DRC of trickling filter particles could be attributed to the heterogeneity in the particle structure. The main source of particles in trickling filter effluents is the detachment of biological solids from biofilms. This process occurs when the external forces, such as hydrodynamic shear, exceeds the internal strength of the matrix that binds the biofilm together (Horn et al., 2002). When biofilms grow and thicken, zones with limiting substrate and oxygen could develop. Detachment of biofilm could also take place as a result of the endogenous decay of microorganisms within these zones (Steinmann, 1989). In addition, some amount of residual

wastewater solids is also present in trickling filter effluents (Zahid et al., 1989). Therefore, the presence of these two types of particles could possibly account for the heterogeneity in particle UV disinfection kinetics as observed within each size fractions.

Moreover, biofilms themselves are known to be typically heterogeneous structures (Costerton et al., 1994; Rapporteur et al., 1989; Zhang et al., 2001). While it was previously thought that biofilms are structurally continuous and homogeneous, recent works had established that spatial variations of physical and chemical parameters exist within biofilms (Bishop, 1997). In terms of the chemical properties, Zhang et al. (2001) found from the dissolved oxygen profile of a biofilm that well-defined layers of aerobic and anoxic conditions existed within the biofilm even when it was grown under an aerobic bulk liquid environment. Extracellular polymeric substance (EPS) yield was also found to decrease with biofilm depth (La Motta et al., 2003; Zhang et al., 2001). Physically, densities of biofilm were found to increase with depth by as much as ten times (Masuda et al., 1991; Zhang et al., 1994). Zhang et al. (1994) also found a corresponding change in biofilm porosities from 84 – 93 % in the top layers to 58 – 67 % in the bottom layers, while mean pore radius decreased from 1.7 – 2.7 μm in the top layers to 0.3 – 0.4 μm in the bottom layers.

In terms of biological properties, viability of biomass was found to decrease with biofilm depth (Zhang et al., 1994; Zhang et al., 2001). It was found that the ratio of viable cells to total biomass decrease from 72 – 91 % in the top layers to 31 – 39 % in the bottom layers (Zhang et al., 1994). This was attributed to the fact that the foremost layer of a biofilm is exposed to a higher concentration of substrate than the inner layer (Zhang et al., 2001), while the mass transfer limitations on the substrates would limit the growth of microorganisms in the inner region.

Many of the factors that contribute to the heterogeneity in the structure and properties of biofilms can have significant impact on particle UV disinfection kinetics – EPS yield, density, porosity, pore size and biomass viability. It is therefore no surprise that several different particle types with different UV disinfection kinetics could have existed within each sieve size fraction. The resulting DRC would then be the sum of the disinfection kinetics of

all the particles. For example, the double-exponential kinetics of effluent could simply be the result of the co-existence of particles from the top and bottom biofilm layers; the gentler tailing region could be caused by the denser and less porous particles from the inner regions. At present, there is still a lack of understanding that relates trickling filter particle disinfection kinetics to the particle structure. This would require more investigation, which was beyond the scope of the discussion.

b) Comparison of Model Parameters With Activated Sludge Particles

Figure 5.5 shows the average DRC's obtained for the trickling filter particles against those of the activated sludge particles (previously presented in Chapter 3). From the graph, the DRC of the 32 – 45 μm and 53 – 63 μm size fractions for both types of particles were very similar, with identical tailing level and only slight differences in their initial slopes. However, in the case of the 90 – 106 μm size fraction, the trickling filter particles showed a significantly greater UV resistance; the tailing level was approximately half a log higher than that of the activated sludge particles, which translated into 3 times greater UV resistance. This difference could be attributed to the differences in the porosity of these particles. It has been shown that porosity of activated sludge particles tend to increase drastically with particle size for particles smaller than 200 μm (Li et al., 1987). Higher porosity translates to reduction in shielding effects and therefore lower UV resistance.

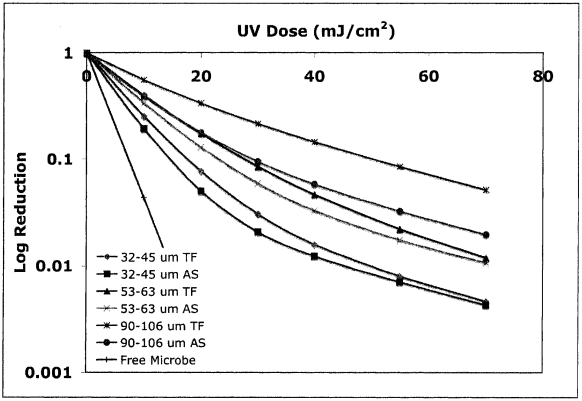

Figure 5.5. Comparison between the average DRC of trickling filter and activated sludge particles for the different size fractions tested.

The average values for the UV disinfection kinetic parameters for trickling filter effluents were determined through non-linear regression analysis, and compared with those of the activated sludge particles as shown in Table 5.1. Trends in the values of k_1, k_2 and β were consistent with earlier observations regarding the shape of DRCs. k_1 for trickling filter were slightly smaller in magnitude than that of the activated sludge particles as a result of the gentler initial slope, while values of k_2 were similar for all three size fractions. β for trickling filter particles in the 90 – 106 μm fraction were found to be more than double of that of the activated sludge particles .

The main difference, however, occurred in the values of fraction of viable particles, p. The p values for the trickling filter particles were obtained using the procedure described in chapter 3. It was found that p value for trickling filter particles was 2-3 time greater than corresponding activated sludge particles. The higher viability in trickling filter particle was

expected given the high biomass viability observed in biofilms by researchers (Zhang et al., 1994).

Table 5.1. Comparison between the UV inactivation model parameters of trickling filter and activated sludge particles for the 3 size fractions tested.

	32-45 um		53-63 um		90-106 um	
	AS	TF	AS	TF	AS	TF
k_1	-0.177	-0.149	-0.119	-0.105	-0.112	-0.0885
k_2	-0.0327	-0.0360	-0.0286	-0.0359	-0.0305	-0.0307
ß	0.0426	0.0583	0.0778	0.136	0.163	0.390
p	0.0550	0.126	0.0614	0.191	0.222	0.685

Based on the above results, the tailing propensity (TP), as discussed in Chapter 3, can be calculated from Equation 3.3. TP value provides a quantification of the overall impact of wastewater particles on the formation of UV disinfection tailing. Values of TP were calculated for the trickling filter size fractions and compared with that of the activated sludge size fractions, and the results are displayed in Figure 5.6.

