Full Length Research Paper

Simulation and characterization of UV reactor for wastewater treatment

Mounaouer Brahmi* and Abdennaceur Hassen

Water Research and Technology Center, BorjCédria Science and Technology Park, P.O. Box 273, Soliman 8020 Tunisia. University Tunis Cartage, Tunisia.

Received 11 March, 2014; Accepted July 14, 2014

Several mathematical models are developed to explain microorganism responses to ultraviolet irradiation. During this study, Pseudomonas aeruginosa was taken as a microorganism model. The experimental results obtained during a batch UV-reactor established that the disinfection kinetics is far from being uniform over the batch. Application of the first-order Chick-Watson model, in its original form or modified form, to validate the speed changes over the disinfection process, does not report any significantly improved results. Application of the Collins-Selleck model fits better the kinetic curves of UV disinfection of wastewater for all the tested strains of P. aeruginosa. At the same time, various continuous alternative reactors are checked, by accounting for the fluid flow hydrodynamics, that is, a perfectly mixing reactor without and with short circuits in the flow stream, or without and with dead zone inside the reactor, a plug flow reactor, and a series of perfectly mixed reactors. The results indicate that the succession of 4 perfectly mixed reactors is the best alternative to the process scale-up.

Key words: Disinfection, hydrodynamics, kinetics model, reactor of disinfection, treated wastewater, UV radiation.

INTRODUCTION

Ultraviolet (UV)-C (short-wavelength ultraviolet) radiation has been projected as one of the successful disinfection practices for water treatment. Thus, UV-disinfection has become a practical solution for the safe disinfection of water.

For many years, chlorination has been the standard method of water disinfection. Chlorine is employed in most water treatment facilities to kill harmful microorganisms that cause severe disease in drinking water (Mohammed and Husam, 2011). Whereas this actually works, the chlorine itself causes several health problems such as asthma, cancer, fertility problems, heart disease, eczema and birth defects. Moreover, the smell and taste of chlorinated water are very unpleasant (Oparaku et al., 2011). Similarly, the residuals and by-products from chlorination may be toxic to aquatic life in the various receiving waters. Some byproducts of chlorination may be carcinogenic and will need removal in a potable treatment plant. It's actually been found that chlorination is significantly less effective in virus destruction than in

*Corresponding author. E-mail: brahmounaouer@yahoo.fr. Tel/Fax: +21679 325 802.

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killing microorganisms. Ultraviolet radiation is presently a preferred method of water disinfection. Actually, UV-disinfection has gained widespread use for municipal effluent and of recent, interest in using ultraviolet radiation for water reuse applications has conjoinly redoubled (Kamani et al., 2006). Ultraviolet light is currently the leading candidate for water disinfection. It has the following inherent advantages over all other disinfection methods: 1. No chemical consumption-eliminates large scale storage, transportation and handling, and potential safety hazards. 2. Low contact time-no contact basin is necessary and space requirements are reduced. 3. No harmful by-products are formed. 4. A minimum of, or no, moving parts - high reliability and low energy requirements” (Brahmi et al., 2013). UV-disinfection therefore solves the environmental and safety problems and is additionally cost-efficient.

Wastewater reuse has been practiced in various forms for decades, with the United States leading the way in reuse research. It is currently a serious issue within the U.S., wherever large areas of the Western and Southern states experience chronic water shortages (Scott and Raschid-Sally, 2012).

UV-disinfection of water employs low-pressure mercury lamps. The lamps generate short-wave UV radiation at 253.7 nm that is lethal to micro-organisms as well as bacteria, protozoa, viruses, molds, yeast, fungi, nematode eggs and algae. The mechanism of micro-organisms destruction is currently believed to be that during which UV causes molecular rearrangements in DNA and RNA, that successively blocks replication (Eccleston, 1998).

UV water purification lamps produce UV-C or germicidal UV, with radiations having much bigger intensities than that of sunlight. The majority of a UV lamp’s output is targeted in a 254 nm region so as to require full advantage that of sunlight. The majority of a UV lamp’s output is UV, with radiations having much bigger intensities than models fairly complex as Collins-Selleck models. This from the simplest model of Chick-Watson of first order to disinfection kinetic models have been proposed in the contaminants from their water supply. homeowners to eliminate a large range of biological effective and economical technology available to contaminants. However, it is probably the foremost cost-compounds (VOCs), heavy metals and other chemical conjointly of the inactivation of strain isolates of UV radiation for effluent disinfection.

<table>
<thead>
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<th>MATERIALS AND METHODS</th>
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**Types and characteristics of treated wastewater used**

The treated wastewater samples used in this study were collected at the outlet of a pilot wastewater treatment plant (WWTP) belonging to the Water Research and Technology Center, Tunisia. The pilot WWTP is connected to the sewerage network of the city of Tunis and has a processing capacity of 150 m³ per day. It is composed of four treatment lines: 1. A trickling filter, 2. rotating biological discs, and 3. a land and lagoon optional filter. Throughout disinfection tests, the physico-chemical characteristics of the wastewater treated by the trickling filter did not show considerable change. The values fluctuated between 47 and 49% for ultraviolet (UV)-C (short-wavelength ultraviolet) light transmission (254 nm), 15 to 47 mg/L for total suspended solids (TSS), 20 to 29 mg/L for biochemical oxygen demand (BOD₅) and 90 to 102 mg/L for chemical oxygen demand (COD).

**Experiments in a batch laboratory irradiation device**

The laboratory UV device used in this study has previously been described by Hassen et al. (1997). This prototype was built with the cooperation of the company Guy Daric S.A (Aubervilliers, France) and contained a sliding rack, with an irradiation board which could receive at the same time six Petri dishes of 90 mm diameter. A low pressure UV-C lamp was used. This lamp emitted an UV-C light of about 7 mW.cm⁻² at wavelengths of 253.7 nm.

