Disinfection of Wastewater by UV Irradiation: Influence of Hydrodynamics on the Performance of the Disinfection

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Abstract
Several mathematical relationships have been developed to describe bacterial responses to UV irradiation. Pseudomonas aeruginosa was taken as a bacterial model. The results obtained showed that the kinetics of disinfection is far to be as uniform. In fact, application of the model of Chick-Watson in its original form or modification, taking into account the speed change during the disinfection process, has not significantly improved results. The application of both models of Collins-Selleck and Hom constitute a major opportunity to simulate goody the kinetics of UV disinfection. The results obtained showed that despite the major advantage held by applying the Hom model in this process of disinfection and for all strains studied, the model of Collins-Selleck gave the best results for the description of the UV inactivation process. The design of reactors, operating in continuous disinfection system, requires taking into account the hydrodynamic behaviour of water in the reactor. Knowing that a reduction of 4-log is necessary in the case of wastewater reuse for irrigation, a model integrating the expression of disinfection kinetics and the hydrodynamics through the UV irradiation room was proposed. The results highlight the interest to develop reactors in series working as four perfectly mixed reactors.

Keywords: Disinfection, Hydrodynamics, Kinetics model, Reactor of disinfection, Treated wastewater, UV radiation

1. Introduction

Ultraviolet (UV)-C (short-wavelength ultraviolet) radiation has been suggested as one of the successful disinfection practices for water treatment. Therefore, 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 used in most water treatment facilities to kill harmful micro-organisms that cause serious disease in drinking water. While this certainly works, the chlorine itself causes many health problems such as asthma, cancer, fertility problems, heart disease, eczema and birth defects. Furthermore, the smell and taste of chlorinated water is very unpleasant [1]. Also, the residuals and by-products from chlorination can be toxic to aquatic life in the receiving waters. Particularly, some by-products of chlorination may be carcinogenic and may require removal in a drinking water treatment plant. It has actually been discovered that chlorination is considerably less effective in virus destruction than in killing bacteria. UV light is currently a more preferable method for water disinfection. Actually, UV-disinfection has gained widespread use for municipal wastewater and has now also increased [2]. It has the following inherent advantages over all other disinfection methods: no chemical consumption, thereby eliminating large scale storage; no transportation, handling and potential safety hazards; low contact time; no contact basin is necessary and space requirements are thus reduced; no harmful by-products are formed; a minimum of, or no, moving parts; and high reliability and low energy requirements [3]. UV-disinfection thus solves the environmental and safety problems and is also cost-effective.

UV-disinfection of water employs low-pressure mercury lamps. The lamps generate short-wave UV radiation at 253.7 nm which is lethal to micro-organisms including bacteria, protozoa, viruses, molds, yeasts, fungi, nematode eggs and algae. The mechanism of micro-organisms destruction is currently believed to be that in which UV causes molecular rearrangements in DNA and RNA, which in turn blocks replication [4]. The acceptance of UV-disinfection at wastewater plants treating in excess of one billion gallons daily is proof that UV is no longer an emerging technology, but rather an accepted technology to be used routinely by engineers to safeguard human health and alleviate environmental pressures. Wastewater reuse has been practiced in various forms for decades, with the United States leading the way in reuse research. It is now a major issue in the U.S., where large areas of the Western and Southern states experience chronic water shortages [5].

UV water purification lamps produce UV-C or germicidal UV, with radiation of much greater intensity than sunlight. Almost all of a UV lamp’s output is concentrated in a 254 nm region in
order to take full advantage of the germicidal properties of this wavelength. Most UV purification systems are combined with various forms of filtration, as UV light is only capable of killing micro-organisms such as bacteria, viruses, molds, algae, yeast and oocysts such as Cryptosporidium and Giardia. UV light generally has no impact on chlorine, volatile organic compounds (VOCs), heavy metals and other chemical contaminants. Nevertheless, it is probably the most cost-effective and efficient technology available to homeowners to eliminate a wide range of biological contaminants from their water supply. This study was therefore carried out to investigate the effectiveness of UV light for wastewater disinfection [1].

