Wastewater disinfection by low-pressure UV and ozone: a design approach based on water quality

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Abstract Disinfection processes are known to be very sensitive to wastewater quality. This paper discusses the parameters that impact the UV light (UV) and ozone disinfection processes and the related mechanisms based on literature review. Low-pressure UV and ozone technologies were investigated on effluents that covered a wide range of water quality. The results are given in terms of design doses required to meet three major disinfection standards. Both processes were found eligible for the majority of effluents tested. Although cost-effectiveness is usually considered more favourable to UV, the ozone alternative should be examined in cases such as the disinfection of low-quality effluents or large treatment plants. Ozonation was also found capable of meeting the stringent Title 22 standard with no coagulation at a dose of 10 mg/l.

Keywords Ozone; process design; regulations; ultraviolet; wastewater disinfection; wastewater quality

Introduction

Although wastewater disinfection has been in practice for years, the choice of disinfectant is rarely obvious because of advances in technology and of evolution in regulations. Chlorination with gaseous chlorine or bleach has been the reference until the mid-eighties, most plants in service being in the US. Since then, alternative disinfectants have emerged, UV (low-pressure, medium-pressure) and ozone being the most referenced. Other processes are also being considered (chlorine dioxide, chloramines, membranes, pulsed UV) or are being developed (excimer lamps, pulsed electric fields).

There are several factors influencing the disinfection of micro-organisms, and they can be more or less difficult to assess on an individual basis. For example, the physiological state of micro-organisms (function of growth stage and previous environmental conditions) remains uncontrollable in field conditions. Other factors include the type of disinfectant and the engineering around its implementation, the type and strain of micro-organism and water quality. Moreover, full-scale implementation dictates site-specific constraints such as the permit requirements (indicator micro-organism, removal or residual concentrations, by-products), flow rates and fluctuations, area available, costs, etc.

The focus of this paper is the influence of wastewater quality on disinfection performances of UV irradiation and ozonation. The water quality parameters that significantly impact these advanced processes are presented and discussed. Field tests were performed to evaluate the feasibility of UV and ozone on a broad water quality range. A discussion is made to link water quality to disinfection efficiency and thereby feasibility with respect to existing regulations.

Basic water quality parameters for the evaluation of UV and ozone disinfection

The qualitative impact of relevant wastewater constituents or bulk parameters on UV and ozone treatment processes is presented in Table 1 and discussed hereafter.

pH

Molecular ozone will self-decompose into radicals in the presence of hydroxyl ions. This could affect disinfection because reactions involving radicals are faster but less selective

Table 1 Qualitative impact of wastewater quality parameters on UV and ozone treatment processes

Quality Parameter	Impacts of wastewater quality UV disinfection Efficiency*	UV disinfection Fouling	Ozonation Efficiency
1) pH	–	–	–
2) Temperature	+	–	+
3) UV transmittance	+++	+	+
4) Particles			
Particle count	+++	–	+++
TSS	+++	–	+++
Turbidity	+++	–	++
5) Dissolved organic matter			
COD	++	+	++
BOD_5	++	+	++
TOC – DOC	++	+	++
6) Dissolved inorganic matter			
Iron III	++	+++	–
Iron II	–	–	+
Manganese	+	–	+
Hardness	–	++	–
Alkalinity	–	+	+
Nitrites	+	–	+
Bromide	–	–	+
Chlorine	+	–	+
7) Grease	+	+++	+

–: no impact; +, ++, +++: small, medium and strong impact
*: with clean lamps

than molecular reactions. Disinfection with molecular ozone is known to be more effective than with radicals, but the effect of pH can be considered as non-existent in the range 6–8 (Evison 1977, Farooq 1977).

Temperature

Low-pressure lamps are effective energy-wise and operate at small wall temperatures (50 to 200°C for conventional and high output technologies). This can make them sensitive to variations of the effluent temperature in terms of UVC output. However, most systems today feature lamps that are stable with wastewater temperature. The effluent temperature will not impact fouling of these lamps either because their operating temperature range remains low.

