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ULTRAVIOLET DISINFECTION OF SECONDARY AND TERTIARY EFFLUENT IN THE MEDITERRANEAN REGION

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ABSTRACT

A study was undertaken to evaluate the efficiency of ultraviolet radiation in disinfecting secondary and tertiary effluents using wastewater from two full scale treatment plants located in the greater Athens area, the one receiving municipal sewage and the other receiving municipal sewage and septage. The effective UV dose for coliform removal, the effects of feedwater characteristics on UV disinfection and the lamp fouling potential were examined. For secondary effluent samples the required UV dose to achieve effluent fecal concentrations of less than 2,000 FC/100 ml varied from 30 to 60 mW-sec/cm^2, depending on the water quality characteristics of the feedwater. High effluent suspended solids significantly increased the UV dose required to achieve adequate disinfection. For tertiary effluent the required UV dose to meet the 2000 FC/100 ml criterion was only 10 mW-sec/cm^2, where as a dose of 40-50 mW-sec/cm^2 was sufficient to achieve effluent coliform concentrations of less than 10 FC/100 ml. The inactivation of coliforms followed first order kinetics for relative low UV doses, with inactivation rates in the 0,107-0,303 cm^2/mW-sec range for secondary effluent and 0,325 cm^2/mW-sec for tertiary effluent. The lamp fouling potential was relatively high and the required lamp cleaning frequency was approximately twice per month. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Coliform inactivation, ultraviolet radiation, wastewater disinfection, wastewater characteristics, lamp fouling potential

INTRODUCTION

Ultraviolet disinfection of treated wastewater has become a viable alternative to chlorination. Gaseous and aqueous chlorination are becoming less favourable due to concerns over potential toxicity and carcinogenicity of chlorination by-products (US EPA, 1986a). In addition reports in the literature suggest that UV dose required to meet coliform effluent limitations achieves better virus inactivation compared to equivalent chlorine dose (Ho *et al.*, 1998; Wolfe, 1990). These factors combined with recent technological advances and design improvements have contributed to an increasing interest in UV radiation as the disinfectant of choice for both secondary effluent and reclaimed wastewater.

The effectiveness of UV radiation is directly related to UV dose absorbed by microorganisms. UV dose (mWatts-sec/cm^2) is defined as UV light intensity (mWatts/cm^2) times the exposure time (seconds). Inactivation of microorganisms can be described by a first order reaction with respect to UV dose (Qualls *et al.*, 1985; EPA 1986b). However, two important deviations from a first order behaviour have been observed (Qualls *et al.*, 1983). First a lag response in microbial inactivation is sometimes obtained at low UV doses attributed to the ability of microorganisms to absorb a substantial UV dose without any apparent decrease in their viability. Second bacteria inactivation appears to decrease at higher UV dose ranges (tailing effect), a phenomenon attributed to the shielding of microorganisms in suspended particles (US EPA, 1986b, Ho *et al.*, 1998).

The most critical wastewater quality parameter generally used in mathematical models describing UV disinfection efficiency is UV transmittance of wastewater at 253.7 nm. Other important water quality parameters that can affect UV disinfection performance include: suspended solids, turbidity, particle size distribution and colour (Darby *et al.*, 1993).

Effluent quality characteristics exhibit significant variation related to wastewater treatment design, sewage collection systems, quantities of industrial wastewater and septage co-treated with municipal wastewater, etc. The scope of this work was to evaluate the efficiency and applicability of UV radiation systems for the disinfection of secondary and tertiary wastewater effluent in the Mediterranean region. The objectives of the research described herein were: 1) to evaluate the efficiency of UV radiation in disinfecting secondary effluents under the operating conditions experienced in the Mediterranean region and to determine the required UV dose to meet secondary effluent standards, 2) to evaluate the effect of wastewater characteristics (turbidity, TSS) on UV disinfection performance, 3) to evaluate the efficiency of UV radiation in disinfecting filtered activated sludge effluent and determine the required UV dose to meet wastewater reclamation standards and 4) to determine the UV lamps fouling characteristics and the required lamp cleaning frequency.