The aim of this study is firstly to evaluate the kinetics of the inactivation of certain isolates of Pseudomonas aeruginosa resistant to UV-C radiation, secondly the aim is to determine the influence of UV dose on the kinetics of disinfection, and thirdly to establish the best combination of contact-time and UV-C dose, used to achieve a given quality of treated wastewater. Meanwhile, another important target of this work is to propose a design methodology for UV-C reactors.

2. Materials and Methods

2.1. 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 operating in parallel: a trickling filter, rotating biological discs, and a soil and lagoon optional filter. During disinfection tests, the physic-chemical characteristics of the treated wastewater by the trickling filter did not significantly change. The values fluctuated between 47% to 49% for UV transmission, 15 to 27 mg/L for total suspended solids (TSS), 20 to 29 mg/L for biochemical oxygen demand (BOD), and 90 to 102 mg/L for chemical oxygen demand (COD).

2.2. Experiments in a Batch Laboratory Irradiation Device

The laboratory UV device used in this study has previously been described by Hassen et al. [6]. A low pressure UV-C lamp is used. This lamp emitted an average intensity of about 7 mW/cm². In addition, all bacterial strains studied were cultivated to a mid-log phase at 37°C in 20 mL of nutrient broth (Pasteur Institute production). All these strains were grown on a nutrient agar (Pasteur Institute production). These kinetic approaches are based on experimental studies using: a laboratory disinfection device; 22 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 Hom and Collins-Selleck models. The model of Chick-Watson is used primarily to express the kinetics of disinfection with chemical disinfectants [9-11]. The first-order kinetics is expressed as follows:

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

The integration of this expression gives:

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

2.3. Bacterial Strains Selected for UV-Disinfection Study

Many pathogens are responsible for waterborne diseases. Despite the development of molecular methods, currently it is not always possible to detect comprehensively all micro-organisms in a water sample. Therefore, most studies in this area have mainly focused on the concentration of fecal indicator bacteria (total coliforms, fecal coliforms, and fecal streptococci in general) to estimate the population of pathogens. However, recent studies showed that the species of P. aeruginosa seems to be a valid indicator for recreational waters [7, 8]. This parameter is actually used as a criterion in the regulation of wading and swimming pools. Moreover, the absence of P. aeruginosa is important not only in terms of its role as an indicator, but also because it is an opportunistic pathogen of which the transmission is often associated with water. Its use for evaluating the effectiveness as a treatment of UV-disinfection seems therefore reliable. Therefore, its kinetics of inactivation by UV irradiation has assumed the same fate as for all other less resistant pathogens. For all of the above reasons, a collection of 22 strains of P. aeruginosa were irradiated with different UV-C doses and all were conditioned by 7 singular contact times ranging between 2 and 90 sec. This collection includes 20 strains 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 at the laboratory for long periods on a nutrient broth (Institute Pasteur production). These 22 strains were referenced from S1 to S22, respectively. By definition, the UV-C dose is the product between the time of exposure(s) to UV-C and the intensity emitted by the UV lamp (mW/cm²).

2.4. The Kinetic Models Used for UV-C Inactivation

These kinetic approaches are based on experimental studies using: a laboratory disinfection device; 22 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 Hom and Collins-Selleck models. The model of Chick-Watson is used primarily to express the kinetics of disinfection with chemical disinfectants [9-11]. The first-order kinetics is expressed as follows:

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

The integration of this expression gives:

\[
\frac{N}{N_0} = e^{K^n t}
\]
Changing the logarithmic form and using a linear regression, the kinetic parameters \( K \) and \( n \) of the latter expression could be determined as follows:

\[
\ln \left( \frac{N}{N_0} \right) \approx \ln(\xi) + n \cdot \ln(T) + \ln(t)
\]

(5)

When \( n < 1 \), the disinfection process is controlled more 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 [13].

### 2.5. Study of the Influence of Hydrodynamics on the UV-C Disinfection

In addition to the kinetics of disinfection, it is well known that the performance of a UV reactor depends on the hydrodynamic behavior. To study the influence of the hydrodynamic behavior on the UV disinfection performance, we used a UV reactor mounted at the exit of the line 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 described by the distribution of residence time and is achieved by a tracer test. The Collins-Selleck model is adopted to describe the kinetics of decrease in the number of \( P. aeruginosa \).