Although negligible in the vast majority of climates, the effect of temperature on ozonation may be considered in extreme conditions. At low temperatures, the kinetics of the reactions involving molecular ozone might be affected. At high temperatures, the mass-transfer of gaseous ozone to water will be reduced. Finally, high temperature will promote ozone self-decomposition (AWWARF/CGE, 1991).

UV transmittance

The passage of light through wastewater is affected by the presence of some dissolved compounds and by the presence of particles. Particulate matter can absorb light partly or totally, and/or scatter it. Light availability (irradiance) in the reactor is crucial for UV disinfection in the sense that it governs the dose delivered by the system. Because of the presence of particles that may scatter light out of the detectors reach in a conventional spectrophotometer, it is recommended to measure UV transmittance by spectrophotometry with an integration sphere, or by actinometry. Yet, these methods require special equipment. In USEPA (1986), an empirical formula is given that corrects the deviations of a conventional spectrophotometer when the purpose is the estimation of doses in reactors with low-pressure lamps (1):

$$T = \exp\left[-0.6 * \left(\left(-\ln\ T_{\text{unfiltered}}\right)^{0.64}\right)\right] \tag{1}$$

T: Corrected transmittance, to be used for the calculation of doses
$T_{\text{unfiltered}}$: Transmittance of raw sample

This correction can be used with reasonable error in a large range of transmittance values. In the case of medium-pressure lamps, the estimation of dose is more complex because the germicidal dose is delivered over a variety of wavelengths. This issue is discussed in Havelaar *et al.* (1990) and Linden (1997). In the ozonation process, unfiltered UV transmittance can be linked with process efficiency because most light absorbers will also contribute to the ozone demand.

Particles

Particles not only consume disinfectant (UV light or ozone), but they also can embed micro-organisms and protect them. In a first approximation, the effect of particles is a function of their quantity, which can be measured with a particle counter. If this apparatus is not available, TSS or turbidity can be used, with some restrictions. TSS gives the total mass of particles, but does not give a number of particles so it does not correlate with the number of colonies that will be counted on a culture media. On the other hand, the size of particles that provoke turbidity might not be in accordance with the particle size range critical for disinfection (viruses, bacteria).

Using DNA probes, Emerick *et al.* (1998) quantified the number of particles with embedded coliform bacteria in particular effluents. This method is believed to be more adequate to quantify disinfectant shielding by particles, but still belongs to the research field. Another outcome of his work was the assessment of the particle size above which coliform bacteria may be embedded (10 µm).

Dissolved organic and inorganic matter

The parameters listed in these categories impact disinfection mainly because they compete with micro-organisms for disinfectant. At 254 nm, many dissolved organics absorb radiation, especially those with conjugated rings. Similarly, dissolved inorganics such as ferric ions, nitrites, bromine, manganese, sulphates are strong absorbers at that wavelength. Industries like textile, food processing, paper or pharmaceutical processes also produce wastes with low UV transmittance. Other dissolved constituents contribute to fouling, such as hardness and ferric ions. In the same way, the ozone demand increases in case of high organic contents, ferrous ions, chloride, bromide or manganese, some of them also being radicals promoters (WPCF, 1996). Alkalinity scavenges radicals and therefore promote molecular ozone reactions and disinfection (Sobsey, 1989).

Although the parameters discussed previously are known to have the greatest impact on treatments, the efforts to correlate in quantitative manner disinfection efficiency with any combination of these parameters have turned unsatisfactory. Empirical or semi-empirical formulae have been used, but they are site-specific and include constants that need to be determined with laboratory or field tests. Therefore, sole water quality data can not be used to predict process efficiency when accuracy is required and pilot testing remains necessary.

Materials and methods

Pilot scale or full-scale installations were used to estimate the impact of water quality on process efficiency. UV disinfection with clean lamps was evaluated in several reactors of the same type – open channels with vertical lamps (Table 2). Critical components of reactor geometry, as well as hydraulic loading ranges, were kept identical from one site to another. The hydraulic characteristics had been optimised with deflectors after a research program involving numerical modelling (Janex *et al.*, 1998a, Chiu *et al.*, 1999). The fouling frequency and lamp cleaning (labor cost evaluation) were not the purpose of the study and were not investigated.