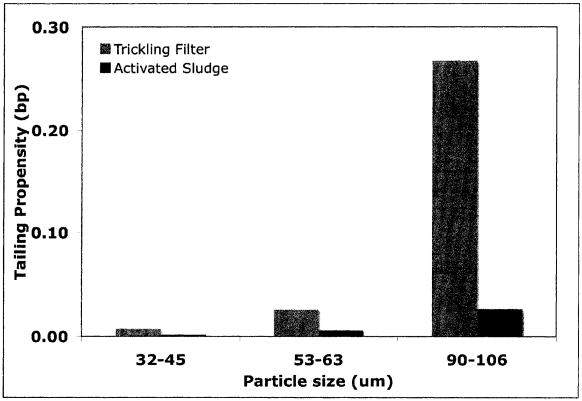

Figure 5.6. Comparisons of values of TP between trickling filter and activated sludge particles.

The TP values for trickling filter particles were 0.00737, 0.0259 and 0.267 for the 32 – 45 μm, 53 – 63 μm and 90 – 106 μm, respectively. This suggests that as much as a quarter of all particles in the 90 – 106 μm range could result in a CFU count at the tailing region of DRC for trickling filter effluents. Moreover, TP values of trickling filter particle fractions were 4-10 times greater than that of the activated sludge fractions, and this difference increased drastically with particle size.

The result therefore showed that the poorer disinfection performance encountered in trickling filter effluents are likely the result of higher TP values in trickling filter particles, as opposed to the poorer settleability of the particles as previously thought. In fact, this is further evident from the PSD and DRC of trickling filter and activated sludge effluents, as depicted in Figures 5.7 and 5.8 respectively.

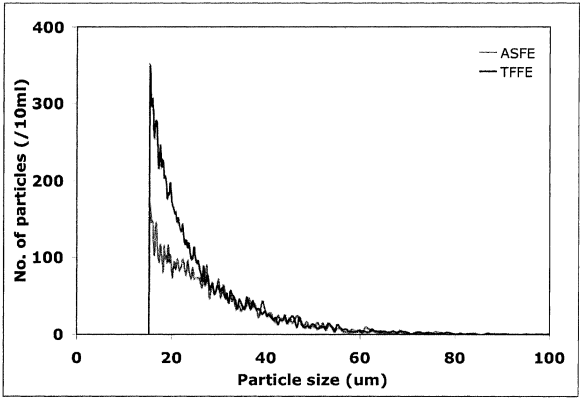

Figure 5.7. Comparison of PSD between a trickling filter and activated sludge secondary effluent.

Comparing the two effluent samples, the total particle count in the trickling filter effluent was almost double that of the activated sludge sample for particles smaller than 30 μm. Although both effluents had very similar number of particle greater than 30 μm, the DRC for these samples were vastly different as shown in Figure 5.8. The CFU count for the trickling filter sample was about 30 times that of the activated sludge sample at low UV doses of zero and 10 mJ/cm^2. This could suggest the presence of a significantly larger amount of free microbes in the trickling filter effluent; the larger amount of small particles in the trickling filter effluent and their higher percentage viability could only partially account for the difference. More importantly, the tailing level of the trickling effluent was found to be about 10 times that of the activated sludge sample. This results support earlier conclusions that the higher TP value is mainly responsible for being the cause of poorer disinfection performance in trickling filter effluent. In fact, the difference in tailing level was in the same order of magnitude as the differences in the TP values for the 53 – 63 μm and 90 – 106 μm size fractions.

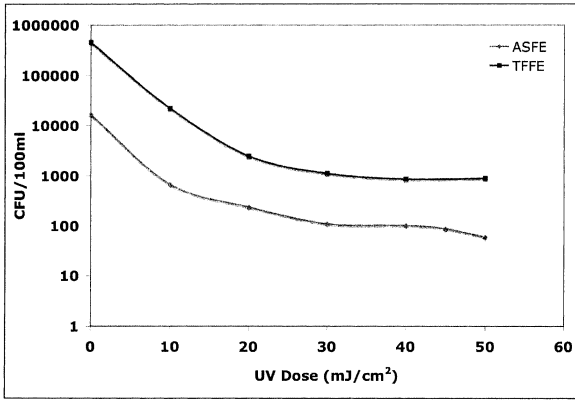

Figure 5.8. Comparison of DRC between a trickling filter and activated sludge secondary effluent.

5.4 Conclusion

The undesirable UV disinfection performance encountered in trickling filter effluent has often been attributed to the poor settleability of its particles. In this paper, the UV disinfection of trickling filter effluent was examined at the particle level, by quantifying the disinfection kinetics of trickling filter particle according to their size. The results showed that the critical particle size lied within the size range of 45 to 53 μm, above which particles will show significant tendency in causing UV disinfection tailing. The DRC for all the particle size fractions tested also showed that trickling filter particles follow a double-exponent inactivation model. There was a strong positive relationship between particle size and UV resistance – the log inactivations at the tailing region were approximately 2 log, 1.5 log and 1 log for the 32 – 45 μm, 53 – 63 μm and 90 – 106 μm size fractions respectively. Comparison with the DRC of activated sludge particles reviewed strong similarity in the general trends of the UV response, apart from the 90 – 106 μm size fraction, which showed a much greater tailing level. Moreover, a much greater percentage of trickling filter particles were viable in

all of the size fractions. This translated to a significantly larger propensity for UV disinfection tailing, as measured by the TP values. It was therefore concluded that the high TP values is the cause for the poor UV disinfection performance experienced in trickling filter effluent. This was further supported by a comparative study on the disinfection performance of trickling filter and activated sludge secondary effluent. The results showed that the tailing level in the trickling filter effluent was 10 times that of the activated sludge sample, despite having the same number of particles greater than 50 μm.

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Chapter 6 Conclusion and Future Work

6.1 Conclusion

The findings of this research can be summarized as follow:

- Particles greater than the size range of 45 – 53 μm are most accountable for UV DRC tailing. By pre-filtering secondary effluent with 32 μm and 75 μm sieves, DRC tailing was found to be reduced by as much as 95% and 80%, respectively. The implication is that upstream filtration for improving UV disinfection would not need to target removal of particles down to the size of 10 μm as suggested in previous researches.

- UV DRC of fractionated wastewater particles was found to show 2 distinct gradient regions. A double-exponential model was used to describe this kinetics:

$$\frac{N}{N_0} = (1-\beta)e^{-k_1 D} + \beta e^{-k_2 D}$$

where k_1 and k_2 are the first-order inactivation rate constant for UV-susceptible and UV-resistant particles, respectively, and β represents the fraction of UV resistant particles.

