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# Multivariable model of an ultraviolet water disinfection system

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**ABSTRACT**

Making clean water with best quality through ultraviolet (UV) disinfection has become a very affordable solution in areas where potable water is highly required. This process is free of the harmful by substances associated with chemical disinfection. Furthermore, it has the added benefit of not compromising the taste, the color and the odor of the treated water. In order to operate UV disinfection plants at the optimum conditions, an efficient control based on multivariable model has to be implemented. The main objective of this paper is development of a novel multiple-input multiple-output model of the UV disinfection process. Compared with other developed models, this new dynamic model, based on empirical transfer matrix and extended to a state-space model, takes into account various water quality parameters. It is also easy to be used in simulation and in practical implementation. The accuracy of our developed model is demonstrated by computer dynamic simulation and validated by experimental results. A good agreement was observed.

*Keywords:* Modeling; Multivariable systems; State-space model; UV water disinfection; UV dose

## 1. Introduction

Groundwater, surface water and stored rainwater are particularly exposed to pollution. Since these water sources are not usually treated or disinfected, they could be factors of certain disease transmission. Numerous studies have been developed to improve water treatment systems [1,2], especially those that aim to disinfect water by eliminating pathogenic microorganisms and ensure safe water.

Disinfection may be accomplished by chemical or physical means [3]. Chlorination, chloramination, ozonation and ultraviolet (UV) systems are the most common methods used for drinking water and wastewater treatment. However, the use of chemical disinfectants leads to the formation of disinfection by-products [4]. For example, at high doses, chlorine can produce carcinogenic or mutagenic by-products, and also adversely affect the odor and taste of the water [5]. These defects and deficiencies have generated interest in disinfection alternatives to chlorination. Therefore, one alternative that has received considerable interest and was widely used in the treatment of drinking water is disinfection with $UV_{254}$ radiation [6,7]. Indeed, UV water treatment offers many advantages; most importantly, it does not introduce any chemicals to the water; it produces no by-products; and it does not alter the taste, pH or other properties of the water [8]. This method is also presented as a technique with: greater effectiveness on a wide range of pathogens including many chlorine-resistant viruses and protozoans; fast contact time typically less than 60 s; low capital and operating costs; and simple operation with minimal system maintenance, hence greater safety for operators [9].

In this context, several research studies have been carried out in order to control the process and the technological support. Blatchley [10] developed the multiple-point source summation model distribution of the UV intensity in

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the space based on the approximation of the lamp by a finite number of point sources. This model was then improved by the study proposed by Bolton [11], which included the effect of reflection and refraction.

In a study on hydrodynamics, Koutchma et al. [12] presented a comparison between laminar and turbulent flows for testing the effect of turbulence on reactor performance. In the same context, the results obtained in reference [13] showed that the fluence distribution and the effluent inactivation levels were sensitive to the turbulence model selection. Chen et al. [14] proposed a computational fluid dynamics model for UV disinfection to calculate the flow field on one hand and to obtain the fluence rate field on the other. Chiu et al. [15] presented a model that provides an attractive representation of the transport of microorganisms in open channel UV systems where the distribution of the estimated dose was obtained by combining measurements of hydrodynamic behavior with estimation of the UV intensity field.

To study the kinetics of bacteria inactivation, several studies have been conducted in the laboratory. A comparison between the sensitivity of microorganisms and UV radiation was presented in reference [6]; this study showed that viruses are generally more resistant than bacteria. The influence of suspended solids and the temperature on the inactivation kinetics of bacterial strains of *Pseudomonas aeruginosa* was studied in reference [16]. Laboratory investigations presented in reference [17] showed that the kinetics of bacterial removal does not obey the results of the Chick–Watson model in its original form, but that there are two types of kinetics according to the UV dose applied: a high rate of inactivation with weak UV doses and a low rate of inactivation with relatively high doses.

In reference [18], a bond graph model of the UV disinfection system was developed. This model was obtained by associating the bond graph models of different elements of the system: UV lamp, ballast and motor pump.