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

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

(6)

with \( E(\theta) = e^{-\theta} \), function of distribution according to the residence time of water in the UV reactor; \( \frac{N}{N_0} \), expression of disinfection kinetics obtained by the batch tests; \( \theta = t/T_{av} \), reduced time; \( T_{av} = V/Q \), the average residence time in the reactor. We considered at first the ideal reactor as a completely mixed and plug flow reactor. Secondly, we used the model of cascading mixers \( j = 2, 4, 6, \) and \( 8 \).

### 3. Results and Discussion

#### 3.1 The 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 [14].

In this study, the curve commonly illustrating the kinetics of inactivation usually showed a significant gap between the experimental points and those simulated by the model in the case of all studied strains of \( P. aeruginosa \) (results not shown). In the same way, the determination of \( \xi \), a representative parameter of the difference between the experimental values \( \frac{N}{N_0} \) and the calculated values by the model \( \frac{N}{N_0} \), appeared to be important for all strains in Tables 1 and 2. Therefore, we found that the model of Chick-Watson, reduced to a first-order kinetic with a coefficient of lethality ranging between 0 and 1, showed its limits, and that the inactivation process is most often non-uniform, and does not necessarily comply with first-order kinetics implies, with an exponential law [12, 15, 16]. However, the adopted experimental protocol showed a very noticeable reduction rate for low doses of radiation. The importance of UV radiation intensity of the lamp allows a yield rate of 2-log to be achieved after only 2 sec of exposure.

A decrease of additional U-log could not be reached, even after an exposure time of 90 sec. To improve the representativeness of the model of Chick-Watson, in taking into account the decrease in speed during the disinfection process, the existence of two stages, each with different kinetics is realized in Fig. 1: 1) Fast inactivation kinetics with low doses varying between 0 and 200 mW/sec/cm² and a coefficient of lethality ranging between -0.0259, -0.0689, and -0.0053 for strains S3, S14, and S15, respectively, taken as an example. This result is confirmed by the work of [17] and [18] concerning the inactivation of bacillus spores by UV rays. 2) Slow kinetics with doses ranging between 200 and 600 mW/sec/cm², and a coefficient of relatively low lethality between -0.0012, -0.0013, and -0.0034, respectively for the same three strains. This result has been described by several authors [19-21]. 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
Table 1. The kinetics characteristics of all the disinfection models studied during ultraviolet (UV) irradiation

<table>
<thead>
<tr>
<th>Kinetic models</th>
<th>Chick-Watson</th>
<th>Amended Chick-Watson</th>
<th>Collin-Selleck</th>
<th>Hom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters strains</td>
<td>ε</td>
<td>K1</td>
<td>R_i^2</td>
<td>ε</td>
</tr>
<tr>
<td>S1</td>
<td>0.2480</td>
<td>0.023</td>
<td>0.64</td>
<td>0.0035</td>
</tr>
<tr>
<td>S2</td>
<td>0.3185</td>
<td>0.017</td>
<td>0.71</td>
<td>0.0013</td>
</tr>
<tr>
<td>S3</td>
<td>0.4514</td>
<td>0.012</td>
<td>0.60</td>
<td>0.0078</td>
</tr>
<tr>
<td>S4</td>
<td>0.7357</td>
<td>0.023</td>
<td>0.57</td>
<td>0.0022</td>
</tr>
<tr>
<td>S5</td>
<td>0.3412</td>
<td>0.012</td>
<td>0.60</td>
<td>0.0035</td>
</tr>
<tr>
<td>S6</td>
<td>0.3402</td>
<td>0.017</td>
<td>0.42</td>
<td>0.0013</td>
</tr>
<tr>
<td>S7</td>
<td>0.3548</td>
<td>0.017</td>
<td>0.54</td>
<td>0.0059</td>
</tr>
<tr>
<td>S8</td>
<td>0.5133</td>
<td>0.017</td>
<td>0.44</td>
<td>0.0660</td>
</tr>
<tr>
<td>S9</td>
<td>0.2905</td>
<td>0.019</td>
<td>0.59</td>
<td>0.0018</td>
</tr>
<tr>
<td>S10</td>
<td>0.2647</td>
<td>0.021</td>
<td>0.63</td>
<td>0.0023</td>
</tr>
<tr>
<td>S11</td>
<td>0.1953</td>
<td>0.027</td>
<td>0.53</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

A, K1, K2, and K3 are characteristics of the models; R_i^2, R_i^2, R_i^2, and R_i^2 are coefficients of determination; ε is the difference between calculated and measured or experimental values = \sqrt{\sum (N_i^\text{cal} - N_i^\text{exp})^2}.