- Contrary to previous suggestions that all particles greater than the size of 10 μm possess equal UV resistance, UV disinfection kinetics exhibited an inverse relationship with particle size. Gradient of initial slope decreased for larger size fractions, while the DRC tailed at a much higher level. A new parameter termed tailing propensity was introduced to quantify the likelihood of a particle surviving high UV irradiation, and it was found that the tailing propensity of particles within the largest size fraction was 90 times that of the smallest fraction.

- UV disinfection performance of secondary effluent from activated sludge system was found to follow an 'additivity rule', i.e. the overall disinfection performance is the sum of the disinfection of all its particulate constituents. By using data of particle disinfection kinetics collected, it was possible to calculate the disinfection performance of an effluent

sample within reasonable accuracy, using the information on the effluent particle-size distribution. This result suggests that changes in effluent PSD and particle count were mainly responsible for the day-to-day fluctuations in effluent UV disinfection performance. More importantly, it highlights the possibility of creating a procedure that allows for a quick and real time prediction of UV disinfection performance.

- In comparing the UV disinfection kinetics of particles from activated sludge and trickling filter processes, strong similarity in the general trends of the DRC was observed, apart from the 90 – 106 μm size fraction in the latter treatment process, which showed a much greater tailing level. Yet, trickling filter particles exhibited a much higher tailing propensity across all size fractions, owing to the significantly higher particle viability. As a result, secondary effluents from trickling filter processes displayed much poorer UV disinfectability compared to that from activated sludge processes, even when the large-particle concentrations are similar.

6.2 Future Work

Several areas have been identified for potential continuation of the existing work and are discussed as follow:

- The whole methodology of concentrating wastewater particles into narrow size fractions and testing their disinfection kinetics could be extended to chemical disinfectant. The chemical disinfectant chosen will be one that could form hydroxyl radicals under UV exposure, and possible candidates include ozone, hydrogen peroxide and peracetic acid (PAA). Studies have demonstrated the increase in disinfection power when UV is applied to both ozone and PAA (Koivunen et al., 2005; Lubello et al., 2002; Magbanua Jr. et al., 2005), and pilot plant studies have shown that by applying PAA upstream of UV disinfection, the Title 22 requirements could be met (Caretti et al., 2002).

- The work so far has indicated that the presence of UV resistant particles is responsible for the UV DRC tailing. A more fundamental understanding on the structure of the resistant particles could potentially shed some light on how to control wastewater treatment processes to minimize the formation of UV resistant flocs. The hypothesis is that disinfection tailing is due to the presence of a dense inner core in wastewater flocs. This could be tested by isolating the dense cores through shearing away of the loose outer layer of flocs, and testing and comparing their disinfectability to un-sheared particles of the same size. In addition, bench-scale simulations could be set up to test the effect of various treatment operating parameters on the formation of the dense cores and the resulting UV disinfection performance of the effluent.

- Part of the work could be aimed at addressing one problem encountered in modeling wastewater disinfection performance – the fluctuations in disinfection kinetics from day to day. Given the myriad conditions in a biological system, it is not feasible to introduce parameters into the model to account for the fluctuations. The objective is therefore to qualitatively observe the trends in the fluctuations, in order to understand how they are affected by plant parameters. Wastewater samples will be regularly obtained from treatment plant, and the particle UV disinfection kinetics determined using the protocol developed. Together with information on plant operating parameters such as SRT, coagulant usage, and flow rate, Multivariate analysis could be use to understand the relationship between plant operating conditions and the magnitude of the disinfection kinetics. The results could possibly be used to substantiate the hypothesis on the origin and formation of UV disinfection tailing. More importantly, it can help in the prediction of UV disinfection performance by correlating plant operating parameters and disinfection kinetics.

- Finally, the limitation of the work in Chapter 5 could be addressed. The samples collected and compared were from 2 different treatment plants, with wastewater influent from different regions. Although the results obtained were conclusive in comparing and accounting for the differences in disinfection performance between activated sludge and trickling filter treatment, part of the differences could have been attributed to site-specific

factors. Hence, a further extension of the work would be to obtain samples from different treatment systems, but from the same treatment site. This could also be extended to comparing other effluents such as primary and secondary effluent disinfectability.

6.3 Reference

1 Caretti, C., Lubello, C. (2002). Wastewater disinfection with PAA and UV combined treatment: a pilot plant study. *Water Research*, Vol. 37, pp. 2365-2371

2 Koivunen, J., Heinonen-Tanski, H. (2005). Peracetic acid (PAA) disinfection of primary, secondary, and tertiary treated municipal wastewaters. *Water Research*, Vol. 39, pp. 4445-4453

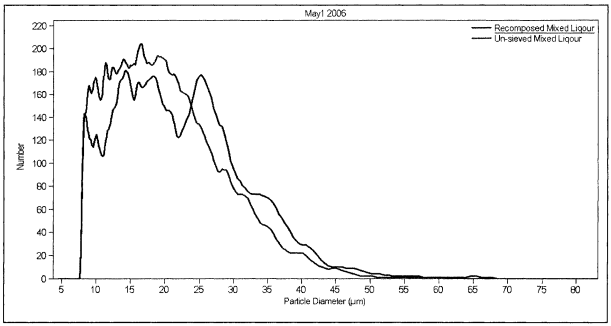
3 Lubello, C., Caretti, C., Gori, R. (2002). Comparison between PAA/UV and H_2O_2/UV disinfection for wastewater reuse. *Water Science and Technology: Water Supply*, Vol. 2, pp. 205-212

4 Magbanua Jr., B. S., Savant G., Truax, D. D. (2005). Combined ozone and ultraviolet inactivation of *Escherichia coli*. *Journal of Environmental Science and Health Part A*, Vol. 41, pp. 1043-1055