EXPERIMENTAL MATERIAL AND METHODS

Experimental work was conducted using a bench scale and a pilot scale UV disinfection unit, both consisting of low pressure mercury lamps. A collimated UV source was employed to derive dose response curves for a variety of treated unchlorinated wastewaters that included: 1) secondary effluent from Metamorphosis municipal wastewater treatment plant (MWTP) receiving 60% septage and 40% sewage in terms of organic loading, 2) secondary effluent from a lab scale activated sludge system operating on primary effluent from Psyttalia's treatment plant that serves approximately 3,500,000 p.e., 3) combined primary and secondary effluent at ratios ranging from 1:3 to 1:8 and 4) tertiary effluent from a lab scale gravity filter. UV light travelled through a vertical tube and irradiated a 50-ml continuously stirred reactor. The intensity of UV radiation was measured using an International Light IL 1700 radiometer with an SED 240 detector. The average UV intensity was calculated using Beer's Law taking into account the reduction of UV light through the depth of the sample. UV dose was calculated as the product of the UV intensity and the exposure time.

The pilot UV disinfection system (Trojan Technologies Inc.) consisted of a 2,4 m x 15,2 cm x 22,9 cm open stainless steel channel that housed four UV lamps. The pilot unit, operating on secondary effluent from MWTP, was employed to assess the feasibility of using a UV system for secondary effluent disinfection. Like many treatment facilities in Greece, MWTP receives both municipal sewage and septage contributed from approximately 100,000 p.e. The average UV intensity was calculated from the point summation method (PSS) described in the EPA design manual (US EPA, 1986b) according to the UV_{254} transmittance of each sample. The UV intensity was corrected for lamp ageing and loss through quartz sleeves based on data provided by the manufacturer. The UV dose was the product of average intensity and exposure time. The quartz sleeves were hand cleaned with commercial scale-removing solution prior to the conduct of any dose response curves.

Samples were analysed for a variety of water quality characteristics that included turbidity, SS, UV_{254} transmittance of filtered and unfiltered samples and fecal coliform concentrations. All methods were according to the Standards Methods (1992, 18th edition).

RESULTS AND DISCUSSION

Feedwater characteristics

Many wastewater treatment plants lack on-line photometers to monitor UV transmittance continuously; attempts were therefore made to determine any correlation between feedwater transmittance and other wastewater characteristics such as turbidity and suspended solids that can be readily measured. Average water quality characteristics of the various types of feedwaters employed in this study are shown in Table 1. In addition to averages the fifth and ninety-fifth percentile values of each quality parameter were calculated.

Table 1 : Wastewater quality characteristics.

	Turbidity, NTU	Transmittance unfiltered %	Transmittance filtered %	Feedwater FC Concentration CFU/100 ml	TSS, mg/l
Secondary effluent from a lab scale AS unit receiving municipal sewage					
Average	37,5	35,8	55,6	42000	95
Maximum	67,0	44,8	67,4	75500	172
Minimum	10,0	32,2	40,6	22500	24
Secondary effluent from full scale MWTP receiving both municipal sewage and septage					
Average	10,2	38,0	46,4	370,000	20
Maximum	29,0	52,3	62,0	1,920,000	58
Minimum	4,50	28,0	37,7	12,200	2
Filtered activated sludge effluent					
Average	4,1	56,6	58,2	7200	11
Maximum	7,0	67,4	67,9	27000	20
Minimum	2,5	44,7	46,0	450	4
Mixture of primary and secondary effluent					
Average	30,3	34,2	54,8	1.8×10^6	74
Maximum	62,0	49,0	63,8	$16,7 \times 10^6$	166
Minimum	16,0	22,5	45,2	80000	34

Feedwater turbidity exhibited a very good correlation with suspended solids (r^2 = 0,81) as shown in Figure 1. Transmittance did not appear to correlate well with either TSS or turbidity (Figure 2). Only at high turbidity values (> 5-7 NTU) and high suspended solids concentrations (TSS > 20 mg/l) did transmittance correlate well with other water quality parameters. These results are in good agreement with similar findings in the literature (Ho *et al.*, 1998) reporting that on-line turbidity measurements can be a good indicator of significant transmittance decreases during high effluent solids and high turbidity incidents.