Hence, we can say that existing models are either: chemical, biological or engineering as regards the design of reactors; and the studies devoted to various aspect of this subject are limited. In fact, methods that have been used for the design of water disinfection systems are based on complex physical equations and present difficulties due to the choice of the system parameters. Disinfection modeling was carried out for the majority of the studies in the stationary mode. Consequently, the absence of dynamic models does not allow the integration of a control strategy. In addition, modeling each part of the UV disinfection system independently of the other parts does not imply a dynamic modeling of the whole system.

The UV disinfection is a highly complex process, and the effectiveness of this technology depends on certain important parameters corresponding to the water flow rate, the $UV_{254}$ intensity, the water quality, the temperature, the exposure time, the microorganism concentration etc. On the other hand, physical, biological and chemical processes involved in wastewater treatment exhibit nonlinear behaviors that are difficult to describe. Consequently, modeling of the disinfection process in a photoreactor is a difficult task [17–19].

The improvement of the disinfected water quality with the minimum cost requires an efficient control and better optimization of the disinfection process by developing a robust mathematical and dynamic model of the disinfection system. The purpose of this study is to develop a new approach to modeling based on a dynamic and useful global model for a UV disinfection system. The proposed model considers the unit as a multiple-input multiple-output (MIMO) system that is the best representation of a dynamic model, based on experimental results. A transfer matrix extended to a state-space model was developed to obtain the relation between output and input variables. We show that the model developed is suitable for simulations, dynamic analysis and optimization. It can easily be used for control strategies in order to ensure optimum operating conditions and to improve water quality.

This paper is organized as follows: the first part is devoted to the description of the UV water disinfection process, the UV disinfection system and the experimental procedure. The transfer model and the state-space model are dealt with in the second part. Finally, results of simulations and model validation are presented in the third section.

## 2. Materials and methods

### *2.1. UV water disinfection process*

UV light is part of electromagnetic radiation. It is characterized by wavelengths between 100 and 400 nm. The UV band is usually subdivided into four regions: vacuum UV (100–200 nm), UV-C (200–280 nm), UV-B (280–315 nm) and UV-A (315–400 nm) where are located the most effective wavelengths for disinfection. The maximum efficiency of UV disinfection corresponds to output energy of 253.7 nm that represents the absorption peak of UV radiation by the microorganisms.

The UV rays, similar to the sun's UV but stronger, alter the nucleic acid (DNA) of microbes such as viruses, bacteria, molds or parasites so that they cannot reproduce and are considered as inactivated [8].

The effectiveness of disinfection is mainly influenced by the design of the experimental system in which disinfection is carried out [7]. Generally, most current UV disinfection systems employ tubular germicidal lamps surrounded by a quartz tube submerged in a chamber through which the fluid flows. The UV source of radiation used is usually a low-pressure mercury arc lamp that generates shortwave UV in the region of 253.7 nm [15,16,20]. Discharge lamps need some electric circuits generated through ballasts for their correct operation. Such circuits have to ensure mainly three general functions that are: the starting of the discharge lamp; the lamp relighting each half cycle and the control of the electric current through the discharge lamp. There are two types of ballasts: magnetic and electronic ballasts. But in recent years, electronic ballasts have been presented as a substitute for magnetic ballasts because of their superior qualities such as their high system performance (improved power factor); their light weight; the light produced per watt; their long service life; the ability to control their light intensity; the non-flashing and the absence of audible noise [21,22]. In the study conducted in reference [23], two types of power supplies were used: the traditional electromagnetic ballast and electronic ballast, allowing modulating frequencies. This study proves that the regulation of a traditional UV lamp at a high frequency supply can provide an enhancement of the UV disinfection process and guarantee the safety of treated water.

Several characteristics must be taken into account when designing, installing and operating a UV reactor. Among them are the water quality characteristics; the distance between the lamp and the reactor wall; the distribution of UV light; the UV intensity; the exposure time and the quality of the quartz sleeve. Several other parameters can also influence the rate of microbial inactivation such as the UV dose applied; the stability of disinfectant; the contact time; the pH and the temperature of water; the number and type of microorganisms in water as well as the geometric and hydrodynamic properties of the reactor [19,24]. On the other hand, it is recommended that the water to be treated must be of a good physicochemical quality and with a UV transmission greater than 50% [17]. In fact, UV radiation is not suitable for water with high levels of suspended solids, turbidity or soluble organic matter. These materials could react with UV radiation and reduce disinfection performance, that is why water should be clarified before disinfection.