**Bacterial strains selected for UV-disinfection study**

A collection of 22 strains of *P. aeruginosastudied were cultivated to a mid-log phase at 37°C in 20 mL of nutrient broth. Each culture was centrifuged at 5,000 rpm/min for 15 min and the pellet was washed twice with sterile distilled water. The washed pellet was resuspended in 10 mL sterile distilled water. Test organisms were then seeded separately, into 20 mL of sterile wastewater with UV transmittance of 50%, to give a viable cell count of approximately a 10⁶ to 10⁷ colony-forming unit (CFU)/mL, the same mean count as that in the secondary wastewater suspension.

All bacterial strains of *P. aeruginosawere irradiated with different UV-C doses and all were conditioned by 7 singular contact times ranging between 2 and 90 s. This collection includes 20 strains (S1 to S20) of clinical origin (Dr C. Fendri, Service of Bacteriology, Hospital of La Rabta, Tunis, Tunisia). Strains 21 and 22 were isolated from the raw wastewater of the pilot plant. All these strains were grown in the laboratory for long periods on a nutrient broth (Institute Pasteur production). These 22 strains were referenced from S1 to S22, respectively. On the other hand, we defined the UV-C dose received by the microbial cells as the product between the time of exposure (Sec) to UV-C and the intensity emitted by the UV lamp (mW.cm⁻²).

**UV pilot equipment**

The study took place in a wastewater treatment pilot plant equipped with a monolamp UV reactor supplied by Katadyn (KatadynProdukte...
AG, Wallisellen, Switzerland). This UV reactor with a useful volume of 2 L and constituted a stainless cylindrical container ran continuously during the study. A low pressure mercury vapor discharge lamp (length = 680 mm, diameter = 18 mm, power of UV emission at 254 nm = 65 W) was inserted into a quartz sleeve for mechanical protection and sealing. Every month, the sleeve was cleaned mechanically with a dilute hydrochloric acid solution to prevent a filthiness of the lamp. A selective detector for UV (253.7 nm) joined to a radiometer (Vilbert- Lourmat, Norme la Vallée, France) allowed the measure of UV intensity at the emerging of the quartz sleeve.

**Calculation of the effective UV dose in the pilot UV system**

UV doses in the irradiation chamber were evaluated using the empirical method recommended by Qualls et al. (1989). This method considers the UV incident intensity, measured on the surface of the quartz sleeve, and the depth of the water layer crossed by UV radiation. Thus, the dose at the area of 1 cm² in the irradiation chamber is set as follows: \( D_c = I_n t_c \), where \( D_c \) is the UV dose calculated at the area of 1 cm², \( I_n \) the UV incident intensity measured on the surface of the quartz sleeve, \( t_c \) the exposure time (s); flow (L.s⁻¹)/ volume of the irradiation chamber (L) as the ratio of UV incident intensity averaged over the surface and the depth of the water layer crossed by UV radiation. Thus, the dose at the area of 1 cm² in the irradiation chamber is set as follows: \( D_c = \frac{I_n t_c}{V/Q} \), where \( D_c \) is the UV dose calculated at the area of 1 cm², \( I_n \) the UV incident intensity measured on the surface of the quartz sleeve, \( t_c \) the exposure time (s); flow (L.s⁻¹)/ volume of the irradiation chamber (L) and \( T_s \) the value of UV transmittance determined in the laboratory according to methods previously described by Hassen et al. (1997) and using a spectrophotometer (UV-visible) with different length quartz vessels and wastewater of various qualities.

**The kinetic models used for UV-C inactivation**

These kinetic approaches are based on experimental studies using: a laboratory disinfection device; 10 selected strains of *P. aeruginosa* grown on a nutrient agar (Pasteur Institute Production, Tunisia); and different simulation models, from the simplest model of Chick-Watson reduced to first-order kinetics, to complex models such as the Collins-Selleck model. The model of Chick-Watson is used primarily to express the kinetics of disinfection with chemical disinfectants (Trussell and Chao, 1977; Hart and Vogiatzis, 1982; Roustan et al., 1991). The first-order kinetics is expressed as follows:

\[
\frac{dN}{dt} = -K \times C^n \times N
\]  

(1)

The integration of this expression gives:

\[
\frac{N}{N_0} = e^{-KC^n t}
\]  

(2)

\( C \) is the concentration of disinfectant used; \( K \) is a coefficient reflecting the specific case of disinfecting lethality potential; \( r \) is the coefficient of dilution, which is a function of disinfectant and pH of water (the value of \( n \) is usually close to unity); and \( t \) is the exposure time to disinfectant. In the case of UV-disinfection, an amendment to this model was made by replacing the concentration of chemical disinfectant (\( C \)) with the intensity of UV radiation, as proposed by Haas (1999). The disinfection kinetics could be rewritten as follows:

\[
\frac{dN}{dt} = K \times I^n \times N
\]  

(3)

The integration of this expression gives:

\[
\frac{N}{N_0} = e^{-KI^n t}
\]  

(4)

Changing the logarithmic form and using a linear regression, the kinetic parameters \((K, n)\) of the latter expression could be determined as follows:

\[
\ln\left(\frac{N}{N_0}\right) = \ln(K) + n \ln(I) + \ln(t)
\]  

(5)

When \( n < 1 \), the disinfection process is more controlled by the contact time than by the UV dose. When \( n > 1 \), the UV dose takes precedence over the contact time in the control of the process (Leahy et al., 1987).