UV disinfection performance

Ultraviolet light disinfection of wastewater was evaluated for a range of UV doses from 10-150 mW-sec/cm^2 to determine UV performance for various types of feedwater with different characteristics (Table 1) and unfilered UV transmittance values that ranged from 23% to 67%. Feedwaters tested included secondary effluent, tertiary effluent and mixture of primary and secondary effluent. Disinfection performance was assessed for UV doses ranging from 10-150 mW-sec/cm^2 using the collimated beam and the UV pilot unit. Performance, reported as average and as 95th percentile of fecal coliforms per 100 ml as a function of UV dose, is presented in Figure 3.

Compliance with EC regulations for bathing waters is based partially on fecal coliform data. EC regulation requires that the 95th percentile of effluent samples does not exceed a FC concentration of 2000 FC/100 ml. A horizontal line representing the standard of 2000 FC/100 ml is shown for illustration purposes. The required UV dose to meet the above criterion ranged from 30 to 60 mW-sec/cm^2 depending on the type of secondary effluent. Compliance with the recommended EC criteria for bathing waters of 100 FC/100 ml required higher UV doses equal to 60 and 90 mW-sec/cm^2 for the full scale and the lab scale secondary effluents respectively. The higher UV disinfection performance obtained with samples from the full scale MWTP was attributed to its lower particulate matter; effluent SS concentrations averaged 11 mg/l versus 95 mg/l for the lab scale effluent.

A significant decrease in UV disinfection efficiency was obtained with samples that contained a mixture of primary and secondary effluent at ratios ranging from 1:8 - 1:3. For fecal coliforms the typical criterion of not exceeding 2000 FC/100 ml was met consistently in samples exposed to a UV dose of 100 mW-sec/cm^2 or greater. These results illustrate the problems of implementing UV disinfection in facilities treating combined sewer. In case of storm events when secondary treatment is maximised primary effluent bypassing the biological treatment and secondary effluent are usually mixed prior to disinfection. A UV disinfection system sized to meet effluent criteria under these conditions will be over-designed resulting in a significant additional capital cost.

Sand filtration increased UV disinfection performance significantly. Suspended solids concentration and turbidity were greatly reduced by filtration followed by a correspondingly significant increase in UV unfiltered transmittance. Average filtered and unfiltered transmittance were approximately equal, indicating that the larger part of UV absorbance by particulate matter can be removed by sand filtration. Compliance with the EC regulations for bathing waters of 2000 FC/100 ml required UV doses not greater than 10 mW-sec/cm^2.

Compliance with many countries' wastewater reuse criteria is also partially based on effluent fecal coliform concentrations. A standard of 10 FC/100 ml was met consistently in sand-filtered effluent samples exposed to a UV dose of 40-50 mW-sec/cm^2.

Curves of log survival of FC versus UV dose

The average FC dose response results for both secondary and tertiary effluents are shown in Figure 4. UV inactivation of bacteria in the ideal case of plug flow conditions and uniform UV exposure, can be described by the following expression (US EPA, 1986b; Scheible, 1987):

$$Nt = N_o \exp(-kIt) + N_p$$

where N_t = bacterial density after exposure to UV (FC/100 ml)
N_o = initial bacterial density (FC/100 ml)

k = inactivation rate constant (cm^2/mW-sec)
I = the intensity of UV radiation (mW/cm^2)
t = exposure time (sec)
N_p = bacterial density associated with particulate matter (FC/100 ml)

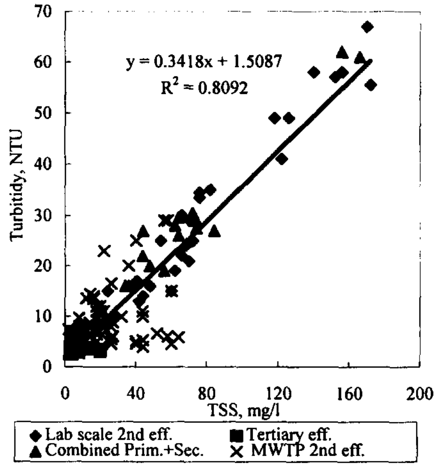

Figure 1. Feedwater turbidity vs. suspended solids concentration.