The key factor of a UV treatment system is the UV dosage, which depends on several factors, including UV lamp output intensity, contact time with the UV light and water quality. UV dose is integral to UV intensity during the exposure period. In the general case, the dose D is given by:

$$D = \int_0^t I.dt \tag{1}$$

where $D$ is the UV dose (mW s/cm$^2$); $I$ is the intensity of UV light (mW/cm$^2$) and $t$ is the time (s). If the UV intensity is constant over the exposure time, the UV dose $D$ is defined as the product of the intensity $I$ and the exposure time $t_{exp}$ (s) [20,25].

$$D = I.t_{exp} \tag{2}$$

In the case of an ideal flow of water in the UV reactor, the exposure time to UV irradiation or water residence time is the quotient of the volume of the irradiation room $V$ and the flow rate $Q$ [3,26]. Thus:

$$t_{exp} = \frac{V}{Q} \tag{3}$$

where $V$ and $Q$ are, respectively, the volume of the reactor and the water flow rate.

To better explain the inactivation process, several disinfection kinetic models have been proposed in the literature to fit experimental results, beginning from the simplest first-order model of Chick–Watson, to fairly complex models such as Collins–Selleck and other multikinetic models [24]. The kinetics of bacterial inactivation usually follows the basic first-order model, which is expressed as:

$$N = N_0.e^{-kIt} \tag{4}$$

where $N_0$ and $N$ are, respectively, the concentration (CFU/100 ml) of viable organisms before and after exposure to UV light; $k$ is the first-order inactivation rate (cm$^2$/m J); $I$ is the UV intensity (mW/cm$^2$) and $t$ (s) is the time of exposure to UV light [7].

Microbial response is a measure of the sensitivity of the microorganism to UV light and is unique to each microorganism. It expresses the degree of destruction of a microbial population or otherwise the level of microbiological inactivation, which is expressed as:

$$\text{Log Inactivation} = \log_{10}\frac{N_0}{N} \tag{5}$$

where $N_0$ and $N$ are, respectively, the concentration of viable organisms before and after exposure to UV light. It should be noted here that log inactivation is also called bacterial abatement [8,25].

### 2.2. Description of the UV disinfection system

The disinfection system that makes the object of this present study consists of a closed cylindrical stainless reactor of annular section, 70 cm length, 6 cm internal diameter and 2 L useful volume. It is equipped with a single low-pressure mercury discharge lamp (55 W power, 60 cm in length and 2 cm in diameter) placed in the axis of the irradiation room and protected by a clean quartz sleeve used to mechanically protect and seal the lamp.

The lamp was supplied via electronic ballast consisting of a single-phase rectifier, a transistor inverter producing 25–100 kHz at its output and a resonant circuit to achieve the lamp ignition [27]. The block diagram of the electronic ballast for powering the gas discharge lamp is shown in Fig. 1.

The disinfection system is also equipped with a motor pump for aspirating contaminated water from the inlet tank, a flow control valve to obtain flow rates ranging from 0.2 to 0.8 L/s and a filter for improving the transmittance of the contaminated water. Treated water in this system could be recycled through a recycling circuit that might enable several passages through the irradiation chamber.

The schematic diagram and a photo of the UV water disinfection system are shown in Fig. 2.

### 2.3. Experimental procedure

The study consisted in monitoring the quality of the contaminated water to deduct the microbial load before ($N_0$) and after ($N$) UV exposure. Experiments in disinfection were conducted using a laboratory strain of *Escherichia coli*, earlier isolated in 2002 from wastewater. The rationale for the choice of this species is that it is a ubiquitous strain that is commonly detected in surface water, wastewater, hospitals, air and even in the soil and plants, and is easily cultivable. Also, *E. coli* strain was used in this study due to its strictly fecal character. Its absence is one of the most common biological indicators of efficient water disinfection, a feature governed by all water

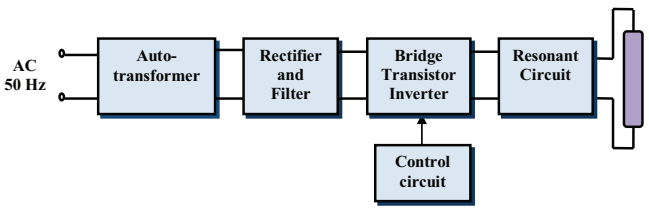


Fig. 1. The block diagram of the electronic ballast for powering the UV discharge lamp.

quality regulations [7]. Additionally, it is the cause of several confirmed outbreaks and is highly resistant to disinfection [28,29]. Therefore, its kinetics of inactivation by UV irradiation resembles those of all other less resistant pathogens [17].

