Disinfection of Drain Water by Means of UVC Radiation - Experimental Prototypes for Small Flows

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Abstract
In the present study two prototypes were constructed to adapt the different physical variables involved in the disinfection of lixiviates to their characteristics, their nature and flow, considering as well the economy of the process. A closed channel contact system prototype was chosen to increase the effectiveness of disinfection. This prototype consisted of a 75 W low-pressure mercury vapour lamp, wrapped in a steel case. With this kind of prototype, a complete disinfection of fungi, bacteria, viruses and weeds can be obtained with doses up to 40 mW s cm⁻² for flows up to 0.5 l s⁻¹. It is also possible to decrease the dose depending on the infectious agent. An open channel UVC reactor prototype was chosen, instead of the closed channel system, in order to eliminate lamp maintenance and obstacles (quartz cover) in the transmission. This prototype consisted of an UV lamp installed longitudinally over a 120 cm long horizontal steel tray through which a 2 mm film of lixiviates circulated constantly. With both prototypes, changing the voltage was an effective method to increase or to decrease the dose to a constant flow, without exceeding the limits of the working lamp. Considering the temperature inside the greenhouse, the UV reactor operated at a temperature close to its optimal efficiency. A clear advantage of this prototype was its cost, far below the price of commercial devices.

INTRODUCTION
The use of irrigation effluents in hydroponic crops may represent savings of up to 20% in water and fertilizers in addition to preventing subsoil contamination. Nowadays commercial devices of ultraviolet radiation for water treatment are used for their disinfection. These devices are only slightly versatile for research due to their excessive size and the lack of information on their physical characteristics. Besides, with the commercial models parameters like flows, dose of UV, etc. are fixed or are only somewhat modifiable.

The main objective of this study was to develop and to test two prototypes of UV radiation reactors with low-pressure mercury vapour lamps, for the disinfection of drain water in hydroponic crops growing under greenhouse conditions.

Sources of UV Radiation
There are four wavelength zones of the UV radiation spectrum (Fig.1), but only the UVC and UVB zones have germicidal properties for disinfection (Meulemans, 1986). Microorganisms are inactivated by UV radiation as a result of the photochemical damage to their nucleic acids (Wright and Caims, 1999). The greatest values of absorption are in the wavelengths next to 265 nm (UVC). The most common sources of UV radiation are low-pressure and medium-pressure mercury vapour lamps.

Low-pressure mercury vapour lamps emit light at a wavelength of 254 nm (Fig. 2); they have an electrical power close to 0.3 W cm⁻², and their efficiency in converting electrical power into UV radiation is close to 40%. Medium-pressure lamps have emission peaks at UVB and UVC radiation (Fig. 2); these lamps have an electrical power between 48 and 126 W cm⁻², and their efficiency is higher than 16% (Phillips, 1983).
In large disinfection plants, medium-pressure lamps are used because of their higher UV power per lamp, in spite of their inferior conversion efficiency. However, low-pressure lamps are often used to disinfect small flows given their enhanced efficiency.

**The Inactivation Kinetic by UV Radiation**

The microbial inactivation kinetic by UV radiation follows Chick-Watson’s law: \( \ln \left( \frac{N}{N_0} \right) = -K I t \), where \( N_0 \) is the initial concentration of microorganisms prior to the application of UV radiation; \( N \) is the concentration of microorganisms after exposure to UV light; \( K \) is the microorganism death-rate constant, in \( \text{cm}^2 \mu\text{W}^{-1} \text{s}^{-1} \); \( I \) is the UV radiation intensity, in \( \text{W cm}^{-2} \); and \( t \) is the exposure time, in seconds (Moura, 2002).

The dose of UV radiation applied is defined as radiation intensity multiplied by exposure time: \( D = I t \ (\text{W s cm}^{-2}) \). In drinking water treatment, doses of up to 40 mW s cm\(^{-2}\) are recommended (Wright and Cairns, 1999). It is also advisable to increase the dose for agricultural water due to the presence of solids in suspension.

The UV radiation is absorbed by the dispersed particles and by the liquid itself; therefore, as the radiation penetrates in the liquid, its value decreases according to Beer-Lambert’s law: \( I = I_0 e^{-\alpha x} \), where \( I \) is the radiation intensity in the liquid; \( I_0 \) is the radiation intensity of the source; \( \alpha \) is the UV radiation absorbance in the liquid, in \( \text{cm}^{-1} \); and \( x \) is the liquid thickness, in cm (Pires et al., 1998).

**MATERIALS AND METHODS**

**Type of Lamp**

The following parameters of 31 commercial models of lamps have been analysed from commercial catalogues: UVC efficiency, working hours, price and length of the lamp according to its application.

A linear correlation with the efficiency of conversion in radiation UVC and electrical power consumed was obtained. The UVC radiation intensity (W cm\(^{-2}\)) was identified for each lamp according to its size. Among lamps that were adaptable to prototype, the lamp with best performance and lower cost was chosen.