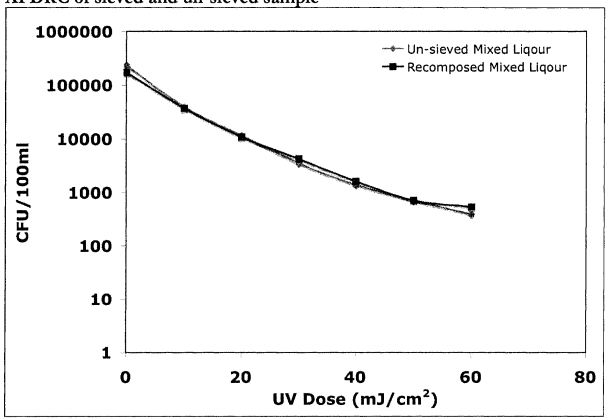
APPENDICES

Appendix A Effects of Sieving on Particle Properties

A1 PSD of sieved and un-sieved sample

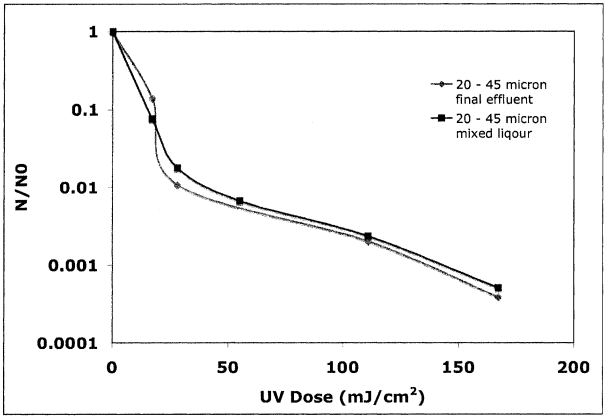


A1 DRC of sieved and un-sieved sample



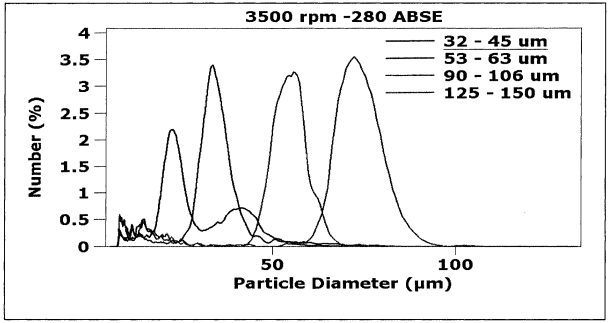
Appendix B Comparison of Disinfection Kinetics of Particles From Mixed Liquor and Secondary Effluent

DRC for 20-45 μm size fraction sieved from mixed liquor and secondary effluent

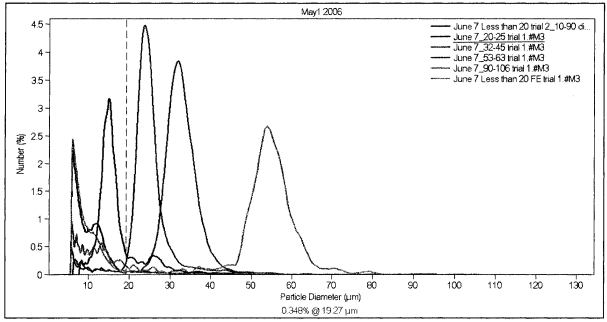


Appendix C Sample Sieving PSD

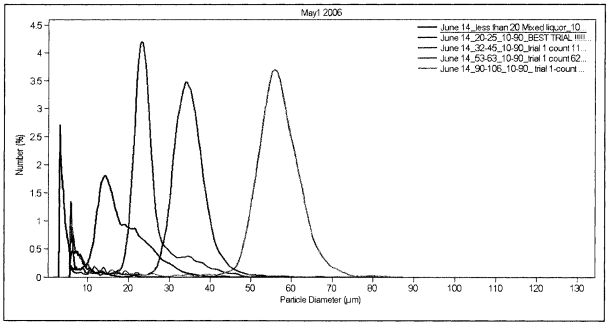
Jan 26th, 2006 Ashbridges' Bay activated sludge mixed liquor sample



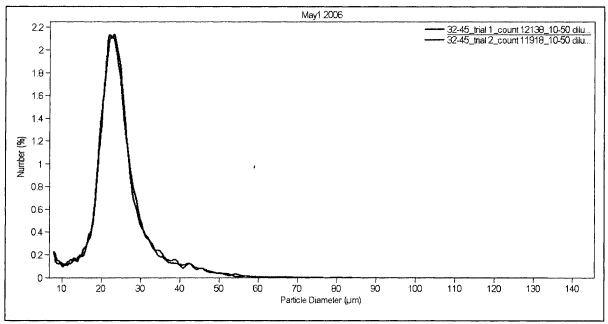
June 7th, 2006 Ashbridges' Bay activated sludge mixed liquor sample



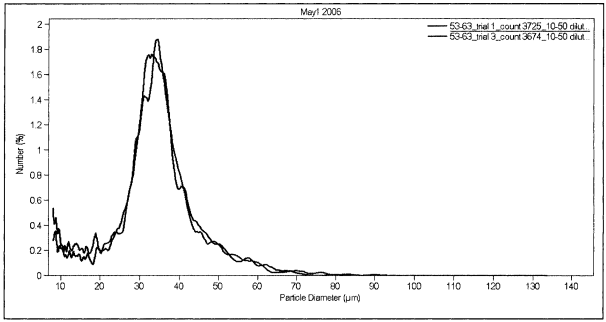
June 14th Ashbridges' Bay activated sludge mixed liquor sample



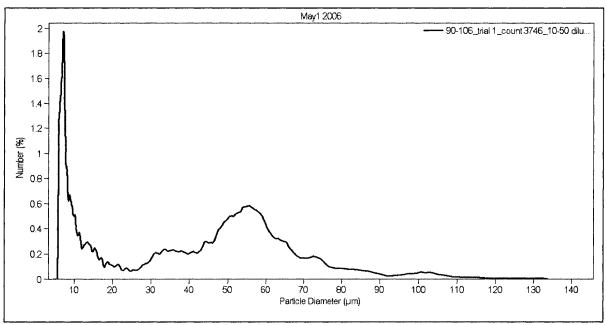
Aug 14th, 2006 Oshawa Trickling Filter sample (32-45 µm)



Aug 14th, 2006 Oshawa Trickling Filter sample (53-63 μm)



Aug 14th, 2006 Oshawa Trickling Filter sample (90-106 μm)



Appendix D UV Bioassay Results

D1 Mixed liquor from Ashbridges' Bay WWTP

Sep 21st, 2005 Ashbridges' Bay Mixed Liquor

20-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	33000	1.00000
1	19000	0.57576
5	18000	0.54545
10	5600	0.16970
20	1525	0.04621
30	310	0.00939
40	205	0.00621
80	67.5	0.00205

53-63um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	61000	1.00000
1	40000	0.65574
5	26750	0.43852
10	16600	0.27213
20	5700	0.09344
30	1410	0.02311
40	815	0.01336
80	400	0.00656

90-106um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	42250	1.00000
1	54500	1.28994
5	33700	0.79763
10	20350	0.48166
20	9025	0.21361
30	3050	0.07219
40	1835	0.04343
80	557.5	0.01320

Sep 26th, 2005 Ashbridges' Bay Mixed Liquor

20-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	107000	1.00000
5	59750	0.55841
10	11400	0.10654
20	1425	0.01332
30	370	0.00346