**Study of the influence of hydrodynamics on the UV-C disinfection**

In addition to the kinetics of disinfection, it is well recognized that the performance of a UV reactor depends on the hydrodynamic behavior. To examine the influence of the hydrodynamic behavior on the UV disinfection performance, we used a UV reactor mounted at the outlet of the trickling filter in the wastewater pilot plant. This plant had a total capacity of treatment of 150 m³ per day. Furthermore, according to a comprehensive approach, the hydrodynamic behavior is identified by the dispersion of the residence time and achieved by a tracing operation. The Collins-Selleck model is adopted to describe the kinetics of decrease in the number of *P. aeruginosa*.

In the case of UV-C disinfection of treated wastewater, the average rate of decrease in the number of bacteria \( N/N_0 \) assured by the UV reactor is given by the following Equation:

\[
\frac{N}{N_0} = \int_0^\infty \left(\frac{N}{N_0}\right) e^{E(\theta) d\theta}
\]  

(6)

With \( E(\theta) = e^{\theta \theta} \), the function of distribution according to the residence time of water in the UV reactor; \((N/N_0)\), expression of disinfection kinetics obtained by the batch tests; \( \Theta = \frac{t}{T_s} \), reduced time; \( T_s = V/Q \), the average residence time in the reactor. We considered at first the ideal reactor as a perfectly mixed or plug flow reactor. Secondly, we used the model of cascading mixers \((j = 2, 4, 6, 8)\). Thirdly and finally, we studied the influence of preferential paths in the reactor, or the presence of stagnant areas not involved in the main flow that alter the hydrodynamics (Julian et al., 2009), decrease the efficiency of devices and could significantly increase health risks.

**RESULTS AND DISCUSSION**

**Inactivation kinetic of *P. aeruginosa*: UV dose-response**

The intrinsic kinetics of bacterial inactivation as a result of exposure to UV radiation are a function of the UV-C dose, expressed as the product of germicidal radiation intensity (\( I \)) and exposure time (\( t \)). Several mathematical relationships have been developed to describe bacterial responses to UV irradiation. UV dose plays an important role in all bacterial inactivation models for UV irradiation (Ben Said et al., 2010).

In this study, the curve commonly illustrating the kinetics of inactivation usually showed a significant gap
Table 1. The kinetics characteristics of all the disinfection models studied during UV irradiation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chick-Watson</th>
<th>Amended Chick-Watson</th>
<th>Collin-selleck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strains</td>
<td>SSR K1 R1^2</td>
<td>SSR K2 R2^2 A</td>
<td>SSR n t R3^2</td>
</tr>
<tr>
<td>S1</td>
<td>0.2480 0.023 0.64 0.0035</td>
<td>0.0072 0.75 0.0022</td>
<td>0.0016 1.85 2.78 0.91</td>
</tr>
<tr>
<td>S2</td>
<td>0.3185 0.017 0.71 0.0013</td>
<td>0.0086 0.92 0.0088</td>
<td>0.0028 1.55 3.36 1.55</td>
</tr>
<tr>
<td>S3</td>
<td>0.4514 0.012 0.60 0.0078</td>
<td>0.0033 0.0033</td>
<td>0.0205 0.045 0.88 0.91 0.76</td>
</tr>
<tr>
<td>S4</td>
<td>0.7357 0.023 0.57 0.0022</td>
<td>0.0063 0.81 0.0015</td>
<td>0.0059 1.40 0.62 0.75</td>
</tr>
<tr>
<td>S5</td>
<td>0.3412 0.012 -3.04 0.0035</td>
<td>0.0061 0.75 0.0097</td>
<td>0.0092 1.43 2.74 0.78</td>
</tr>
<tr>
<td>S6</td>
<td>0.3402 0.017 -3.42 0.0013</td>
<td>0.002 0.30</td>
<td>0.0017 0.002 0.52 0.0004 0.38</td>
</tr>
<tr>
<td>S7</td>
<td>0.3548 0.017 0.54 0.0059</td>
<td>0.0042 0.64 0.0057</td>
<td>0.0026 1.11 0.75 0.87</td>
</tr>
<tr>
<td>S8</td>
<td>0.5133 0.017 0.44 0.0060</td>
<td>0.0003 0.52</td>
<td>0.5602 0.0628 0.07 0.03 0.71</td>
</tr>
<tr>
<td>S9</td>
<td>0.2905 0.019 0.59 0.0018</td>
<td>0.0051 0.77</td>
<td>0.0027 0.00054 1.41 1.26 0.92</td>
</tr>
<tr>
<td>S10</td>
<td>0.2647 0.021 0.63 0.0023</td>
<td>0.0067 0.74</td>
<td>0.0029 0.0004 1.75 2.75 0.85</td>
</tr>
<tr>
<td>S11</td>
<td>0.1953 0.027 0.53 0.0002</td>
<td>0.0057 0.70</td>
<td>0.0003 0.00075 1.46 0.27 0.84</td>
</tr>
</tbody>
</table>

A decrease in additional U-log could not be attained, even after an exposure time of 90 s. To improve the representativeness of the model of Chick-Watson, we might take into consideration the change of speed during the disinfection process, and the existence of two stages of different kinetics (Figure 1). The fast inactivation kinetics correspond to UV low doses varying among 0 and 200 mW.s.cm^-2 and a constant $K$ of the kinetic model ranging among -0.0259, -0.0689 and -0.056 for strains S3, S14 and S15, respectively, taken as example. This result is supported by the works of Nicholson and Galeano (2003) and Mamane-Gravetz and Linden (2004) concerning the inactivation of bacillus spores by UV rays: 2) Slow kinetics with doses ranging among 200 and 600 mW.s.cm^-2 and a coefficient of relative low lethality among -0.0012, -0.0053 and -0.0034, respectively for the same three strains. This result has been described by several authors (Mañas and Pagán, 2005; Chiu et al., 1999; Mamane-Gravetz and Linden, 2005). It is therefore necessary to assume the existence of at least two stages during the inactivation process of which only the second was explored during these tests.