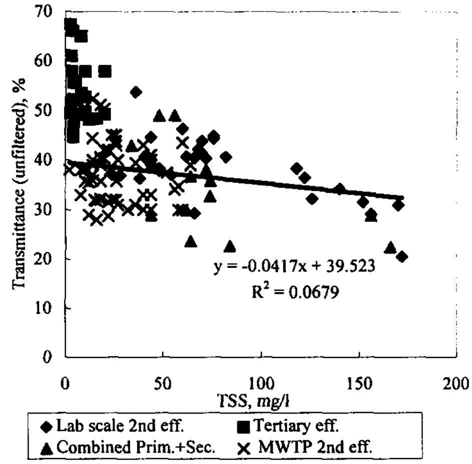

Figure 2. Unfitered transmittance vs.suspended solids concentration.

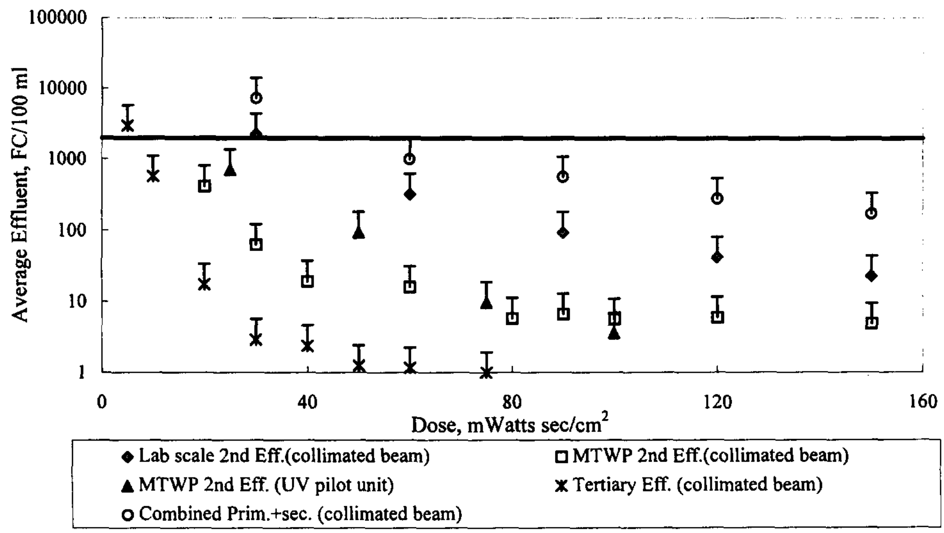

Figure 3. Fecal colifom dose response curves for various types of feedwater.

As shown in Figure 4 the experimental results appear to follow the general trend expressed by the above equation. The inactivation curves show a linear portion at low UV doses with a slope equal to the inactivation rate, followed by a gradual flattening at higher UV doses often attributed to particulate matter. To eliminate the effect of particulate matter that can protect embedded microbes from UV radiation, only data obtained at lower UV doses (< 60 mW-sec/cm^2) were used for linear regression to calculate inactivation rate constants. The inactivation rate constants ranged from 0.107 - 0.325 (cm^2/mW-sec), depending on the quality of the feedwater. The inactivation rate determined for tertiary effluent samples was approximately 2,5 times greater than the inactivation rates determined for secondary effluent samples indicating that occlusion of bacteria in particulate matter can significantly impair UV disinfection performance. These results are in good agreement with the values reported in the literature (US EPA, 1986b) that range from 0.067-0.38 (cm^2/mW-sec).