40	142.5	0.00133
80	22.5	0.00021

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	28750	1.00000
5	19400	0.67478
10	9700	0.33739
20	3900	0.13565
30	1210	0.04209
40	590	0.02052
80	190	0.00661

Oct 12th, 2005 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	100000	1.0000
10	18300	0.1830
20	4510	0.0451
30	2500	0.0250
40	1792.5	0.0179
60	795	0.0080
70	585	0.0059

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	31750	1.0000
10	12000	0.3780
20	4100	0.1291
30	2070	0.0652
40	970	0.0306
60	255	0.0080
70	265	0.0083

Oct 20th, 2005 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	31750	1.0000
10	5000	0.1493
20	415	0.0124
30	162.5	0.0049
40	57.5	0.0017
60	27.5	0.0008
70	2.5	0.0001

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	33500	1.0000
10	9800	0.2925
20	2400	0.0716
30	2250	0.0672
40	990	0.0296
60	330	0.0099
70	255	0.0076

Oct 24th, 2005 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	85250	1.0000
10	15600	0.1830
20	1110	0.0130
30	400	0.0047
40	670	0.0079
60	300	0.0035
70	87.5	0.0010

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	23750	1.0000
10	10700	0.4505
20	4475	0.1884
30	2380	0.1002
40	1410	0.0594
60	570	0.0240
70	462.5	0.0195

Oct 26th, 2005 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	30000	1.0000
10	5350	0.1783
20	420	0.0140
30	115	0.0038
40	187.5	0.0063
60	110	0.0037
70	50	0.0017

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	33500	1.0000
10	9400	0.2806
20	3150	0.0940

30	1280	0.0382
40	720	0.0215
60	455	0.0136
70	242.5	0.0072

Nov 24th, 2005 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	78500	1.00000
10	14500	0.18471
20	1880	0.02395
30	635	0.00809
40	328	0.00417
60	123	0.00156
70	78	0.00099

90-106um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	51500	1.00000
10	21000	0.40777
20	5650	0.10971
30	3083	0.05987
40	1830	0.03553
60	715	0.01388
70	478	0.00927

Nov 25th, 2005 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	108965	1.00000
10	13554	0.12439
20	2340	0.02147
30	900	0.00826
40	558	0.00512
60	338	0.00310
70	240	0.00220

90-106um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	50680	1.00000
10	16865	0.33277
20	5450	0.10754
30	2610	0.05150
40	1560	0.03078
60	548	0.01080
70	413	0.00814

Jan 26th, 2006 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	8700	1.00000
5	4100	0.47126
10	2020	0.23218
20	720	0.08276

53-63um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	20063	1.00000
5	13800	0.68785
10	9350	0.46604
20	3780	0.18841

75-90um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	32250	1.00000
5	28250	0.87597
10	9500	0.29457
20	5550	0.17209

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	24500	1.00000
5	20500	0.83673
10	18333	0.74830
20	6400	0.26122

125-150um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	26000	1.00000
5	22500	0.86538
10	13667	0.52564
20	7800	0.30000

32-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	51750	1.00000
10	16500	0.31884
20	10300	0.19903
30	4350	0.08406
40	2700	0.05217
60	1095	0.02116
70	840	0.01623

Feb 7th, 2006 Ashbridges' Bay Mixed Liquor

20-32um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	2317	1.0000
5	2000	0.8632
10	890	0.3841
20	325	0.1403

32-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	23800	1.0000
5	13725	0.5767
10	7750	0.3256
20	2743	0.1152

53-63um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	8050	1.0000
5	5150	0.6398
10	3838	0.4767
20	1458	0.1811

75-90um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	17250	1.0000
5	12800	0.7420
10	6683	0.3874
20	3156	0.1830

90-106um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	2550	1.0000
5	1517	0.5948
10	1310	0.5137
20	467	0.1830

125-150um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	15175	1.0000
10	7450	0.4909
20	3850	0.2537

30	2017	0.1329
40	1460	0.0962
60	898	0.0591
70	660	0.0435

20-125um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	31063	1.0000
10	11100	0.3573
20	4333	0.1395
30	2688	0.0865
40	1850	0.0596
60	695	0.0224
70	570	0.0184

Mar 2nd, 2006 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	14000	1.0000
20	1740	0.1243
40	663	0.0473
60	343	0.0245
70	315	0.0225

53-63um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	5875	1.0000
10	2300	0.3915
20	1350	0.2298
30	810	0.1379
40	565	0.0962
60	290	0.0494
70	168	0.0285

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	6750	1.0000
10	3650	0.5407
20	2500	0.3704
30	1575	0.2333
40	1050	0.1556
60	515	0.0763
70	468	0.0693

Mar 2nd, 2006 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	19000	1.0000
10	5700	0.3000
20	2040	0.1074
30	895	0.0471
40	630	0.0332
60	185	0.0097
70	130	0.0068

53-63um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	11350	1.0000
10	4500	0.3965
20	2300	0.2026
30	1220	0.1075
40	715	0.0630
60	390	0.0344
70	353	0.0311

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	9125	1.0000
10	4750	0.5205
20	2467	0.2703
30	1450	0.1589
40	1056	0.1158
60	507	0.0555
70	243	0.0266

Apr 6th, 2006 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	140333	1.0000
10	19975	0.1423
20	4380	0.0312
30	1460	0.0104
40	588	0.0042
50	405	0.0029
60	325	0.0023

53-63um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	91475	1.0000
10	18633	0.2037

20	5400	0.0590
30	2670	0.0292
40	1190	0.0130
50	720	0.0079
60	458	0.0050

May 18th, 2006 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	214750	1.0000
10	46700	0.2175
20	9733	0.0453
30	2260	0.0105
40	2310	0.0108
60	960	0.0045
70	383	0.0018

53-63um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	14500	1.0000
10	6350	0.4379
20	2117	0.1460
30	720	0.0497
40	350	0.0241
60	145	0.0100
70	120	0.0083

90-106um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	60800	1.0000
10	24100	0.3964
20	8125	0.1336
30	3590	0.0590
40	1925	0.0317
60	1173	0.0193
70	730	0.0120

Jun 7th, 2006 Ashbridges' Bay Mixed Liquor

20-25um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	23333	1.0000

10	3600	0.1543
20	980	0.0420
30	185	0.0079
40	90	0.0039
50	83	0.0035
60	45	0.0019

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	61000	1.0000
10	16167	0.2650
20	3050	0.0500
30	1150	0.0189
40	305	0.0050
50	190	0.0031
60	115	0.0019