The application of a first order kinetic during the second stage involves the change of the model by introducing a dimensionless coefficient $A$, in order to reflect the decline achieved during the first fast kinetics stage (Roustan et al., 1991). The expression of the bacterial inactivation model is as follows:

$$\frac{N}{N_0} = Ae^{-Kt}$$  \hspace{1cm} (7)

With $A$ representing the initial decline or initial abatement in the number of bacteria. The parameters
Table 2. The kinetics characteristics of all the disinfection models studied during UV irradiation.

<table>
<thead>
<tr>
<th>Kinetic models</th>
<th>Chick-Watson</th>
<th>Amended Chick-Watson</th>
<th>Collin-selleck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parametres</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strains</td>
<td>SSR</td>
<td>K1</td>
</tr>
<tr>
<td>S12</td>
<td>0.2245</td>
<td>0.028</td>
<td>0.77</td>
</tr>
<tr>
<td>S13</td>
<td>0.3635</td>
<td>0.016</td>
<td>0.71</td>
</tr>
<tr>
<td>S14</td>
<td>0.2213</td>
<td>0.024</td>
<td>0.66</td>
</tr>
<tr>
<td>S15</td>
<td>0.2658</td>
<td>0.02</td>
<td>0.63</td>
</tr>
<tr>
<td>S16</td>
<td>0.3234</td>
<td>0.016</td>
<td>0.39</td>
</tr>
<tr>
<td>S17</td>
<td>0.8539</td>
<td>0.019</td>
<td>0.52</td>
</tr>
<tr>
<td>S18</td>
<td>0.2114</td>
<td>0.023</td>
<td>0.56</td>
</tr>
<tr>
<td>S19</td>
<td>0.2276</td>
<td>0.024</td>
<td>0.50</td>
</tr>
<tr>
<td>S20</td>
<td>0.3733</td>
<td>0.014</td>
<td>0.55</td>
</tr>
<tr>
<td>S21</td>
<td>0.3018</td>
<td>0.018</td>
<td>0.71</td>
</tr>
<tr>
<td>S22</td>
<td>0.3191</td>
<td>0.016</td>
<td>0.73</td>
</tr>
</tbody>
</table>

*R, K1, K2 and K3: Characteristics of the models; $R^2$, $R^2_1$, $R^2_2$, and $R^2_3$: Coefficients of determination; $\tau$, $m$ and $n$: Parameters of adjustment of the model; SSR: sum of squares of residuals.

Figures 1. Study of the disinfection efficiency during the UV disinfection of *P. aeruginosa* as a function of irradiation dose according to the approach of Chick-Watson:

\[ y = e^{-0.025x} \quad R^2 = 0.47 \]
\[ y = e^{-0.0073x} \quad R^2 = 0.18 \]
\[ y = e^{-0.0689x} \quad R^2 = 0.54 \]
\[ y = 0.0004e^{-0.0053x} \quad R^2 = 0.61 \]
\[ y = e^{-0.056x} \quad R^2 = 0.33 \]

Reduction = $N/N_0$ with $N$: number of micro-organisms at the instant $T$; $N_0$: number of bacteria at the instant $T=0$; $R^2$: coefficient of determination; Dose (mW.s.cm$^{-2}$) = $I \times T$; UV Intensity (mW.cm$^{-2}$) × time of contact (s) = (mJ.cm$^{-2}$).
to identify in this case are $K$ and $A$.

In the same way, passing to the logarithm scale, the expression becomes:

$$\ln\left(\frac{N}{N_0}\right) = \ln(A) - KI$$  \hspace{1cm} (8)

We can define the kinetic equations and the coefficient of reliability of the model for each strain studied using a linear regression. The kinetic parameters obtained by this modified model ($A$, $K$, $R^2$ and SSR) are listed in Tables 1 and 2.

Referring to the results of the kinetic parameters of the model summarized in Tables 1 and 2, we can deduce a remarkable similarity between the values of the kinetic constant $K$ for some strains, although divergence is observed for the values of the initial abatement $A$. This result demonstrated that these strains therefore follow the same kinetics of disinfection. If we assume the coefficient $K$ of inactivation as a taxonomic criterion, all strains studied will be sorted into three groups as follows:

1) If $0.0002 \leq K \leq 0.0004$, group 1 would contain strains S3, S6, S7, S16, S17, and S20.
2) If $0.0005 \leq K \leq 0.0007$, group 2 would cover strains S1, S2, S4, S5, S9, S10, S11, S13, S15, S18, and S21.
3) Group 3 includes strains S14 and S22 with a $K$ value of 0.0008, and strains S8 and S13 with values of $K$ equal to 0.0003 and 0.01, respectively.

By working out the difference in these two cases, the values obtained depending on the model of Chick-Watson in its modified form were smaller than those calculated using the same model in its initial form. In the same way, the correlation coefficient $R^2$ obtained using the amended model of Chick-Watson were generally higher than those obtained using the same model in its original form. Thus, we found that the adjustment of the same model but considering an initial reduction describes quite well the kinetics of disinfection for most of the studied strains.

$$\ln\left(\frac{N}{N_0}\right) = A e^{-K_I t}$$  \hspace{1cm} (9)

A key feature of kinetic modeling is not only its simplicity but also that it idealizes a complex phenomenon of disinfection systems. Observation and mathematical modeling of microbial inactivation provide indirect information on the physiological mechanism of inactivation, and equally the mechanisms of resistance.