This strain of *E. coli* is grown in Pasteur Institute nutrient broth laboratory and, prior to each experiment, is cultivated to mid-log phase at 37°C in 20 mL of the nutrient broth. For this study the culture was centrifuged at 5,000 rpm for 15 min, and the pellet was washed twice with sterile distilled water. The washed pellet was resuspended in 10 mL sterile distilled water, vortexed vigorously for at least 4 min in order to remove all bacterial aggregates, and to ensure a total disaggregation of the microbial cells. These last *E. coli* microbial cells were then seeded separately into 15 L of freshwater filled in the inlet tank (the artificial contamination of water) to give a viable cell count of approximately $10^4$/mL and $10^6$/mL. The UV transmittance of the used freshwater was around 90%; the electrical conductivity of around 1,704 μS/cm and the pH was 7.8. All experiments were performed at laboratory temperature between 20°C and 25°C.

After having artificially contaminated 15 L of freshwater with the bacterial cell pellet recovered after centrifugation, intense and prolonged homogenization was required to ensure the dispersion of the pellet in the whole volume of water. Infected water, aspirated gradually by the motor pump, enters at the bottom of the reactor and flows around the lamp, before exiting the unit. The disinfected water exits the unit after a well-determined passage of time in relation to the chosen flow rate.

Seeded freshwater served for counting bacteria, before ($N_0$) and after ($N$) the passage through the UV system for different working conditions. The water samples were collected in sterile glass bottles for microbiological analyses. Analysis was done immediately on receipt of samples in the laboratory, usually within 1–3 h of sample collection [17].

For bacteria counting, a volume of 500 μL collected from decimal dilution of each sample was plated on the surface of Petri dishes containing nutrient agar. After incubation at 37°C for 24 h, colonies were counted, and the results were expressed by colony-forming units. Bacterial counting was performed by the pour plate technique on a PCA medium according to French standards (Standard NF T 90-401).

During each handling, UV intensity emitted by the lamp of the photoreactor was measured by using an UV product, Vilber–Lourmat digital radiometer. Flow rate was set at the desired value by manipulating the valve connected to the motor pump.

UV dose absorbed by the microorganisms along the disinfection process was determined using expression (2). Owing to the fact that it is impossible to physically or chemically measure the exact UV dose in a reactor [30]. Residence time and bacterial reduction are, respectively, determined according to expressions (3) and (4).

## 3. The disinfection system model

### 3.1. The static model

The goal in designing UV reactors for drinking water disinfection is to efficiently deliver the dose necessary to inactivate pathogenic microorganisms [25]. Thus, the determination of bacterial reduction as well as the dose delivered by the reactor is of major importance in the UV water

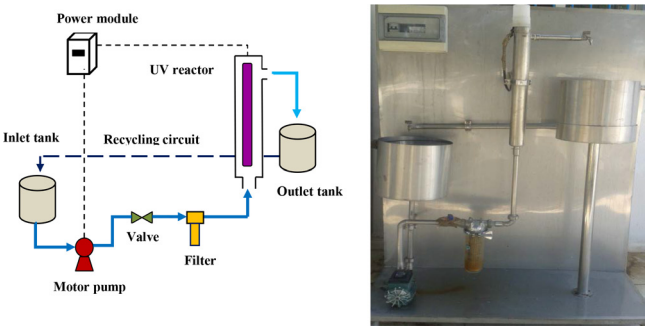


Fig. 2. Schematic diagram and a photograph of the UV disinfection system used in this study.