53-63um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	38167	1.0000
10	14100	0.3694
20	4250	0.1114
30	1760	0.0461
40	590	0.0155
50	275	0.0072
60	148	0.0039

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	10250	1.0000
20	2317	0.2260
30	1640	0.1600
40	975	0.0951
50	615	0.0600
60	415	0.0405

Jun 14th, 2006 Ashbridges' Bay Mixed Liquor

20-25um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	14375	1.0000
10	2600	0.1809
20	650	0.0452
30	85	0.0059
40	135	0.0094
55	38	0.0026
70	23	0.0016

32-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	24250	1.0000
10	6333	0.2612
20	1850	0.0763
30	900	0.0371
40	438	0.0180
55	300	0.0124
70	163	0.0067

53-63um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	18375	1.0000
10	5600	0.3048
20	2100	0.1143
30	710	0.0386
40	415	0.0226
55	280	0.0152
70	160	0.0087

90-106um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	54500	1.0000
10	24167	0.4434
20	11200	0.2055
30	6125	0.1124
40	3383	0.0621
55	1500	0.0275
70	1064	0.0195

Jun 21st, 2006 Ashbridges' Bay Mixed Liquor

20-25um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	20250	1.0000
10	3600	0.1778
20	1480	0.0731
30	728	0.0359
40	480	0.0237
55	225	0.0111
70	130	0.0064

32-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	22000	1.0000
10	6300	0.2864
20	3025	0.1375
30	1600	0.0727

40	845	0.0384
55	588	0.0267
70	428	0.0194

53-63um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	24583	1.0000
10	9000	0.3661
20	3975	0.1617
30	2095	0.0852
40	1090	0.0443
55	603	0.0245
70	370	0.0151

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	18167	1.0000
10	8800	0.4844
20	4475	0.2463
30	2600	0.1431
40	1800	0.0991
55	1080	0.0594
70	673	0.0370

Jul 20st, 2006 Ashbridges' Bay Mixed Liquor

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	229250	1.0000
10	46900	0.2046
20	11663	0.0509
30	3856	0.0168
40	1948	0.0085
55	1333	0.0058
70	878	0.0038

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	80688	1.0000
10	33600	0.4164
20	19050	0.2361
30	9600	0.1190
40	5840	0.0724
55	2360	0.0292
70	1440	0.0178

D2 Secondary effluent from Oshawa Trickling Filter WWTP

Jul 11th Oshawa Trickling Filter sample

<32um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	144750	1.0000
10	2470	0.0171
20	538	0.0037
30	270	0.0019
40	105	0.0007
45	33	0.0002
50	23	0.0002

32-45um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	4600	1.0000
10	1275	0.2772
20	323	0.0701
30	123	0.0266
40	100	0.0217
55	45	0.0098
70	23	0.0049

53-63um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	16250	1.0000
10	6325	0.3892
20	2130	0.1311
30	1093	0.0673
40	740	0.0455
55	203	0.0125
70	135	0.0083

90-106um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	6575	1.0000
40	340	0.0517
55	268	0.0407

Jul 24th Oshawa Trickling Filter sample

<32um

UV Dose (mJ/cm²)	CFU/100ml	Log Reduction
0	308000	1.0000
10	9325	0.0303

20	538	0.0017
30	148	0.0005
40	90	0.0003
45	40	0.0001
50	13	0.0000

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	36350	1.0000
20	2285	0.0629
30	840	0.0231
40	488	0.0134
55	253	0.0069
70	153	0.0042

53-63um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	9300	1.0000
10	4400	0.4731
20	1688	0.1815
30	1050	0.1129
40	415	0.0446
55	113	0.0121
70	73	0.0078

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	14850	1.0000
20	6150	0.4141
30	2740	0.1845
40	1856	0.1250
55	850	0.0572
70	493	0.0332

Aug 14th Oshawa Trickling Filter sample

<32um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	219000	1.0000
10	10850	0.0495
20	530	0.0024
30	485	0.0022
40	135	0.0006
55	63	0.0003
60	40	0.0002

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction

0	60333	1.0000
10	14200	0.2354
20	3780	0.0627
30	1280	0.0212
40	830	0.0138
55	418	0.0069
70	298	0.0049

53-63um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	33750	1.0000
10	17675	0.5237
20	5930	0.1757
30	3260	0.0966
40	1753	0.0519
55	1300	0.0385
70	558	0.0165

90-106um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	33900	1.0000
10	16250	0.4794
20	11225	0.3311
30	5870	0.1732
40	5421	0.1599
70	2003	0.0591

Aug 22nd Oshawa Trickling Filter sample

<32um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	50350	1.0000
10	16150	0.3208
20	380	0.0075
30	215	0.0043
40	108	0.0021
45	95	0.0019
50	55	0.0011

32-45um

UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	70500	1.0000
10	19550	0.2773
20	4517	0.0641
30	1564	0.0222
40	670	0.0095
55	363	0.0051
70	130	0.0018

53-63um

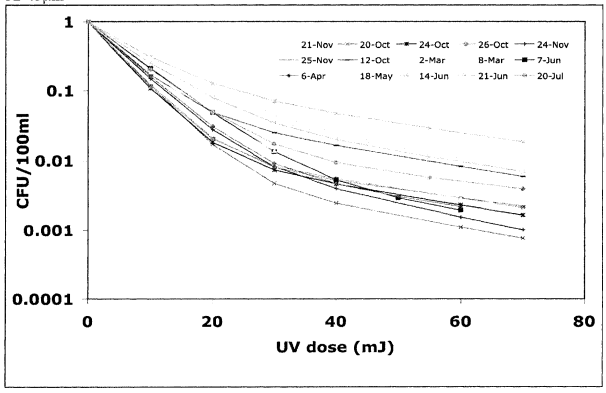
UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	71750	1.0000
10	28100	0.3916
20	12425	0.1732
30	7838	0.1092
40	3621	0.0505
55	1945	0.0271
70	1070	0.0149

90-106um

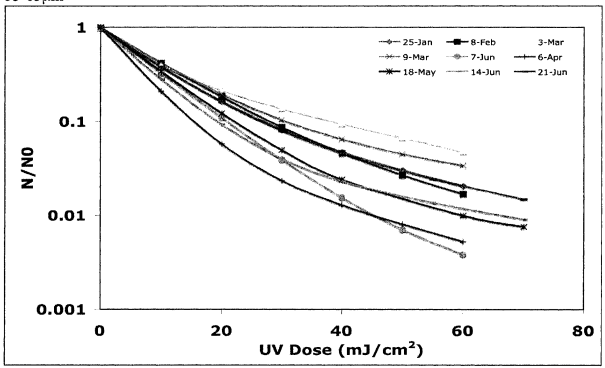
UV Dose (mJ/cm^2)	CFU/100ml	Log Reduction
0	54000	1.0000
10	29600	0.5481
20	20500	0.3796
30	15050	0.2787
40	7250	0.1343
55	5790	0.1072
70	3315	0.0614