**UV Reactor Design**

UV reactors can be classified according to the position of both the radiation source and the liquid in the open channel system, closed contactless channel system and the closed channel contact system (Wright and Cairns, 1999).

The UV radiation is absorbed by liquids which are coloured or contain suspended matter, and thus, decrease the efficiency of the disinfection. In this research, the drain water were filtered, using a sand filter of 0.4 mm.

The thickness of the liquid film was small enough (2-5 mm) for a uniform penetration of the radiation. The liquid can contaminate the lamp or its case so it is necessary to clean them.

In this study, two UV reactor prototypes were tested:

1. **Prototype 1. Closed Channel Contact System** (Fig. 3). This prototype consisted of a 75 W low-pressure mercury vapour lamp, with emission at the wavelength of 254 nm, wrapped in a steel case. The liquid flowed between the quartz pipe of the lamp and the steel case. Thus, the quartz pipe was used as an inner wall of the reactor to increase the effectiveness of the disinfection.

2. **Prototype 2. Open Channel System** (Fig. 4). This prototype consisted of a UV lamp, similar to the one previously described, with a reflecting parabolic cylinder. The lamp was installed longitudinally over a horizontal steel tray measuring 120 cm in length and 10.5 cm in width, through which a film of lixiviates circulated constantly. With this prototype, there was no contact between the lamp and the liquid, and their cleaning was not necessary.

The prototype effectiveness depended on the kind of reflector. In addition, the amount and uniformity of the dose depended on the position of the lamp within the...
Four kinds of reflecting parabolic cylinder were tested, using the same width base (10.5 cm) and four different heights (9.5 - 7.0 - 4.7 - 4.2 cm). For each height tested, the lamp was placed at different vertical axis positions, and the radiation intensity on a transversal section of the reflector base was measured (Fig. 5).

Characterization of Lamp Performance
The effect of pipe temperature on lamp performance was analysed for the prototype 1. Voltage source, voltage applied to the lamp, voltage applied to the ballast, lamp temperature, ballast temperature and electric current were measured for different water flows.

A variable-voltage source (autotransformer) was installed in order to control the radiation intensity and to determine voltage as well as current limits.

Disinfection Tests
Fungi are often transmitted through irrigation water, causing extensive damage to hydroponics crops (Magán, 2000). Two types were used to verify the effectiveness of the disinfection.

1. *Fusarium* spp. Initial experiments were conducted in the laboratory in order to verify the effectiveness of the open channel prototype. A *fusarium* ssp. saturated suspension was irradiated with different UVC doses, next the suspension was cultivated in petri dishes (four repetitions per dose), and finally the colonies were counted after 7 and 15 days of being cultivated in chamber (Department of plant Pathology, UPV). Four water flows ware studied: 0.25, 0.5, 1 and 3 l/min, voltage = 220 V.

2. *Olpidium brassicae*. Initial experiments with hydroponic tomato crops growing in a greenhouse are currently being carried out. The infected plant lixiviates have been treated with different UVC radiation doses, and three repetitions per dose are being performed. This treated water is being used to irrigate the crop, twice a week, at a rate of 200 cm$^3$ per plant. Afterwards, the fungi invasion of plant roots will be analysed.

RESULTS AND DISCUSSION
As a result of the experiments carried out with commercial models of lamps, the following correlation between the efficiency of conversion in UVC radiation and the consumed electrical power was obtained: $y = 0.3453x + 0.0551$ ($r^2 = 0.957$). Based on this data, the lamp model TUV 75W-HO (Phillips International, Inc.) was chosen because it proved to have the highest efficiency and to be the most adaptable to the reactor conditions.

Prototype 1
1. **Consumed Electrical Power Variation in Terms of the Applied Voltage.** Electric current and consumed electrical power vary according to the voltage. Source voltage down to 155 V was appropriate for the performance of 75 W low-pressure mercury vapour lamps (230V). Consequently, the variation of applied voltage using an autotransformer was used to obtain different values of UVC radiation intensity.

A linear correlation between applied voltage and consumed electrical power at both a constant temperature and flow was obtained: $y = 1.6514x+103.14$ ($r^2 = 0.997$). Figure 6 shows the variation of different electrical parameters in terms of voltage at a constant lamp temperature of 65°C.

Figure 7 illustrates voltage and electric current waves on the oscilloscope screen. It can be observed that they did not match with sine waves so electrical power was measured by an electrodynamic wattmeter. The following linear correlation between electrical power measured by a wattmeter and calculated by the expression $V I \cos \phi$ was obtained: $y = 1.0827x -21.678$ ($r^2 = 0.994$). Consequently, the electrical power can be obtained from easily measurable parameters ($V$ and $I$).

2. **Consumed Electrical Power Variation in Terms of Temperature.** The lamp temperature was variable because of the contact between the circulating liquid and the
As a result, the electrical power consumed by the lamp varied. Figure 8 illustrates that consumed electrical power, and consequently UVC radiation, reached the highest values between 30 and 40 °C.