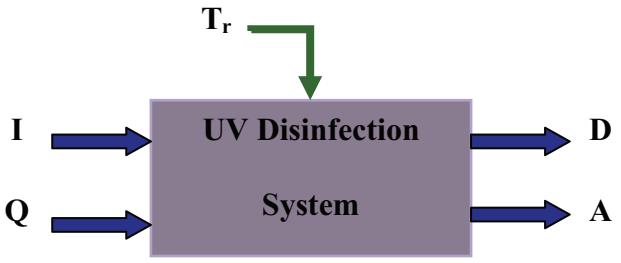


Fig. 3. Static model of the disinfection system: $I$ – UV lamp intensity; $Q$ – water flow rate; $D$ – UV dose; and $A$ – bacterial abatement.

disinfection process. Both of these variables are dependent on several parameters such as UV intensity, exposure time, transmittance, temperature, pH and the hydraulic characteristics of the disinfection unit. In this study, only UV intensity, exposure time and UV transmittance are considered. The formulation of the disinfection problem is then as follows: the water to be disinfected is characterized by a UV transmittance$T_r$; an initial number of microorganisms $N_0$ and an inlet flow rate $Q$. The treated water collected in the reactor outlet is characterized by the number $N$ of microorganisms, while the UV dose $D$ delivered by the reactor depends on the UV light intensity $I$, the exposure time $t_{exp}$ and the water quality.

In this work, the feed flow $Q$ and the UV lamp intensity $I$ were considered as input parameters or manipulated variables. UV dose $D$ and bacterial reduction $A$ that are fundamental to determine bacteriological water quality were defined as output parameters or set variables. The transmittance $T_r$ at the entry was considered as a disruptive input. Thus, we deduce the static model where the disinfection unit is shown as a multivariable system with two inputs and two outputs (Fig. 3). The following representations (that is the transfer model and the state-space model) could be associated with the established multivariable model.

### 3.2. The disinfection system transfer model

The disinfection process could be considered in a system approach since it has inputs and outputs. Thus, the automatic tools, identification, command and robustness analysis can be applied to this process. Modeling is the basic step in the study of a system; it reflects the relationship between

the different variables of the system. It consists in building a mathematical model that can describe the static and dynamic behavior of the system. According to reference [31] a model is a simplistic representation of a system, which artificially reproduces and describes the original system, and allows the study system for understanding the properties of the original system and its behavior prediction.

In the present study, the dynamic model of the unit is given by a transfer function matrix that describes the relationship between inputs and outputs of the system. For MIMO systems, with $m$ inputs and $n$ outputs, the transfer function is an ($m \times n$) dimension matrix. If $T$ is the transfer matrix, $U$ is the input vector and $Y$ is the output vector, the process will be described by:

$$Y = \left[T\right]U \tag{6}$$

For the disinfection system, the control vector $U$ and the output vector $Y$ are given by:

$$U = \begin{bmatrix} I \\ Q \end{bmatrix}, \quad Y = \begin{bmatrix} D \\ A \end{bmatrix} \tag{7}$$

where $I$ is the UV lamp intensity; $Q$ is the water flow rate; $D$ is the UV Dose and $A$ is the bacterial abatement.

The transfer matrix $T$ with (2 × 2) dimension is given by:

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \tag{8}$$

where:

$$T_{11} = \frac{D}{I} \text{ For } Q \text{ and } T_r \text{ constants} \tag{9}$$

$$T_{12} = \frac{D}{Q} \text{ For } I \text{ and } T_r \text{ constants} \tag{10}$$

$$T_{21} = \frac{A}{I} \text{ For } Q \text{ and } T_r \text{ constants} \tag{11}$$

$$T_{22} = \frac{A}{Q} \text{ For } I \text{ and } T_r \text{ constants} \tag{12}$$

Elementary transfer functions that obey, as the case, at first- or second-order dynamics were determined by conducting a series of experimental measurements. Subsequently, the stored measurements were introduced in the identification procedure of the MATLAB software [32], which is a MATLAB tool used to obtain dynamic models of systems by using input–output data from the system to identify. The System Identification Toolbox provides a graphical user interface that covers most of the toolbox's functions and gives easy access to all variables that are created during a session. The identification by this procedure is based on the use of recursive least square method [33]. Three steps are needed to achieve the identification operation: importing data, estimating and validating models.