D3 DRC of all size fractions from Ashbridges' Bay sample

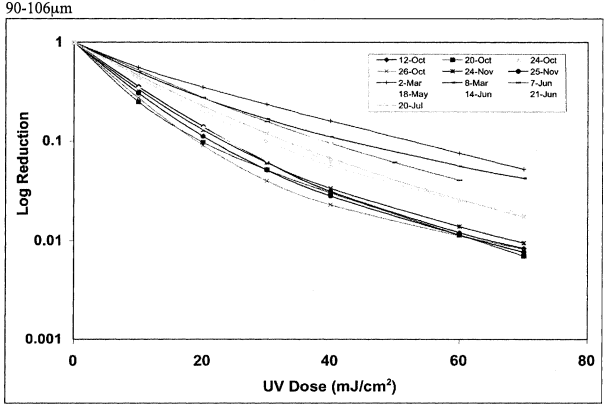
32-45μm



53-63μm

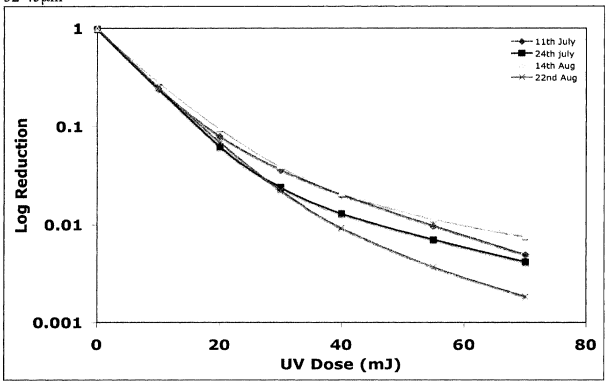


90-106μm

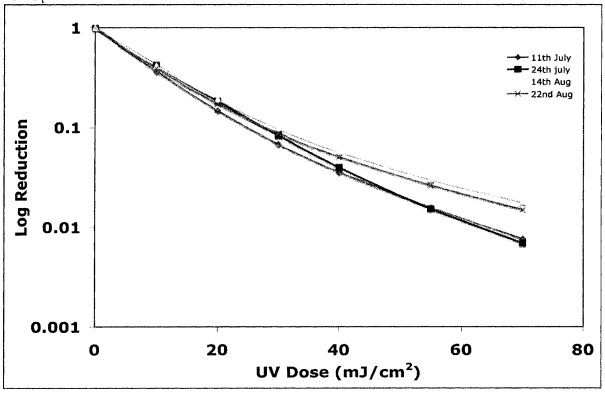


D4 DRC of all size fractions from Oshawa Trickling Filter sample

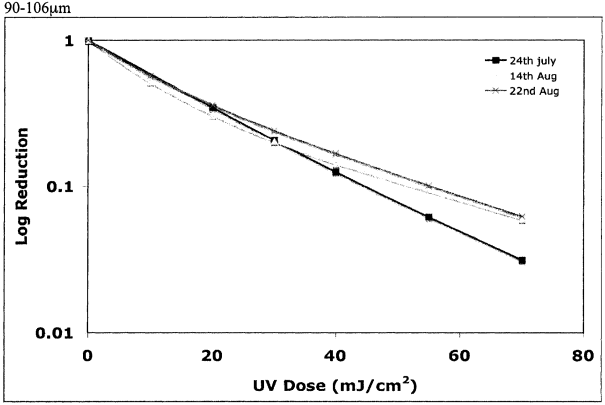
32-45μm



53-63μm



90-106μm



Appendix E Regression of Disinfection Kinetics

E1 Mathematica Regression code

<<Statistics`NonlinearFit`

data={{0, 1}, {10, -0.9377969}, {20,-1.4706015}, {30, -1.9814271}, {40, -2.3416356}, {60,-3.0085804}}

NonlinearRegress[data,Log[(1-b) Exp[-k1 x]+b Exp[-k2 x]],x, {{b, 0, 1},{k1, 0.1, 0.6}, {k2, 0.01, 0.06}}]

E2 Regression results for all Ashbridges' Bay sample

32-45μm

Date	β	k1	k2
12-Oct	0.0640	-0.201	-0.0342
20-Oct	0.0099	-0.219	-0.0365
24-Oct	0.0175	-0.233	-0.0338
26-Oct	0.0183	-0.226	-0.0309
21-Nov	0.0631	-0.145	-0.0297

24-Nov	0.0194	-0.196	-0.0423
25-Nov	0.0148	-0.218	-0.0272
24-Jan	0.0682	-0.162	–
7-Feb	0.0478	-0.117	–
2-Mar	0.1582	-0.153	-0.0312
8-Mar	0.0769	-0.133	-0.0384
6-Apr	0.0140	-0.187	-0.0310
18-May	0.0262	-0.174	-0.0373
7-Jun	0.0117	-0.157	-0.0307
14-Jun	0.0617	-0.150	-0.0313
21-Jun	0.1473	-0.145	-0.0297
20-Jul	0.0211	-0.164	-0.0242

53-63μm

Date	β	**k1**	**k2**
24-Jan	0.139	-0.112	–
7-Feb	0.100	-0.097	–
2-Mar	0.369	-0.151	-0.0337
8-Mar	0.110	-0.099	-0.0208
6-Apr	0.061	-0.171	-0.0409
18-May	0.030	-0.112	-0.0203
7-Jun	0.017	-0.114	-0.0303
14-Jun	0.052	-0.136	-0.0248
21-Jun	0.112	-0.109	-0.0292

90-106 μm

Date	β	**k1**	**k2**
12-Oct	0.068	-0.110	-0.0307
20-Oct	0.122	-0.167	-0.0403
24-Oct	0.071	-0.091	-0.0202
26-Oct	0.064	-0.142	-0.0294
24-Nov	0.118	-0.125	-0.0363
25-Nov	0.113	-0.135	-0.0387
24-Jan	0.379	-0.090	-
7-Feb	0.271	-0.138	-
2-Mar	0.723	-0.155	-0.0377
8-Mar	0.269	-0.091	-0.0271
18-May	0.074	-0.116	-0.0252
7-Jun	0.213	-0.079	-0.0308
14-Jun	0.121	-0.092	-0.0272
21-Jun	0.243	-0.098	-0.0271
20-Jul	0.161	-0.088	-0.0335