Table 2. The kinetics characteristics of all the disinfection models studied during ultraviolet (UV) irradiation

<table>
<thead>
<tr>
<th>Kinetic models</th>
<th>Chick-Watson</th>
<th>Amended Chick-Watson</th>
<th>Collin-Selleck</th>
<th>Hom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters strains</td>
<td>ε</td>
<td>K1</td>
<td>R_i^2</td>
<td>ε</td>
</tr>
<tr>
<td>S12</td>
<td>0.2245</td>
<td>0.028</td>
<td>0.77</td>
<td>0.0568</td>
</tr>
<tr>
<td>S13</td>
<td>0.3635</td>
<td>0.016</td>
<td>0.71</td>
<td>0.0086</td>
</tr>
<tr>
<td>S14</td>
<td>0.2213</td>
<td>0.024</td>
<td>0.66</td>
<td>0.0035</td>
</tr>
<tr>
<td>S15</td>
<td>0.2658</td>
<td>0.02</td>
<td>0.63</td>
<td>0.0034</td>
</tr>
<tr>
<td>S16</td>
<td>0.3234</td>
<td>0.016</td>
<td>0.39</td>
<td>0.0024</td>
</tr>
<tr>
<td>S17</td>
<td>0.8539</td>
<td>0.019</td>
<td>0.52</td>
<td>0.0030</td>
</tr>
<tr>
<td>S18</td>
<td>0.2114</td>
<td>0.023</td>
<td>0.56</td>
<td>0.0002</td>
</tr>
<tr>
<td>S19</td>
<td>0.2276</td>
<td>0.024</td>
<td>0.50</td>
<td>0.0088</td>
</tr>
<tr>
<td>S20</td>
<td>0.3733</td>
<td>0.014</td>
<td>0.35</td>
<td>0.0037</td>
</tr>
<tr>
<td>S21</td>
<td>0.3018</td>
<td>0.018</td>
<td>0.71</td>
<td>0.0014</td>
</tr>
<tr>
<td>S22</td>
<td>0.3191</td>
<td>0.016</td>
<td>0.73</td>
<td>0.0072</td>
</tr>
</tbody>
</table>

A, K1, K2, and K3 are characteristics of the models; R_i^2, R_i^2, R_i^2, and R_i^2 are coefficients of determination; ε is the difference between calculated and measured or experimental values = \sqrt{\sum (N_i^\text{cal} - N_i^\text{exp})^2}.

\[ A, K1, K2, \text{and } K3 \text{ are characteristics of the models; } R_i^2, R_i^2, R_i^2, \text{ and } R_i^2 \text{ are coefficients of determination; } \varepsilon \text{ is the difference between calculated and measured or experimental values } = \sqrt{\sum (N_i^\text{cal} - N_i^\text{exp})^2}. \]
stage requires the modification of the model by introducing a dimensionless coefficient $A$, in order to reflect the decline achieved during the first fast kinetics stage [11]. The expression of the bacterial inactivation model becomes as follows:

$$\frac{N}{N_0} = Ae^{-Klt}$$

(7)

with $A$ representing the initial decline or initial abatement in the number of bacteria. The parameters to identify in this case are $K$ and $A$.

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

$$\ln\left(\frac{N}{N_0}\right) = \ln(A) - KIt$$

(8)

We can determine the kinetic equations and the coefficient of reliability of the model for each strain studied using a linear regression. The kinetic parameters obtained of this modified model ($A$, $K$, $R^2$, and $r$) 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, despite the divergence observed for the values of the initial abatement $A$. This result showed that these strains therefore obey the same kinetics of disinfection. If we assume the coefficient $K$ of inactivation as a taxonomic criterion, all strains studied will be classified into three groups as follows:

1) If $0.002 \leq K \leq 0.004$, group 1 containing strains S3, S6, S7, S16, S17, and S20.

2) If $0.005 \leq K \leq 0.007$, group 2 covering 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 0.008, and strains S8 and S13 with values of $K$ equal to 0.0003 and 0.0004, respectively.