Several models have been proposed to explain the kinetics of inactivation resulting from the existence of the latency period following the contact of water and disinfectant (Fair et al., 1948; Haas and Karra, 1984; Hom, 1972; George et al., 2000). During this period of latency, the decrease rate of bacteria number is not measurable. This was observed for *Escherichia coli* in the presence of chlorine dioxide (Kerwick et al., 2005). The latency period may also be due to the probability of contact between the disinfectant molecules and micro-organisms present in the water as conglomerates of different sizes (Rubin et al., 1983; James, 1985). The existence of many species of micro-organisms and their varying sensitivities to the product used for disinfection may also explain the latency period, which is detected through a comprehensive measure giving an apparent rate of inactivation (Berney et al., 2006).

In UV-disinfection, several models, for example, the model of Collins-Selleck (George et al., 2000), the Series event model (Berney et al., 2006) and the multi-shock model (Kowalski and Witham, 2001) have been developed to describe the initial plateau observed when micro-organisms are exposed to a sub lethal UV dose. In this case, bacterial inactivation is not significant and the bacteria decline is of low amplitude (Mamane-Gravetz and Linden, 2005; Pruitt and Kamau, 1993; Kowalski et al., 2000).

This latency stage of inactivation for certain strains of *P. aeruginosa* has been observed with low UV doses in Figure 1 (Brahmi et al., 2010) and is confirmed by using the model proposed by George et al. (2000). On the other hand, a stage of initial delay was sometimes found for the majority of bacterial strains used in this experiment (Brahmi et al., 2010). The use of the proposed model of Collins-Selleck (George et al., 2000) was justified in this situation (Kowalski et al., 2000). In fact, besides the reduction in the rate of inactivation in the case of high doses of UV radiation (Shayeb et al., 1998), this model admits the existence of a period of initial latency. Unlike chemical disinfection, the latency period could be explained here, not by the time required to spread the disinfectant and its incorporation into the active sites of micro-organisms, but by the fact that the dose of radiation absorbed by micro-organisms might reach a critical threshold to become lethal. The two following relations expressed this model:

$$\frac{N}{N_0} = 1 \quad \text{for} \quad I t \leq \tau$$  \hspace{1cm} (10)

$$\frac{N}{N_0} = (\tau/I t)^n \quad \text{for} \quad I t \geq \tau$$  \hspace{1cm} (11)

$\tau$ is the least dose of radiation to be reached to start the process of micro-organism inactivation; $n$ is a constant; $I$ is the radiation intensity; and $t$ is the exposure time. Accordingly, the parameters $\tau$ and $n$ could be determined by the transition to the logarithmic form and the use of a linear fit showed, for instance, the position of experimental points as compared to simulated points determined by the model for all the studied strains. We noticed in general that it was necessary to exceed a
minimum radiation dose in order to start the critical process of inactivation. The obtained values seemed valid for all examined strains, below the UV dose of 5.5 mW.s.cm\(^{-2}\) supposed necessary by Wolfe (1990) to achieve 90\% of \textit{P. aeruginosa} inactivation. In the same way, the determination of SSR, a parameter representing the difference between the measured values \(N/N_0\)\(_{mes}\) and the calculated values by the model \(N/N_0\)\(_{cal}\) (denominator sum of squares of residuals), appeared very low for all strains as compared to the values calculated using the model of Chick-Watson in its original or modified form (Tables 1 and 2). Consequently, the model of Collins-Selleck appeared to represent more accurately the disinfection process kinetics. The low values of parameter \(r\) indicated that the disinfection process started quickly with a relatively short latency period.

In some cases, as mentioned above, laboratory results showed that the disinfection law proposed by the model of Chick-Watson was problematic in simulating the experimental data. The study of Chan (2000) on the inactivation of a strain of \textit{Giardia mufis} by chlorine showed that a deviation occurred at the rate of inactivation that it is not quite linear, but that it may decrease or increase. This deviation remains question-able when applying the model of Collins-Selleck.

For an overall approach in Figure 2, and for all regression models, the correlation coefficients were respectively 0.13 for the original Chick-Watson model, 0.32 for the amended Chick-Watson model and 0.69 for the Collins-Selleck model. However, even an \(R^2\) close to 1 is not always a sufficient criterion to validate the quality of a regression model (Chan, 2000). Therefore, other criteria must be analyzed for a better description and better understanding of the phenomena involved in the kinetics of inactivation.

In this regard, the determination of sum of squares of residuals SSR, the parameter representing the difference between the experimental values \(N/N_0\)\(_{mes}\) and the calculated values by the model \(N/N_0\)\(_{cal}\) using a comprehensive approach, seems to be crucial. This parameter is variable as 0.35, 0.013 and 0.0071, for the original Chick-Watson, amended Chick-Watson and Collins-Selleck models, respectively. As compared to all existing models and based on these two parameters, the model of Collins-Selleck gave the best results for describing the bacterial inactivation curves.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figures2.png}
\caption{Study of the disinfection efficiency as a function of irradiation dose according to the models of Chick-Watson (a), Amended chick-Watson (b), and Collin-Selleck (c), respectively. \(y\): reduction = \(N/N_0\) with \(N\): number of bacteria at the instant \(T\); \(N_0\): number of bacteria at the instant \(T=0\); \(R^2\): correlation coefficient; SSR: sum of squares of residuals; \(m\): kinetic characteristic of the model; dose (mW.s.cm\(^{-2}\)) = \(I\times T\) = UV intensity (mW.cm\(^{-2}\)) \times time of contact (s) = (mJ.cm\(^{-2}\)).}
\end{figure}

\textbf{Influence of hydrodynamics on the performance of the disinfection}

To study the hydrodynamic influence on the UV reactor performance, we used treated wastewater at the exit of the line of the trickling filter in the pilot plant, and we considered at first the ideal reactor as a perfectly mixed or plug flow reactor. Secondly, we used the model of cascading mixers \((j = 2, 4, 6, \text{ and } 8)\). The Collins-Selleck model is adopted to describe the kinetics of decrease in the number of \textit{P. aeruginosa}.