For the ozonation tests, bubble-column pilots (volume: 10, 35 or 185 litres) of similar design were also used on several sites in France and in England.

All pilots were built to simulate full-scale processes, with near plug-flow conditions. The disinfection performances were evaluated with influent and effluent samples at different conditions (liquid and gas flow rates, ozone gas concentration).

Physico-chemical parameters were measured using Standard methods. Several microbiological parameters were investigated, but for clarity, this paper only presents the disinfection efficiency on the basis of the results obtained with faecal coliform or *E.coli* bacteria. They were analysed by standard filtration methods, except in the case of primary effluent (Evry I), where an MPN method with microplates was used because the high particle content. Based on these results, the pilot efficiency was investigated for each effluent or class of wastewater.

Wastewater quality

The characteristics of the effluents used for the UV and ozonation studies are given in Table 3. For the parameters that were monitored, the water quality was globally equivalent in Indianapolis and in Staunton WWTP. Considering their destination (disposal in a receiving stream), both can be described as “high quality secondary effluents”. Although there was no tertiary filtration in Staunton, the particle content of the matrix was remarkably low, probably because of the good quality of the plant influent and good clarification. Therefore, the Staunton effluent was considered in that study as “equivalent to a tertiary effluent”. On the other hand, the secondary effluent at Washington WWTP was low-quality for all parameters monitored, with a great variability in the data.

Bacteria counts in Evry I and in Washington effluents were closer than expected. This result should be taken with care because of the difference in the microbiological analytical methods.

Results and discussion

Disinfection performances with UV and ozone

The fecal coliform concentration after UV is represented in Figure 1 as a function of the UV dose, calculated with the UV-DIS (USEPA 1986) program and Equation 1. Initial concentrations (N_0) were calculated as the geometric mean between the different tests. Fast disinfection kinetics were observed in the effluents from Indianapolis and Staunton. Total removal of fecal coliforms occurred at doses lower than 40 mJ/cm^{2}m. On the other hand, residual coliforms counts remained high in the effluent at Washington despite large dosages.

Table 2 Reactors used for the evaluation of UV disinfection

Location	**Indianapolis (USA)**	**Staunton (USA)**	**Washington (UK)**
Reactor type	pilot	full-scale	pilot
Number of modules	1	1	2
Number of lamps	20	40	40
Type of lamps	low-pressure	low-pressure	low-pressure, high output

Table 3 Characterisation of wastewater quality for the UV tests

Location		Indianapolis (USA)		Staunton (USA)	Evry II (France)	Washington (UK)		Evry I (France)
Treatment		Tertiary : bio-roughing (C+N), AS (C+N), multi-media filtration		secondary : OD (C)	secondary : AS (C+N)	AS (C+N) AS (C+N)		AS (C+N)
Sludge age (days)		8–15		–	15	2		NA
Loading (kg BOD / kg VSS.d)		extended aeration 0.03		–	extended aeration 0.09	medium load (0.39)		NA
Nature of test		UV	Ozone	UV	Ozone	UV	Ozone	ozone
pH	average	7.0	7.0	7.6	–	7.4	7.5	7.6
	min–max	6.9–7.4	6.9–7.2	7.3–7.8	–	7.0–7.7	7.4–8	7.4–7.8
$T_{unfiltered}$ (%)	average	–	–	78.2	62.2	45	45	–
	min–max	–	–	58.4–81.3	60–67	30–59	31–55	–
$T_{filtered}$ (%)	average	67.6	70.0	80.1	65.6	60	–	25.5
	min–max	61.9–70.4	61.9–75	71–82.8	62–72	55–69	–	18.9–36.7
$T_{corrected}$ (%)	average	67.6	–	79.6	–	56.7	–	–
Particle count	average	368	–	–	–	2836	–	–
(# >10 µm/ml)	min–max	77–938	–	–	–	724–4390	–	–
TSS (mg/l)	average	2.9	2.3	2 5	14	18	100	
	min–max	2–4	<1–4	<2–3	3–6	5–36	7–33	62–123
Turbidity (NTU)	average	1.9	2.0	1.0	–	16	9.2	–
	min–max	1.3–3.2	0.8–3.3	0.7–1.2	–	2–44	1–28	–
COD (mg O_2/l)	average	–	30	10	36	59	71	285
	min–max	–	24–38	<10–18	26–56	39–80	41–150	364–588
BOD_5 (mg O_2/l)	average	7	–	–	<5	7	9	218
	min–max	3–12	–	–	–	4–22	5–24	145–308
DOC (mg/l)	average	–	8.0	4.6	<10	26	24	–
	min–max	–	5.5–10.2	3–8	–	11–72	11–30	–