By calculating the difference $\epsilon = \sum [\ln(N/N_0)_{cal} - (\ln(N/N_0)_{exp})]$ for these two models, 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 coefficients of determination $R^2$ 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.

$$\ln\left(\frac{N}{N_0}\right) = Ae^{-KIt}$$

(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 provides 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 [22-26]. 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 [27]. 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 [28, 29]. 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 [30].

In UV-disinfection, several models, for example, the model of Collins-Selleck [24], the Series event model [30] and the multi-shock model [30, 31] 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 [20, 32-34].

This latency stage of inactivation for certain strains of *P. aeruginosa* has been observed with low UV doses in Fig. 1 [8] and is confirmed by using the model proposed by George et al. [24]. On the other hand, a stage of initial delay was sometimes found for the majority of bacterial strains used in this experiment [8]. The use of the proposed model of Collins-Selleck [24] was justified in this situation [34]. In fact, besides the reduction in the rate of inactivation in the case of high doses of UV radiation [16], 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 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:

$$\begin{cases}
N/N_0 = 1 & \text{for } t \leq \tau \\
N/N_0 = \frac{N_0 - \epsilon}{\epsilon} \left(1 - \left(\frac{I}{I_r}\right)^n\right) & \text{for } t \geq \tau
\end{cases}$$

(10)

$$N/N_0 = \frac{N_0 - \epsilon}{\epsilon} \left(1 - \left(\frac{I}{I_r}\right)^n\right)$$

(11)

$r$ 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 $r$ is the exposure time. Accordingly, the parameters $r$ 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 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/sec/cm$^2$ supposed necessary by Wolfe [35] to achieve 90% of *P. aeruginosa* inactivation. In the same way, the determination of $\epsilon$, a parameter representing the difference between the measured values ($N/N_0$)cal and the calculated values by the model ($N/N_0$)exp appeared very low for all strains 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 was likely to be the most efficient in terms of changing kinetics during the disinfection process. However, this model did not give an unexpected explanation for the kinetics decrease when the dose increased [8]. 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 [36] on the inactivation of a strain of *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 questionable when applying the model of Collins-Selleck. The Hom model can describe this deviation. Indeed, in 1972, Hom amended the law of Chick-Watson with additional term denoted as $m$ [37]. In this case, the Equation is:
When \( n = 1 \) (constant intensity is for each strain), we obtain the model of Fair and Geyer [22]:

\[
\ln \left( \frac{N}{N_0} \right) = -K.1.t^m
\]

(14)

Integrating this Equation for the constant \( C \) gives:

\[
\ln \left( \frac{N}{N_0} \right) = -KC.n.t^m
\]

(13)

where \( m = \) constant that controls the deflection of inactivation rate.

In the Hom model, if the parameter \( m \) is equal to unity, the model of Chick-Watson is applied. If \( m \) is greater than 1, there is an increase in the inactivation rate and vice versa. This fluctuation depends on the physicochemical parameters of water and the type of disinfectant used. In this Equation, \( k \) is the removal or the decline rate of micro-organisms; \( n \) is the constant that takes into account the performance of disinfectant used; and \( m \) is constant which takes into account deviation in the rate of inactivation as previously mentioned. Previous studies have shown that the model can satisfactorily simulate Hom experimental data for Giardia [38], Cryptosporidium parvum [39], spores of aerobic bacteria [40] and heterotrophic bacteria [41]. Therefore, its application to simulate the experimental data obtained following the inactivation strains of \( P. aeruginosa \) may be justified.

In the case of UV-disinfection, the factor \( C \) (concentration of the disinfectant) is replaced by the intensity \( I \) of radiation. The model Equation becomes [42]:

\[
\ln \left( \frac{N}{N_0} \right) = -K.I.t^m
\]

(14)

When \( n = 1 \) (constant intensity is for each strain), we obtain the model of Fair and Geyer [22]:

\[
\ln \left( \frac{N}{N_0} \right) = -K.1.t^m
\]

(15)

the parameters to be identified in this case are \( K \) and \( m \).