Numerical computing and integration of all functions that express the rates of decline for the 6 strains of \textit{P.aeruginosa}, taken arbitrarily (\(S1, S2, S4, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20\), \(S21\) and \(S22\)) are operated by the Matlab version 5.1 (MathWorks, Paris, France). All results that explain the rates of reduction via the number of bacteria \(N/N_0\) reached the reactor outlet are shown in Figure 3.

In our approach and in order to model the hydrodynamic flow in the reactor and the short distance between the outlet of the trickling filter and the UV reactor, the average residence time in the irradiation room of the UV reactor is calculated experimentally using the time of passage theoretically observed (10, 20, 30, 40, 50, 60, 70, 80 and 90 s) and for all flows tested.
without resorting to the technique of chemical tracing.

**Case of Plunger reactor**

In a plug flow reactor, there is no distribution of the residence time. The batch kinetics is sufficient to give the performance of disinfection:

\[
\frac{N}{N_0} = \frac{N}{N_0} \bigg|_{\text{IT}_S} = \int_{\text{IT}_S}^\infty \frac{1}{1-e^{-\theta}} e^{-\theta} d\theta > \tau
\]

\[
\frac{N}{N_0} = \frac{1}{\text{IT}_S} e^{-\tau} \text{ for } \tau < \text{IT}_S
\]

**Case of perfectly mixed reactor (j=1)**

During UV-disinfection and for all the strains studied, we use the Collins-Selleck model to express the kinetics of disinfection in a closed reactor. We can therefore write:

\[
\frac{N}{N_0} = \int_0^\infty \frac{N}{N_0} \bigg|_b^a e^{-\theta} = \int_0^\infty e^{-\theta} d\theta + \int_{\text{IT}_S}^\infty \frac{\tau}{\text{IT}_S} e^{-\tau} d\theta
\]

Where \( \tau \) is the kinetic parameter of the model of Collins-Selleck; \( I \) is the average UV intensity expressed by mW.cm\(^{-2} \); \( t \) is the irradiation time in the batch reactor expressed in seconds; and \( T_s \) is the average residence time in the reactor expressed also in seconds. The integration of this expression has allowed the calculation of changes in rates of decline according to the average residence time \( T_s \) and the doses of UV radiation expressed in mW.s.cm\(^{-2} \).

**Model of cascading mixers (j >1)**

In a closed reactor, if we combine the hydraulic model of \( j \) perfectly mixed reactors in a series with the Collins-Selleck model used to express the kinetics of UV-disinfection of the 8 strains of *P. aeruginosa*, we can then write the overall model using the following formula:

\[
\frac{N}{N_0} = \int_0^\infty \frac{N}{N_0} \bigg|_b^a e^{-\theta} = \int_0^\infty e^{-\theta} d\theta + \int_{\text{IT}_S}^\infty \frac{\tau}{\text{IT}_S} e^{-\tau} d\theta
\]

\[
\frac{\gamma}{N_0} - \frac{\gamma}{N_0} \bigg|_b^a e^{-\theta} = \int_{\text{IT}_S}^\infty \frac{\gamma}{\text{IT}_S} e^{-\tau} d\theta
\]

Where \( \tau \) is the kinetic parameter of the model of Collins-Selleck; \( I \) is the average intensity of UV expressed by
mW.cm\(^{-2}\); \(t\) is the irradiation time in the batch reactor expressed in seconds; and \(T_s\) is the average residence time in the reactor expressed in seconds. The integration of this expression allowed for the calculation of the rate change of inactivation of bacteria examined as a function of the average residence time \(T_s\) and the average intensities of UV radiation.

Influence of defects in design of UV reactors on the performance of disinfection leads to a decrease in the number of fecal coliforms of about 3 U-log. However, the complexity of current processes and requirements for environmental safety, microbiology, public health and even industry, require the introduction of advanced monitoring systems based on the methodologies built on the principle of analytical redundancy. For this reason, a second standard requires a reduction of the number of \(P.\ aeruginosa\) of the order of 4 U-log for treated wastewater reuse. These waters are before loaded with about \(10^6\) CFU/100 mL of \(P.\ aeruginosa\). The examination of the results mentioned in Figure 3 and for most of the strain studied, showed that a perfectly mixed reactor was inefficient in the case of wastewater UV disinfection. Indeed, the average turnover rate for 2 strains examined, which are respectively S1 and S19, has not exceeded 2 U-log for residence times of up to 70 s. For strains S12, S15 and S18, the rate of inactivation could not exceed 3 U-log regardless of the residence time examined and for the same reactor.

In the same process, if we consider that our UV reactor would operate as a plug flow reactor, in this case an improvement of the disinfection process has been observed for some \(P.\ aeruginosa\) strains. Indeed, the interpretation of the results, described in Figure 3, showed that a perfectly mixed reactor was inefficient in the case of wastewater UV disinfection. Indeed, the average turnover rate for 2 strains examined, which are respectively S1 and S19, has not exceeded 2 U-log for residence times of up to 70 s. For strains S12, S15 and S18, the rate of inactivation could not exceed 3 U-log regardless of the residence time examined and for the same reactor.