The first step is to import data into the identification tool. During this phase, input and output variables are specified. The next step is the model estimation where the process model is selected; this model is characterized by a static gain, time constant and a delay. The third step is the model validation where the model-output plot is used to check how well the model output matches the measured output in the validation data set. The best fits area of the model output plot shows the agreement (in %) between the model output and the validation-data output. The elementary transfer functions given by the identification procedure with the disturbed parameter fixed at its maximum value (transmittance equal to 90%: clear freshwater) are as follows:

$$T_{11} = \frac{k_{11}}{p} = \frac{1}{p} \tag{13}$$

$$T_{12} = \frac{k_{12}\omega_{0_{12}}^2}{p^2 + 2\xi_{12}\omega_{0_{12}}p + \omega_{0_{12}}^2} = \frac{98.86}{p^2 + 6.77p + 6.02} \tag{14}$$

$$T_{21} = \frac{k_{21}\omega_{0_{21}}^2}{p^2 + 2\xi_{21}\omega_{0_{21}}p + \omega_{0_{21}}^2} = \frac{0.55}{p^2 + 1.67p + 0.70} \tag{15}$$

$$T_{22} = \frac{k_{22}}{1 + \tau_{22}p} = \frac{2.79}{1 + 1.78p} \tag{16}$$

### 3.3. The disinfection system state-space model

By considering the following vector $X$ as state vector:

$$X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} \text{With}: X_1 = D,\ X_2 = \frac{dD}{dt},\ X_3 = A \text{ and } X_4 = \frac{dA}{dt} \tag{17}$$

The state equation representing the system is:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX \end{cases} \tag{18}$$

Matrices $A$, $B$ and $C$ are defined as follows:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\omega_{0_{12}}^2 & -2\xi_{12}\omega_{0_{12}} & 0 & 0 \\ 0 & 0 & \dfrac{-1}{\tau_{22}} & 1 \\ 0 & 0 & -\omega_{0_{21}}^2 & -2\xi_{21}\omega_{0_{21}} \end{bmatrix} \tag{19}$$

$$B = \begin{bmatrix} k_{11} & 0 \\ 0 & k_{12}\omega_{0_{12}}^2 \\ 0 & \dfrac{k_{22}}{\tau_{22}} \\ k_{21}\omega_{0_{21}}^2 & 0 \end{bmatrix} \tag{20}$$

By replacing the parameters with their values obtained in the identification procedure, we obtained:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -6.02 & -6.77 & 0 & 0 \\ 0 & 0 & -0.56 & 1 \\ 0 & 0 & -0.70 & -1.67 \end{bmatrix} \quad (21)$$

$$B = \begin{bmatrix} 1 & 0 \\ 0 & 98.86 \\ 0 & 1.56 \\ 0.55 & 0 \end{bmatrix} \quad (22)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (23)$$

## 4. Experimental results and model validation

### *4.1. Experimental results and discussion*

We have shown that we conducted a series of experiments in order to study the behavior of outputs parameters based on inputs ones, on the one hand, and to get an idea about the dynamic behavior of the disinfection unit, on the other hand. The experiments were carried out in a UV disinfection system according to operational conditions as outlined previously. In this study, the impacts of flow rate and UV irradiation on UV dose and bacterial inactivation were then investigated.

Three lamp UV intensity values were considered: $I_1$ = 10 mW/cm², $I_2$ = 7 mW/cm² and $I_3$ = 5 mW/cm². For each value of the UV intensity, water flow rate at the entry of the rector was varied from 0.2 to 0.8 L/s. Transmittance of water was kept constant and equal to 90%. The results of the experiments are presented in Figs. 4 and 5. Fig. 4 shows the variation of the UV dose delivered by the reactor vs. water flow rate. The curves obtained show that the UV dose received by the microorganisms decreased with the increase of the flow rate, while an increase of the UV intensity of the lamp led to an increase of UV dose received by the microorganisms. Fig. 5 shows the variation of the bacterial reduction vs. the water flow rate. According to this figure, the bacterial reduction was inversely proportional to the flow rate and increased with the increase in the UV intensity.