NA: Not applicable T: Transmittance
AS: Activated sludgeOD: oxidation ditch
(C): Removal of carbon(C+N): Removal of carbon and ammonia

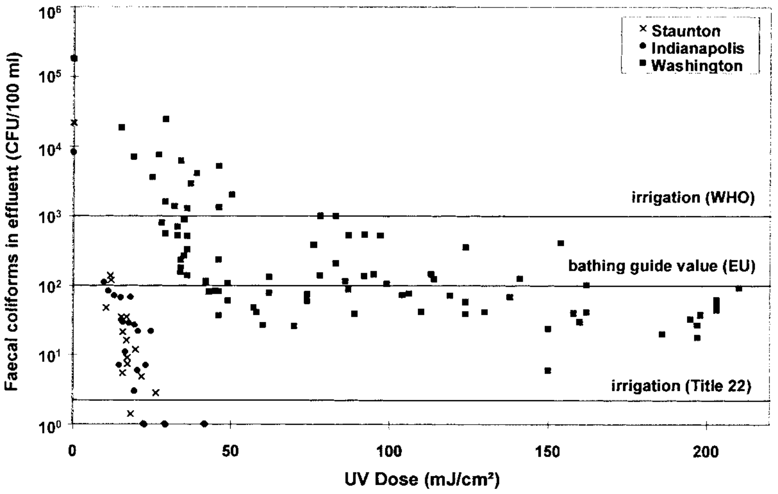

Figure 1 Results of UV disinfection of three different wastewater effluents for three main disinfection objectives

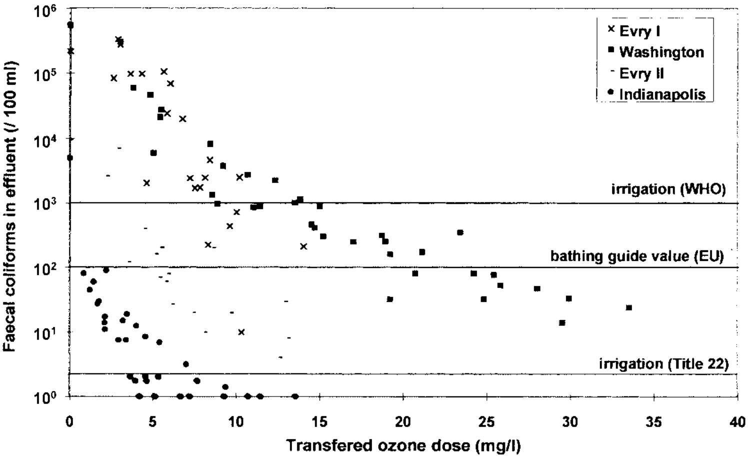

Figure 2 Results of ozone disinfection of different wastewater effluents for three main disinfection objectives

The results of the ozonation tests are presented in Figure 2 in terms of fecal coliforms concentration in the effluent as a function of the transferred ozone dose.