3. Applied Doses. Figure 9 shows the relationship between the voltage applied and the doses for a uniform thickness of liquid and for different flows (between 10 and 30 l min⁻¹). Clearly, the minimum dose recommended for effective disinfection (40 mW.s.cm⁻²) was reached with flows inferior to 30 l min⁻¹.

Prototype 2
Figure 10 shows the radiation intensity emitted through the pipe. It is worth pointing out that the radiation decreased at the lamp extremes. Accordingly, these extremes were not useful for disinfection and were not taken into account in the applied dose.

1. Reflector Selection. The main factor taken into consideration in the selection of the reflector was the uniformity of the radiation on the liquid surface since the movement of the liquid is almost laminar.

Dose and uniformity of the UVC radiation. The closer the lamp was to the liquid, the more the average dose on the liquid increased. By contrast, the greater the distance between the lamp and the reflector, the lesser the degree of uniformity.

Table 1 illustrates the distance between the lamp and the reflector that provided the maximum uniformity. The relative average dose is indicated in each case. It is worth noting that the highest average doses and uniformity were achieved with the lowest reflector (4.2 cm in height).

Figure 11 shows the values of relative UVC radiation through the liquid, indicating the specific distances between the lamp and the reflector. The maximum uniformity was clearly reached when the lamp was placed close to the reflector.

2. Disinfection Results. Table 2 summarises the effectiveness of different UVC doses on a *Fusarium* ssp. saturated solution. We observe that in contaminated solutions, the disinfection was complete with the highest doses and only a few colonies survived with the lowest doses.

CONCLUSIONS
- Different UVC radiation doses can be obtained by varying the applied tension.
- The highest emission efficiency of the lamp was achieved for lamp temperatures between 30 and 40 °C.
- The doses supplied by prototype 1 ensured total disinfection for a wide range of water flows.
- With prototype 2, the lowest reflector was the most efficient considering the dose applied and its uniformity. The maximum uniformity was clearly reached when the lamp and the reflector were in contact.
- The assembly of these prototypes is easy and economical, the cost being far below that of commercial devices.

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Literature Cited

Tables

Table 1. Effect of the geometrical shapes of the reflector on the relative radiation. Prototype 2. Standard deviation indicates a dose uniformity.

<table>
<thead>
<tr>
<th>Parabola length cm</th>
<th>Parabola height cm</th>
<th>Distance lamp-base reflector cm</th>
<th>Distance lamp-top reflector cm</th>
<th>Relative radiation W cm⁻²</th>
<th>Standard deviation (uniformity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0</td>
<td>9.5</td>
<td>7.65</td>
<td>1.85</td>
<td>0.660</td>
<td>0.13</td>
</tr>
<tr>
<td>19.5</td>
<td>7.0</td>
<td>5.15</td>
<td>1.85</td>
<td>0.843</td>
<td>0.31</td>
</tr>
<tr>
<td>16.0</td>
<td>4.7</td>
<td>3.45</td>
<td>1.25</td>
<td>0.933</td>
<td>0.08</td>
</tr>
<tr>
<td>14.0</td>
<td>4.2</td>
<td>2.95</td>
<td>1.25</td>
<td>1.000</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 2. Effect of UVC radiation doses on the number of fusarium ssp. colonies.

<table>
<thead>
<tr>
<th>Dose</th>
<th>750 mW s / cm²</th>
<th>375 mW s / cm²</th>
<th>187.5 mW s / cm²</th>
<th>62.5 mW s / cm²</th>
<th>0 mW s / cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>0,25 l/min</td>
<td>0,5 l/min</td>
<td>1 l/min</td>
<td>3 l/min</td>
<td></td>
</tr>
<tr>
<td>Colonies</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>195</td>
</tr>
</tbody>
</table>

Figures

Fig. 1. UV electromagnetic spectrum.
Fig. 2. (a) Low-pressure and (b) medium-pressure mercury vapour lamp spectrums.

Fig. 3. Schematic representation of prototype 1.

Fig. 4. Schematic representation of prototype 2.
Fig. 5. Positions of the lamp within the reflector of prototype 2 for measuring radiation intensity on a transversal section of the reflector base at liquid level.

Fig. 6. Effect of the applied voltage on electrical parameters of the lamp in prototype 1. Lamp temperature: 65 °C.

Fig. 7. Voltage and electric current waves on the oscilloscope screen. Prototype 1.

Fig. 8. Electrical power consumed by the lamp in terms of its temperature. Prototype 1. $y = -0.021x^2 + 1.4606x + 50.255$. 
Fig. 9. Relationship between applied voltages and doses obtained, for a uniform thickness of liquid and different circulating flows. Prototype 1.

Fig. 10. Relative radiation intensity on the liquid emitted through the pipe depending on the distance to the lamp extreme. Prototype 2.

Fig. 11. Relative UVC radiation through the liquid according to the distance from the lamp to the reflector. Prototype 2. Parabola length 16 cm.