By shifting to the logarithmic form:

\[
\ln \left[ -\ln \left( \frac{N}{N_0} \right) \right] = \ln(K) + \ln(I) + m.\ln(t),
\]

(16)

and using a linear fit, we can determine the different values of \( m \) and \( K \). The values of these parameters for different strains, and the corresponding coefficients \( R^2 \) and \( \varepsilon \) are illustrated in Tables 1 and 2.

Similarly, the determination of \( \varepsilon \) results in very low values for most strains compared to the values calculated by the model of Chick-Watson in its original or altered form Tables 1 and 2. This parameter, more collated than the Collins-Selleck model, showed a remarkable similarity. We therefore found that the Hom model also showed a strong significance in describing the kinetics of disinfection for most strains tested in this study. The Hom model of the form:

\[
\ln \left( \frac{N}{N_0} \right) = -K.I.t^m
\]

describes fairly well the kinetics of disinfection.

For an overall approach in Fig. 2, and for all regression models,
the correlation coefficients were respectively -1.86 for the original Chick-Watson model, 0.32 for the amended Chick-Watson model, 0.62 for the Hom 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 [36]. 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 $\varepsilon$, the parameter representing the difference between the experimental values ($N/N_0$)$_{\text{exp}}$ and the calculated values by the model ($N/N_0$)$_{\text{calc}}$ using a comprehensive approach, seems to be crucial. This parameter is variable as 0.35, 0.0013, 0.0071, and 0.0059 for the original Chick-Watson, amended Chick-Watson, Collin-Selleck, and Hom models, respectively. Compared to all existing models and based on these two parameters, the model of Collin-Selleck gave the best results for describing the inactivation curves.

### 3.2. 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 completely mixed and plug flow reactor. Secondly, we used the model of cascading mixers ($j = 2, 4, 6,$ and 8). The Collins-Selleck model is adopted to describe the kinetics of decrease in the number of $P. aeruginosa$.

Numerical computing and integration of all functions that express the rates of decline for the 8 strains of $P. aeruginosa$, taken arbitrarily (S1, S2, S4, S11 S12, S15, S18, and S19), 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 at the reactor outlet are shown in Fig. 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 was calculated experimentally using the time of passage theoretically observed (10, 20, 30, 40, 50, 60, 70, 80, and 90 sec) and for all flows tested without resorting to the technique of chemical tracing.

### 3.3 Case of Plunger Reactor

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

$$\frac{N}{N_0} = \left( \frac{N_0}{N_0} \right)b = \left( \frac{\tau}{\Pi T_s} \right)^n \text{ for } \Pi T_s \tau$$

$$\frac{N}{N_0} = 1 \text{ for } \Pi T_s \tau$$

### 3.4. Case of Perfectly Mixed Reactor ($j=1$)

In 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:

$$\frac{N}{N_0} = \frac{N_0}{N_0} = \left( \frac{N_0}{N_0} \right)b = \left( \frac{\tau}{\Pi T_s} \right)^n \text{ for } \Pi T_s \tau$$

$$\frac{N}{N_0} = 1 \text{ for } \Pi T_s \tau$$

where $r$ is kinetic parameter of the model of Collins-Selleck; $I$ is average UV intensity expressed by mW/cm$^2$; $\tau$ is irradiation time in batch reactor expressed in sec; and $T_s$ is the average residence time in the reactor expressed also in sec. The integration of this expression has allowed the calculation of changes in rates of decline according to the average residence time $T_s$ and doses of UV radiation expressed in mW/sec/cm$^2$.

### 3.5. 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:

$$\frac{N}{N_0} = \frac{N}{N_0} \left( \frac{N_0}{N_0} \right)_b \left( \frac{\tau}{\Pi T_s} \right)^n \text{ for } \Pi T_s \tau$$

$$\frac{N}{N_0} = 1 \text{ for } \Pi T_s \tau$$

where $r$ is kinetic parameter of the model of Collins-Selleck; $I$ is average intensity of UV expressed by mW/cm$^2$; $\tau$ is irradiation time in batch reactor expressed in sec; and $T_s$ is the average residence time in the reactor expressed in sec. 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.