During all these tests, *no influence of contact time was measured* (Janex *et al.*, 1998b). Contact times varied from 2 to 10 minutes for the secondary and tertiary effluents, and from 6.7 to 20 minutes for the primary effluent. The process efficiency was a function of the transferred dose only. This was attributed to the fast reaction kinetics between the coliforms and ozone. Because the disinfection objectives are usually less severe than for drinking water applications, large reductions in contactor volume and costs can be expected.

Compliance with regulations

The results are discussed in terms of achievement of three major disinfection regulations or guidelines. The first one, the 1989 WHO “Health guidelines for the use of wastewater in agriculture and aquaculture”, is the only existing international guidelines for wastewater reuse. It sets a limit for faecal coliforms (FC) in category A effluents equal to 1000 FC/100 ml (geometric mean over the irrigation period). The second guideline is the 1975 European standard for the microbiological quality of surface waters for recreational activities. This regulation sets, among other microbiological indicators, a guide limit for faecal coliforms of 100 FC/100 ml in 80% of the samples (2000 FC/100 ml being the imperative value). The final standard is the Californian Title 22 (1978), which among other limits sets a total coliforms limit of 2.2 MPN/100 ml (7-day median). Reaching that concentration is considered as an aggregation issue, and neither a kinetic nor influent concentration issue. For that reason, conclusions on faecal coliforms for the achievement of Title 22 will be considered as applicable for total coliforms.

The UV and ozone doses found to meet the different standards during the pilot studies are given in Table 4. *UV doses do not take into account lamps fouling and ageing. Design factors of 0.7 each are usually taken for that purpose.* It is also important to stress that design doses should be delivered at peak flow.

Compliance with the 1989 WHO guidelines. The WHO guideline could be achieved successfully on all effluents. Extremely low UV and ozone doses were required on the high-quality effluents (Staunton, Indianapolis). The ozone doses obtained were also low on

Table 4 Minimum doses required to achieve standards compliance, as determined from pilot tests results

	UV dose (mJ/cm?)			Transferred ozone dose (mg/l)		
	WHO*	EU*	Title 22*	WHO*	EU*	Title 22*
Evry I	–	–	–	9	>14	NA
Washington	32	160	NA	14	25	NA
Evry II	–	–	–	5	8	>13
Indianapolis	<10	15	>25	<1	<2	10
Staunton	<10	15	>27	–	–	–

* doses required to achieve WHO 1989, EU 1975 or Title 22 1978
NA: not applicable

the conventional secondary effluent (Evry II), and reasonable even on both low-quality effluents (Washington, Evry I) despite their great differences in water quality.

Compliance with the 1975 EU guidelines. Medium-quality effluents were not investigated with UV because of the number of plants in operation that already provide data on that configuration. The 1975 EU guide values can be considered as slightly more stringent than most US discharge permits in surface waters (100 to 1000 coliforms, geometric mean, achieved with design doses of 25 to 35 mJ/cm^2). Therefore, doses should be superior to 25 mJ/cm^2. The data from Indianapolis and Staunton WWTP show that the UV doses are low when a filtration is added to the treatment. Disinfection to the 1975 EU standard was also possible with UV on the Washington effluent, but a high dose was required. On that effluent, ozonation might be a cost-effective alternative to UV. Finally, ozone could effectively disinfect conventional secondary effluents, as well as high quality effluents.

The dose requirements are quite different between Washington and Evry II secondary effluents. This was attributed to effluent quality. However, sludge age and microorganism physiology may also play an important role. Because of the low sludge age, coliforms in the Washington secondary effluent may have remained in the slime configuration they were in human guts, which would mean increased resistance to disinfection.

Compliance with the 1978 Title 22 regulation. With faecal coliforms concentrations between 10 and 100 after a UV dose of 200 mJ/cm^2, the Washington effluent could not meet the Title 22 standard when treated with UV. This standard also sets requirements on the treatment chain, namely coagulation-flocculation, filtration and disinfection (chlorine or UV). The conditions for meeting consistently Title 22 were not experienced with UV, but ozone data provided a feasible design dose of 10 mg/l with no coagulation.