The lowest value of the flow rate was 0.2 L/s; the corresponding exposure time was then 10 s. The corresponding UV doses to the UV used intensities (10, 7 and 5 mW/cm²) were, respectively, 100, 70 and 50 mW s/cm². Bacterial abatements were, respectively, 4.4, 4 and 3.7 log inactivation. On the other hand, the highest value of the flow rate was 0.8 L/s; the corresponding exposure time was 2.5 s. The corresponding UV doses to the UV used intensity (10, 7 and 5 mW/cm²) were, respectively, 25, 17.5 and 12.5 mW s/cm². Bacterial abatements were, respectively, 2.9, 2.1 and 1.4 log inactivation.

It is clear from the obtained results that the efficacy of the treatment was hardly affected by the flow rate and the UV lamp intensity. In fact, the application of a low flow at the inlet of the reactor, involved an increase in the exposure time of the bacteria with the germicidal radiation and therefore an increase in the UV dose. In this case, the passage of particles in the reactor will be prolonged, and the probability of their escape from the UV radiation would decrease; so the inactivation rate will be important. On the contrary, an increase in flow causes a reduction of the exposure time to the UV-C radiation, and therefore, a decrease in the UV-C dose and consequently a decrease of the inactivation rate would occur. On the other hand, an increase in the UV light systematically caused an increase in the amount of UV dose received by the bacterial cells in the water to be treated, causing the reduction in the number of cells, and therefore the increase in the bacterial reduction.

Therefore, to summarize, the degree of disinfection is dependent on a UV dose that can be calculated from the exposure time and the average UV intensity in the reactor. The dose may be adjusted by acting either on the UV lamp intensity or on the exposure time set by the choice of the corresponding flow rate. To provide the adequate dose of UV light and therefore a high inactivation rate, the best combination of contact time flow rate should be established.

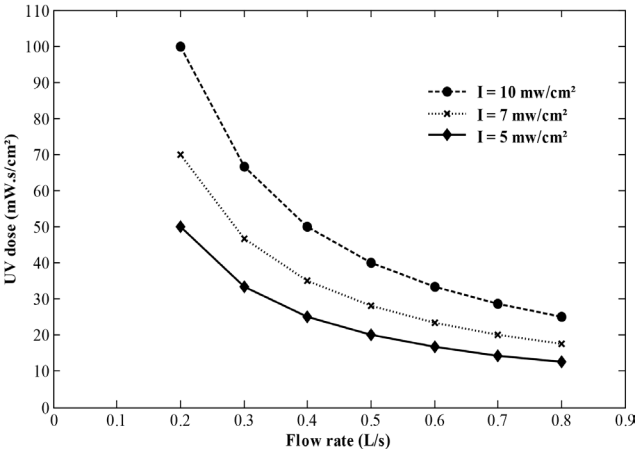


Fig. 4. UV doses vs. flow rates.

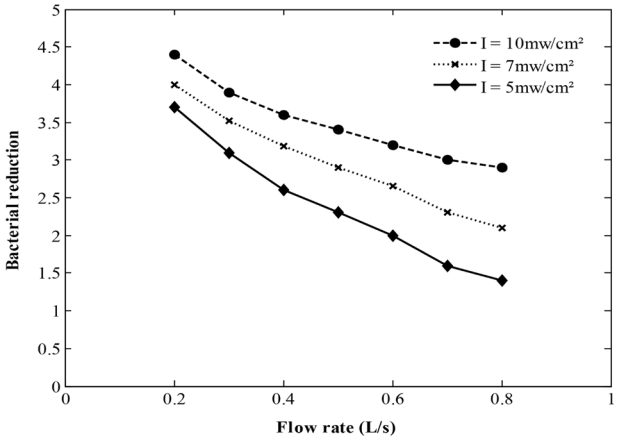


Fig. 5. Bacterial reduction vs. flow rate.

*4.2. Models validation*

Step signals of the input parameters (UV intensity $I$ and flow rate $Q$) were applied in order to get step responses of the outputs (UV dose $D$ and bacterial reduction $A$) on the one hand, and to validate the established models on the other hand.

Figs. 6 and 7 show, respectively, the validation of the UV dose and the bacterial reduction models, for a step of flow rate of 0.3 L/s and UV lamp intensity fixed at 10 mW/s.