E2 Regression results for all Oshawa Trickling Filter sample

32-45 μm

Date	b	k1	k2
jul 11th	0.1154	-0.165	-0.0450
jul 24th	0.0431	-0.159	-0.0333
aug 14th	0.0416	-0.130	-0.0242
aug 22nd	0.0333	-0.144	-0.0416

53-63μm

Date	b	k1	k2
jul 11th	0.1695	-0.1175	-0.0447
jul 24th	0.0533	-0.0899	-0.0333
aug 14th	0.1518	-0.1019	-0.0309
aug 22nd	0.1688	-0.1120	-0.0349

90-106μm

Date	b	k1	k2
jul 24th	0.201	-0.0601	-0.0333
aug 14th	0.395	-0.1026	-0.0271
aug 22nd	0.574	-0.1028	-0.0318

Appendix F Prediction of Secondary Effluent DRC

Mar 23rd, 2006 Ashbridges' Bay secondary effluent

UV Dose (mJ/cm²)	Actual	Prediction Average	Prediction Max	Prediction Min
0	76000	76000	76000	76000
5	8300	14524	15194	13996
10	1030	3157	3746	2736
20	163	383	703	191
30	88	148	325	50
40	70	83	191	26
60	35	37	86	11

Mar 24th, 2006 Ashbridges' Bay secondary effluent

UV Dose (mJ/cm²)	Actual	Prediction Average	Prediction Max	Prediction Min
0	57250	57250	57250	57250
5	10200	11042	11625	10586
10	1040	2446	2953	2086
20	255	310	580	149
30	123	119	267	39
40	80	67	156	20
60	63	30	70	9

Mar 24th, 2006 Ashbridges' Bay secondary effluent 32μm pre-sieved

			Prediction	
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	72250	72250	72250	72250
10	770	2545	2761	2395
20	35	167	275	105
30	14	45	101	15
40	8	24	58	7
60	4	11	26	3

Mar 24th, 2006 Ashbridges' Bay secondary effluent 75μm pre-sieved

			Prediction	
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	56750	56750	56750	56750
10	1140	2189	2515	1962
20	145	199	358	106
30	50	65	149	21
40	21	36	86	10
50	16	23	56	6

Apr 5th, 2006 Ashbridges' Bay secondary effluent

			Prediction	
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	336250	336250	336250	336250
5	43950	60408	60824	60084
10	4400	11075	11427	10825
20	418	505	684	398
30	233	88	185	36
40	113	45	104	14
50	88	29	68	9

Apr 6th, 2006 Ashbridges' Bay secondary effluent

			Prediction	
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	201000	201000	201000	201000
10	2167	6760	7078	6533
15	570	1384	1619	1232
20	215	362	531	260
30	115	82	175	31
50	60	28	65	8

Apr 26th, 2006 Ashbridges' Bay secondary effluent

			Prediction	
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	95500	95500	95500	95500
10	2530	3672	4201	3301
20	633	332	591	180
30	343	110	246	36

40	213	61	144	18
45	188	49	116	14
50	100	40	95	11

Apr 26th, 2006 Ashbridges' Bay secondary effluent plus mixed liquor

		Prediction		
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	213125	213125	213125	213125
10	28150	15098	21971	10305
20	7383	3179	6487	1247
30	2330	1322	3049	402
40	950	751	1786	213
45	660	602	1436	168
50	553	493	1178	137

Jun 7th, 2006 Ashbridges' Bay secondary effluent

		Prediction		
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	58250	58250	58250	58250
10	1320	2653	3259	2213
20	345	406	747	194
30	238	171	366	61
40	163	98	219	32
45	95	78	175	26
50	63	64	143	21

Jun 14th, 2006 Ashbridges' Bay secondary effluent

		Prediction		
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	16500	16500	16500	16500
10	680	1366	2022	897
20	240	352	699	143
30	110	159	350	53
40	103	91	208	29
45	88	73	167	23
50	60	59	137	18

Jun 21st, 2006 Ashbridges' Bay secondary effluent

		Prediction		
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	66875	66875	66875	66875
10	1580	2937	3559	2487
20	133	416	764	202
30	75	171	369	60
40	75	97	219	32
45	43	78	176	25
50	48	63	143	20

Jul 24th, Oshawa Activated Sludge secondary effluent

		Prediction		
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	60500	60500	60500	60500
10	5340	2276	2567	2071
20	1238	190	329	107
30	505	60	133	20
40	308	34	78	10
45	208	27	63	8
50	105	22	52	7

Aug 14th, Oshawa Activated Sludge secondary effluent

		Prediction		
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	14500	14500	14500	14500
10	600	767	1019	591
20	95	125	247	54
30	100	50	114	16
40	65	28	67	8
45	53	23	54	6
50	33	19	44	5

Aug 22nd, Oshawa Activated Sludge secondary effluent

		Prediction		
UV Dose (mJ/cm²)	**Actual**	**Average**	**Max**	**Min**
0	16583	16583	16583	16583
10	1465	1070	1512	759
20	480	221	445	90
30	290	93	213	29
40	138	53	125	15
45	183	42	100	12
50	160	34	82	10

Appendix G Number of Coliform Bacteria Per Particle

Mixed liquor sample was sieved into 2 size fractions: 32 – 45 μm and 90 – 106 μm. Sieved samples were then blended at varying RPM and time (Waring Blender), and cultured to enumerate CFU. The ratio of CFU after to before blending was calculated and presented as $N/N_{t=0}$.

32-45μm

18K RPM			22K RPM		
Time (min)	**Average CFU/100ml**	**$N/N_{t=0}$**	**Time (min)**	**Average CFU/100ml**	**$N/N_{t=0}$**
0	98000	1.00	0	98000	1.00
1.5	105750	1.08	0.5	101250	1.03
3	121750	1.24	1	91750	0.94
4.5	118500	1.21	1.5	86500	0.88
6	94250	0.96	2	61250	0.63

90-106μm

18K RPM			22K RPM		
Time (min)	**Average CFU/100ml**	**$N/N_{t=0}$**	**Time (min)**	**Average CFU/100ml**	**$N/N_{t=0}$**
0.0	46650	1.00	0.0	46650	1.00
1.5	84688	1.82	0.5	81188	1.74
3.0	94083	2.02	1.0	128333	2.75
4.5	82083	1.76	1.5	115750	2.48
6.0	62313	1.34	2.0	80938	1.73
			3.0	54250	1.16