A succession of 6 or even though 8 perfectly mixed reactors in series do not significantly improve the efficiency of UV-disinfection for almost all strains examined and with residence times of up to 70 sec. In addition, Figure 3 taken as a model showed that the removal rate of bacteria if the reactor operates as a perfect mixture of 4 reactors in series for about 5 strains, which are respectively S2, S4, S11, S18 and S19. Figure 3 taken as a model showed the higher effectiveness of the UV-disinfection process when the reactor works as four perfectly mixed reactors in series when compared with other reactors previously cited. Withal, a removal efficiency of about 4 U-log and even higher has been observed if a succession of four reactors in series is applied for a residence time of 15 s. For some strains (such as S2), this efficiency cannot be achieved with residence times of up to 70 s if the reactor is perfectly mixed with a succession of two reactors in series or even in the piston. For other strains (such as S4), in order to achieve this performance, the residence time of 27 s is needed, where the reactor would operate as two perfectly mixed reactors in series, and more than 65 s in the case of a reactor close enough to plug flow (KaymakandHaas, 2001).

A succession of 6 or even though 8 perfectly mixed reactors in series for disinfection leads to a decrease in the number of fecal coliforms of about 3 U-log. However, the complexity of current processes and requirements for environmental safety, microbiology, public health and even industry, require the introduction of advanced monitoring systems based on the methodologies built on the principle of analytical redundancy. For this reason, a second standard requires a reduction of the number of \(P.\ aeruginosa\) of the order of 4 U-log for treated wastewater reuse. These waters are before loaded with about \(10^6\) CFU/100 mL of \(P.\ aeruginosa\). The examination of the results mentioned in Figure 3 and for most of the strain studied, showed that a perfectly mixed reactor was inefficient in the case of wastewater UV disinfection. Indeed, the average turnover rate for 2 strains examined, which are respectively S1 and S19, has not exceeded 2 U-log for residence times of up to 70 s. For strains S12, S15 and S18, the rate of inactivation could not exceed 3 U-log regardless of the residence time examined and for the same reactor.

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Influence of defects in the design of UV reactors on the performance of disinfection

The existence of preferential paths in the reactor, or the presence of stagnant areas not involved in the main flow, are examples of abnormalities that affect the hydrodynamic flow (Julyan et al., 2009), decrease the effectiveness of the reactor and therefore can significantly increase health risks.

A thorough knowledge of these design flaws is necessary to examine their influence on the actual performance of UV disinfection reactor (Mohajeraniet al., 2012). For this, and as it was shown in the case of ideal reactors, that hydrodynamic model would work as 4 perfectly mixed reactors appears to be the most efficient process for disinfection of treated wastewater by UV
irradiation, so we adopt this model priority which we assume to be a dead zone or a short circuit (Ben Messaoud, 2009).

**Case with short circuit**

In a closed reactor, if we combine the hydraulic model of $j$ perfectly mixed reactors in a series showing a short-circuit, and the use of the Collins-Selleck model to express the kinetics of UV-disinfection of the 6 strains of *P. aeruginosa*, we can then write the overall model using the following formula:

$$
\frac{N}{N_0} = \left( \frac{1}{(1 - \theta)^j} \right) \left( \frac{1}{1 - \theta} \right)^j \left( \frac{\theta^{jm}}{m!} \right) \left( \frac{1}{m!} \right) \frac{1}{(1 - \theta)^j} \left( \frac{\theta^{jm}}{m!} \right) \left( \frac{1}{m!} \right) \frac{1}{(1 - \theta)^j} \left( \frac{\theta^{jm}}{m!} \right) \left( \frac{1}{m!} \right) \frac{1}{(1 - \theta)^j} \left( \frac{\theta^{jm}}{m!} \right) \left( \frac{1}{m!} \right)
$$

(21)

Where $r$ is the kinetic parameter of the Collins-Selleck model; $I$ is the average intensity of UV expressed by mW.cm$^{-2}$; $t$ is the irradiation time in batch reactor expressed in seconds; and $T_j$ is the average residence time in the reactor expressed as well in seconds; $n$ represents the fraction of perfectly mixed volume of each reactor. The integration of this expression allowed the calculation of the rate change of inactivation of bacteria examined as a function of the average residence time $T_s$ and the average intensities of UV radiation.

**Cases with dead zone**

In a closed reactor, if we combine the hydraulic model of $j$ perfectly mixed reactors in a series showing a dead volume, with the Collins-Selleck model used to express the kinetics of UV-disinfection of the 6 strains of *P. aeruginosa*, we can then write the overall model using the following formula:

$$
\frac{N}{N_0} = \int_0^\infty \frac{1}{m!} \left( \frac{1}{1 - \theta^j} \right) \left( \frac{1}{1 - \theta} \right)^j \left( \frac{\theta^{jm}}{m!} \right) \left( \frac{1}{m!} \right) \frac{1}{(1 - \theta)^j} \left( \frac{\theta^{jm}}{m!} \right) \left( \frac{1}{m!} \right) \frac{1}{(1 - \theta)^j} \left( \frac{\theta^{jm}}{m!} \right) \left( \frac{1}{m!} \right) \frac{1}{(1 - \theta)^j} \left( \frac{\theta^{jm}}{m!} \right) \left( \frac{1}{m!} \right)
$$

(22)

Where $r$ is the kinetic parameter of the model of Collins-Selleck; $I$ is the average intensity of UV expressed by mW.cm$^{-2}$; $t$ is the irradiation time in batch reactor expressed in seconds; and $T_s$ is the average residence time in the reactor expressed as well in seconds; $m$ represents the fraction of perfectly mixed volume of each reactor. The integration of this expression allowed the calculation of the rate change of inactivation of bacteria examined as a function of the average residence time $T_s$ and the average intensities of UV radiation.