Several standardized international guidelines stipulate that the reuse of wastewater requires a decrease in the number of fecal coliforms of about 3-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-log for treated wastewater reuse. These waters are loaded prior to about 10$^{5}$ CFU/100 mL of $P. aeruginosa$. The examination of results mentioned in Fig. 3 and for most of the strains studied, showed that a perfectly mixed reactor was inefficient in the case of disinfection of wastewater by UV radiation. Indeed, the average turnover rate for 2 strains examined, which are respectively S1 and S19, has not exceeded 2-log for residence times of up to 70 sec. For strains S12, S15, and S18, the rate of inactivation could not exceed 3-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 Fig. 3, showed that average removal efficiency of about 4-log was observed for the 2 strains, S18, and S19. Dissidence occurred
Fig. 3. Changes in the rate of inactivation of the number of *Pseudomonas aeruginosa* tested at the exit of the ultraviolet (UV) reactor, considering the average residence time, the mean intensities of UV radiation and the hydraulic model. \( y_{\text{reduction}} = \frac{N}{N_0} \) with \( N \): Number of micro-organisms at the instant \( T \); \( N_0 \): number of micro-organisms at the instant \( T=0 \); \( T_s \) the average residence time in the reactor(s); PMR: perfectly mixed reactor; PMRs: perfectly mixed reactor in series.
on the inactivation rate for the other strain, which failed to reach $10^4$, the performance required by several standardized international guidelines if purified water is reused for agricultural purposes. Similarly, we can deduce here that the nature of flows in the reactor has more impact on the final yield of disinfection. We can see for example in Fig. 3 (strain S19), a plug flow reactor is 14 times more efficient than a perfectly mixed reactor where the residence time is 40 sec. This divergence is even more prominent for higher residence times, and is thus most important for UV doses, and this result is valid for strain S12 taken as an example.

A significant improvement in the microbiological water quality is observed when the UV reactor operates as two perfectly mixed reactors in series. This is noticed mainly for strains S1, S18, and S19 where a removal efficiency of 4-log is figured despite the wide divergence in their responses to residence time as discussed. Indeed, a residence time of 27 sec appeared sufficient to meet the standards required for the S4 strain; on the contrary, to reach the same performance, a time of residence of 10 and 50 sec is required for strains S11 and S19, respectively.

With regard to the major observations advanced earlier and to better meet the requirements of environmental microbiological safety, public health and even industry, seeking other alternatives to replace the first simulation that has shown its limits seems to be indisputable, despite the improvement of the rate of efficiency registered for some strains. If we assimilate our UV-C reactor by a succession of reactors in series. This is noticed mainly for strains S1, S18, and S19 where a removal efficiency of 4-log is figured despite the wide divergence in their responses to residence time as discussed. Indeed, a residence time of 27 sec appeared sufficient to meet the standards required for the S4 strain; on the contrary, to reach the same performance, a time of residence of 10 and 50 sec is required for strains S11 and S19, respectively.

A succession of 6 or even 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 if the reactor is perfectly mixed with a succession of two reactors in series or even in piston. For other strains (such as S4), in order to achieve this performance, the residence time of 27 sec is needed, where the reactor would operate as two perfectly mixed reactors in series, and more than 65 sec in the case of a reactor close enough to plug flow [40, 43].

A succession of 6 or even 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, Figs. 1 and 2 taken as a model showed that the removal rate of bacteria if the reactor operates as a succession of 6 and even 8 perfectly mixed reactors in series seemed to be a combination of 4 reactors placed in series. With respect to all interpretations that we advanced for the process of UV-disinfection of treated wastewater, in order to assume 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 result is not only 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.

4. Conclusions

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 described, very well the kinetics of disinfection. According to parameter $\varepsilon$ 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 $\varepsilon$ were very low for all strains. Thus, we see that the model of Collins-Selleck seems to be most effective given the change in the kinetics during the disinfection process. Similarly, we therefore find that the Hom model also shows a significant performance in describing the kinetics of disinfection for most strains tested. Compared to an overall approach, for all the regression models and based on the two parameters (the correlation coefficient $R^2$ and $\varepsilon$), the model of Collins-Selleck gave the best results for the description of UV inactivation, and it will be chosen as a basic model for all hydrodynamic modeling concerning the UV-C reactor performance study.

Finally, in considering all the interpretations advanced previously concerning the process of disinfection of treated wastewater by UV radiation and for a complete microbial cleaning, we need to simulate the operation of the UV reactor as a succession of four perfectly mixed reactors in series.

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