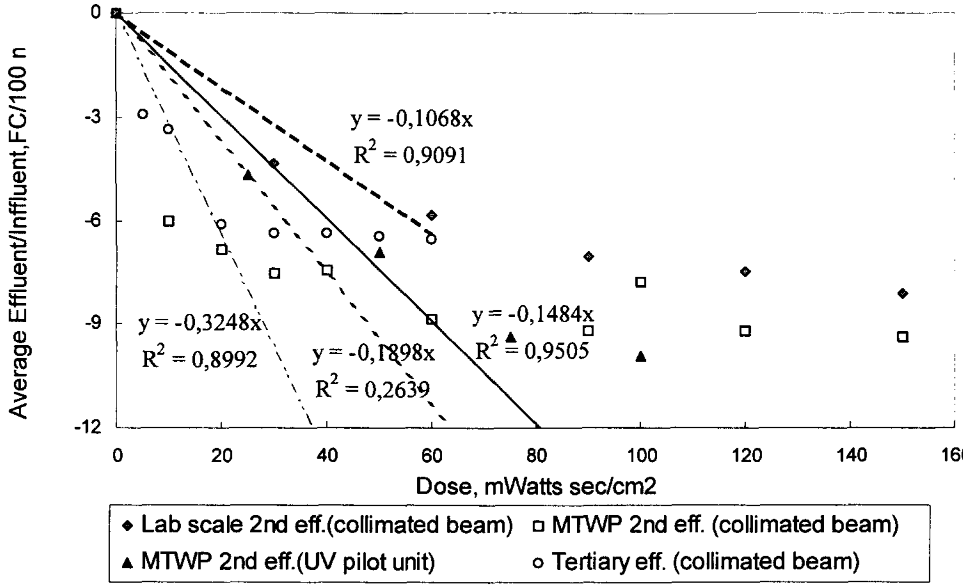

Figure 4. Evaluation of FC inactivation rates for secondary and tertiary effluent.

Effect of particulate matter on UV disinfection performance

As described previously, survivals encountered for the secondary effluent samples from the lab scale unit were higher than the effluent samples from the full scale MWTP, due to the higher particulate content of the former. In order to evaluate the effect of particulate matter on UV disinfection efficiency in a more quantitative way, UV disinfection performance was determined using secondary effluent samples spiked with mixed liquor suspended solids. Feedwater samples were divided into four groups according to their suspended solids content: 0-50 mg/l, 50-100 mg/l, 100-150 mg/l and 150-200 mg/l (Figure 5). The results illustrate that increasing solids concentration causes a decrease in UV disinfection efficiency. In order to describe the correlation between suspended solids concentration and bacterial population resistant to UV light radiation, the following expression has been proposed (Scheible, 1987):

$$N_p = a\,(TSS)^b$$

where Np = bacteria associated with particulate matter (FC/100 ml)

At high UV doses the residual effluent FC coliform should be attributed to bacteria occluded in particulate matter. The above relationship was applied for effluent coliform data obtained at high UV doses (> 90 mW-sec/cm^2). As indicated by a low correlation coefficient (r^2 = 0.16) the residual FC did not appear to show a strong correlation with effluent particulate matter. Similar results have been reported in the literature (Ho *et al.*, 1998), where no strong correlation was obtained between effluent FC and particulate matter.

Lamp Fouling

The lamp fouling characteristics and the required cleaning frequency were determined using the pilot UV unit operating on secondary effluent from the full scale MWTP that received domestic sewage and septage. The UV dose was maintained at approximately 75 mW-sec/cm^2, a dose that according to the dose response study was found to provide adequate disinfection and effluent coliform concentrations of less than 100 CFU/100 ml. For each run the unit was hand-cleaned thoroughly with commercially available scale removal cleaners and thereafter kept in operation without cleaning till the effluent fecal coliform concentration consistently exceeded the FC criterion of 2000 CFU/100 ml. In order to evaluate the percent decrease in UV disinfection due to fouling effluent inactivation data were correlated to inactivation data obtained using a collimated beam. In all three consecutive runs a significant increase in effluent FC concentrations was obtained after 12-14 days have elapsed from cleaning the lamps (Figure 6). The fouling characteristics of the feedwater employed appeared to be higher than the average cleaning frequency of approximately once per month, reported in the literature (EPA, 1992).