Relation between wastewater quality and disinfection performances

Disinfection results were classified by distinguishing three categories of water quality, according to the concentration in Total Suspended Solids. These categories are indicated in Table 5.

Measured faecal coliforms removals are represented in Figure 3 for the different categories of effluents. They correspond to UV doses of 20 to 30 mJ/cm^2 and transferred ozone doses of 4 to 6 mg/L respectively. The high difference observed between the categories shows that TSS can be considered as a significant parameter for disinfection, at least in a first approach.

Additional considerations

The comparison between UV and ozone should not be limited to pure disinfection data. Both of these technologies have advantages that have to be taken into account in process

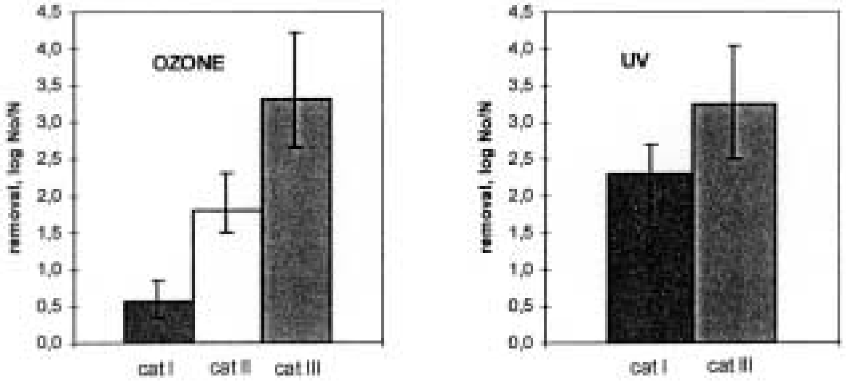

Figure 3 Faecal coliform log removal by ozone (transferred ozone doses between 4 and 6 mg/L) and UV (doses between 20 and 30 mJ/cm^2) for the three categories of wastewater effluents (average, minimum and maximum values)

Table 5 Categories of water quality

Category	Cat. I	Cat. II	Cat. III
TSS range, mg/L	>10	4–7	1–4
Type of effluent	primary effluent, secondary effluent from high load AS or TF*	good quality secondary effluent after extended aeration	tertiary effluent
Location of the WWTP	Washington, Evry I	Evry II	Indianapolis, Staunton

*AS – activated sludge, TF – trickling filters

design. For example, ozone can be produced from pure oxygen, transported in the oxygen stream, and consumed for disinfection. After this first contact with the effluent, the carrier gas can be recycled to the activated sludge to reduce secondary treatment size requirements. Ozone may also be a good alternative when the disinfection of viruses is required because most of them (including enteric viruses) are more sensitive to ozone than coliform bacteria (Janex *et al.*, 1998b). Ozone also removes odour and colour, which would be appreciated for some reuse applications. Ozonation leads also to an increase in the bulk oxygen concentration, as well as to an enhancement of the biodegradability of the residual organic matters.

UV and ozone are both considered as safe processes, but safety measures with UV are more straightforward. The maintenance of an ozone system usually requires more skills than a UV system. Finally, most studies show that UV and ozone will not increase effluent toxicity.

Conclusions

Pilot tests have confirmed the extent of wastewater quality impact on the design of advanced disinfection processes. Suspended solids concentration in the effluent was found to be a critical parameter, and various effluents could be classified according to that parameter in a first approach.

No disinfection process will be the more technically or economically feasible on the whole variety of effluent qualities and discharge permits. Today, UV is considered as the primary disinfectant in the majority of applications. It has proved cost-effective and environmentally friendly in many projects. The results of this study confirmed the efficiency of UV, but pointed out cases when ozonation should be considered as a competitive alternative. The disinfection of low-quality effluents to meet the 1989 WHO an irrigation standard was achieved with ozone doses around 15 mg/l. Also, a stringent regulation such as the Californian Title 22 could be met with filtration only as a tertiary treatment followed by ozonation with a transferred dose of 10 mg/l.

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