Several standardized international guidelines stipulate that the reuse of wastewater requires a lessening in the number of fecal coliforms of about 3 U-log. However, the complexity of current processes and requirements for environmental safety, microbiology, public health and even industry, require the introduction of advanced monitoring systems based on monitoring methodologies built on the principle of analytical redundancy. For this reason, a second standard requires a reduction ratio of the number of *P. aeruginosa* of the order of 4 U-log for treated wastewater reuse. These waters are loaded with about $10^6$ CFU/100 mL of *P. aeruginosa*. The examination of the results listed in Figure 4 and for all strains studied showed that the efficiency of the reactor was completely lost whatever residence time considered, if a short circuit pitying the proportion (1-n) is superimposed on the flow rate it would function as a four perfectly mixed reactor in series. Indeed, contrary to the results obtained in the case where the reactor has a dead zone, the standard of 4 U-log previously required, will not be reached.

The presence of a short circuit would affect 10% of the total volume of the reactor and making only 20 s (case of the strain S1), would result in a loss of inactivation of the reviewed strain of about 10%. If short-circuit both duplicate and with the same residence time, this would result in a loss of inactivation of about 2.10^2 in the same strain. This rate is even more exciting than the residence time which is higher. So we can conclude that a short-circuit whatever its content, and for all residence times examined, would have a major influence on the effectiveness of the UV reactor assimilated to 4 perfectly mixed reactors in series.

As mentioned previously, a reuse of treated wastewater requires an abatement rate of the number of *P. aeruginosa* of about 4 U-log, and similarly it has been shown in the case of ideal reactors, a hydrodynamic model would work as 4 perfectly mixed reactors which appears to be the most efficient process for disinfection of treated wastewater by UV radiation, so it is useful to test the influence of deadband on the disinfection process. Indeed, the examination of the results shown in Figure 5 and for almost all strains studied showed that it would reach a standard of 4 U-log, the residence time of the order, respectively, 20, 45, 20, 10, 10 and 10 s for the six strains, if the reactor function as a series of four reactors in series. These residence times would duplicate if a dead zone affects only 10% of the total reactor volume. Similarly, we can deduce that the nature of the flows in the reactor here have more impact on the final disinfection performance. We see for example, and for all residence times examined, the presence of a dead area would result in a 10% drop in efficiency of approximately 300%. This rate is even more exciting than the residence time which is higher.

An increase in dead zones of 20 and 30% in a reactor operate as four perfectly mixed reactors; will not affect its effectiveness. Indeed, the same loss of efficiency caused by the presence of a dead zone would affect 10% of the total volume of the reactor reached. This can be explained
Figures 4. Changes kinetic curves of bacteria inactivation, in terms of N/No, as function of exposure time. The cell colony density is recorded at the exit of the UV-reactor, by considering the average residence time, the mean intensity of UV radiation, and taking into account the impact of the presence of a short circuit. y: Reduction = N/No; with N: number of micro-organisms at the instant T; No: number of micro-organisms at the instant T= 0; T: the average residence time in the reactor (s); PMRs: perfectly mixed reactor in serie; n: perfectly mixed volume fraction of each reactor; (1-n): rate of short circuit.

Figures 5. Kinetic curves of bacteria inactivation, in terms of N/No, as function of exposure time. The cell colony density is recorded at the exit of the UV-reactor, by considering the average residence time, the mean intensity of UV radiation, and taking into account the impact of the presence of a dead zone. y: Reduction = N/No; with N: number of micro-organisms at the instant T; No: number of micro-organisms at the instant T= 0; T: the average residence time in the reactor (s); PMRs: perfectly mixed reactor in series; m: perfectly mixed volume fraction of each reactor; (1-m): rate of dead band.
by the short distance between the outlet of the trickling filter and the output of the reactor not exceeding 50 cm and the low flow treaty.

Regarding all interpretations that we gained for the process of UV-disinfection of treated wastewater, in order to acquire a complete inactivation of P. aeruginosa species, we need to simulate the UV-C reactor as a series of 4 reactors placed in series. It will be important to note that this event is not merely the outcome of the disinfection process by UV-C but also concerns other disinfection processes when all factors influencing disinfection are well controlled and the reactors implemented do not have design deficiencies.

In summary of this research dedicated to the study of the purification and optimization of UV disinfection of treated wastewater, we can maintain that it is vital to develop a disinfection reactor of useful volume of 4.3 L; an average residence time of 15 s, debit flow of 0.281 L/s, an average UV ray intensity of 5.3 mW/cm², an average UV dose of 80 mW.s.cm⁻² and functioning as a succession of 4 reactors thoroughly mixed in series. A satisfactory treatment of the physico-chemical pollution materialized through a UV transmittance greater than 45% can improve the process of disinfection.

Conclusion

The application of the original model of Chick-Watson was not sufficiently representative to describe the kinetics of bacterial inactivation. Therefore, a modification based on the same model, but after taking into consideration an initial inactivation, can describe very well the kinetics of disinfection. According to the parameter SSR representing the difference between the experimental and the calculated values using the model of Chick-Watson in its original form or reformed, the obtained values of SSR were very low for all strains. Thus, we discover that the model of Collins-Selleck seems to be the most effective in describing the change in the kinetics during the disinfection process. Likened to an overall approach, for all the regression models and based on the two parameters (the correlation coefficient R² and SSR), the model of Collin-Selleck gave the best results for the description of UV inactivation, and it will be taken as a basic model for all hydrodynamic modeling concerning the UV-C reactor performance study.

Finally, by considering all the interpretations previously advanced concerning the process of disinfection of treated wastewater by UV radiation and for a completely microbial disinfecting, simulations have revealed that the operation of the UV reactor as a succession of four perfectly mixed reactors in series represents the best alternative to scale-up of the process.

Conflict of Interests

The authors have not declared any conflict of interests.

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