Inactivation data were used to construct the UV lamp fouling curves presented in Figure 6. Lamp fouling appeared to follow an S-type curve. Initially there was a period of time where no decrease in UV disinfection was observed indicating the absence of any biological or chemical fouling. Following this period UV performance decreased dramatically till after approximately 20 days of operation that UV disinfection system failed completely. This type of behaviour resembles chemical precipitation kinetics: the initial period represents the time required for nucleation followed by the formation of a precipitate. The inorganic nature of the fouling material was also supported by chemical analysis of the fouling material that revealed a high Ca content of approximately 10% on a dry solids basis and high hardness values of secondary effluent (average hardness approximately 235 mg/l as $CaCO_3$).

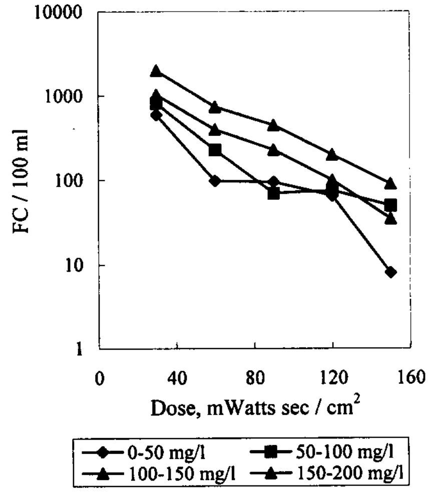

Figure 5. Effect of suspended solids on effluent FC concentration.

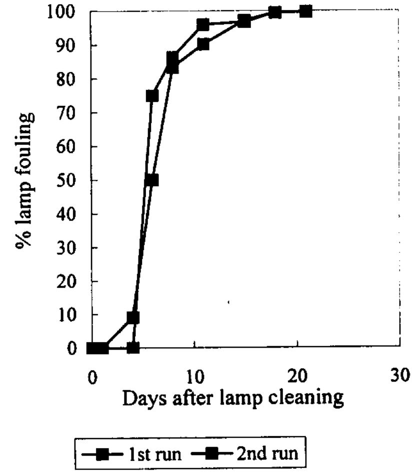

Figure 6. Percent fouling as a function of elapsed time after lamp cleaning.

CONCLUSIONS

- Wastewater quality parameters such as turbidity and suspended solids appear to have some weak correlation with UV_{254} transmittance: high suspended solids concentrations and turbidities were associated with low UV_{254} transmittance values. Only at high turbidities (> 5-7 NTU) and high suspended solids concentrations (TSS > 20 mg/l) did transmittance correlate well with other water quality parameters.

- Inactivation of bacteria by UV radiation appears to follow first order reaction kinetics with inactivation rates in the 0.107-0.303 cm^2/mW-sec range, for secondary effluent samples and 0.325 cm^2/mW-sec for tertiary effluent samples.
- Secondary effluent quality, as characterised by TSS levels significantly affected UV disinfection. Particulate matter appears to provide some degree of protection to bacteria associated with suspended solids. Attempts to correlate the residual fecal coliform concentration at high UV doses with TSS concentrations were not successful.
- Filtration of secondary effluent significantly improved UV disinfection efficiency by removing most of the bacteria associated with suspended matter and significantly increasing UV transmittance. Additionally, filtration appears to provide a buffer to any large fluctuations of feedwater quality caused by plant upsets or by variations of the incoming sewage and septage.
- The required UV dose to meet the EC criterion for bathing waters of 2000 FC/100 ml, ranged from 30-60 mW-sec/cm^2 depending on the type of secondary effluent. Sand-filtered effluent samples required a UV dose of 10 mW-sec/cm^2 to meet the EC criterion for bathing waters and 40-50 mW-sec/cm^2 to meet a reuse standard of 10 FC/100 ml.
- Unfiltered or filtered transmittance values obtained during the present study were 30-40% lower than the values reported in the literature for secondary or tertiary effluents. This significant difference could be attributed to the combined domestic sewer and sewage treatment provided at MWTP and to potentially large quantities of industrial wastewater discharged into the municipal sewerage.
- Lamp fouling potential appeared to be high with a required lamp cleaning frequency of twice per month. Due to the high calcium content of the fouling material, quartz jacket coating was mostly attributed to inorganic scale formation.

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