Fig. 8 shows the validation of the bacterial reduction model for a step of UV intensity of 10 mW/cm$^2$ and a fixed flow rate of around 0.2 L/s.

The comparison between the experimental and simulated results, illustrated in Figs 6, 7 and 8, shows that the simulated curves lag slightly behind the experimental ones. Thus, we can affirm that the model we developed reflects the real dynamic of the system. In fact, the error or the difference between model and measured values is practically zero in permanent regime. Consequently, we can deduce good agreements between the dynamic behavior of the UV water disinfection system and its developed state-space model.

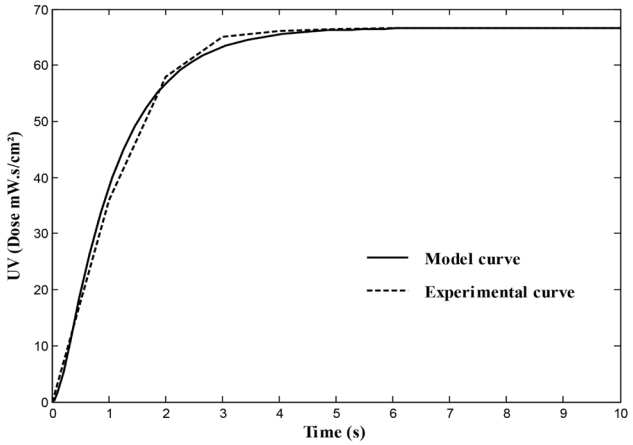


Fig. 6. UV dose model validation on a step response of the flow rate.

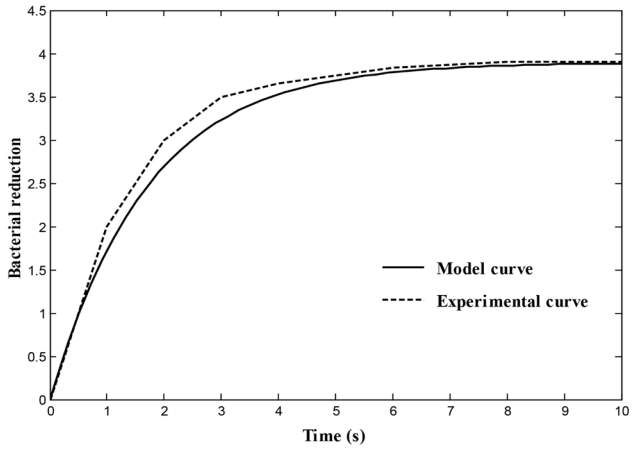


Fig. 7. Bacterial reduction model validation on a step response of the flow rate.

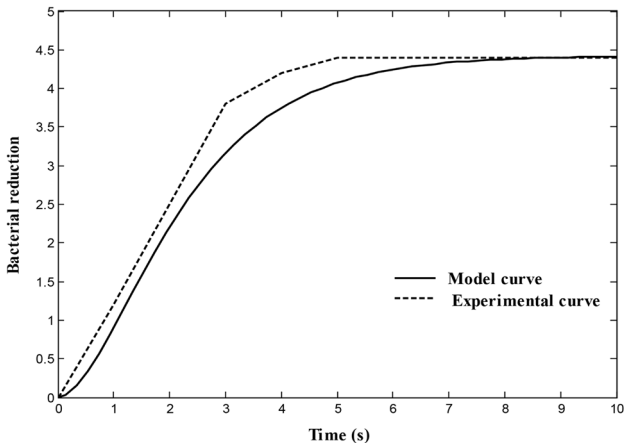


Fig. 8. Bacterial reduction model validation on a step response of the UV intensity.

## 5. Conclusion

In this study a new dynamic model of a UV water disinfection process based on experimental results was proposed. The unit dynamic model is given by a transfer function extended to a state-space model. The model presents the unit as an MIMO system. The input parameters are the feed water flow and the UV intensity of the germicidal lamp, while the output parameters are the disinfection level and the UV dose. These parameters traduce the treated water quality and the system efficiency. The proposed model was simulated, and an experimental platform was tested to validate the model dynamic. It has been shown that the agreement between experiment and simulation was positive. To operate the UV water disinfection system under optimum conditions, the use of this established model to develop a control strategy was a key perspective of this study.

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