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POSSIBILITIES OF USING THE GERMICIDAL EFFECT OF UV-C LIGHT FOR DISINFECTING THE WATER USED IN FOOD INDUSTRY

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Abstract: *Drinking water, like every other substance, contains small amounts of bacteria. Thus, chlorine is usually added to drinking water to prevent bacterial growth. Since minimal remnant amounts of chlorine are found in drinking water, new sterilization alternatives were developed over time. Due to its germicidal effectiveness, UV-C light became an alternative to chemicals. Nowadays, UV-C light is often used to disinfect water for a wide variety of applications. The sterilization technology based on UV-C light is used to disinfect drinking water, to purify water for pharmaceuticals and semiconductors processing, to disinfect water for the food and beverage industry etc.*

Key words: *disinfection, germicidal effectiveness, UV-C light.*

1. Introduction

UV disinfection is an established technology supported by decades of fundamental and applied research and practice in North America and Europe. Downes and Blunt (1877) discovered the germicidal properties of sunlight.

The development of mercury lamps as artificial UV light sources in 1901 and the use of quartz as a UV transmitting material in 1906 were soon followed by the first drinking water disinfection application in Marseilles, France, in 1910. The development of the fluorescent lamp in the 1930s led to the production of germicidal tubular lamps [1].

Considerable research on the mechanisms of UV disinfection and the inactivation of microorganisms occurred during the 1950s. The germicidal effectiveness of UV-C light is in the 180-320 nm regions with an optimum at 265 nm. Approximately 95% of the energy radiated by a low-pressure mercury arc is at the 253.7 nm line, so this source is the most effective one for germicidal applications.

Ultraviolet light (UV) is an established and increasingly popular alternative to chemicals for the disinfection of drinking water, wastewater, and industrial waters of various qualities [2].

2. Material and Methods

Ultraviolet (UV) radiation is a form of non ionizing radiation and behaves in accordance with the laws and principles of

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geometric optics. Electromagnetic radiation (Figure 1) can be described as a "wave" that consists of an electric field and a magnetic field.

Electromagnetic radiation is usually characterized by wavelength, frequency and/or photon energy. The term wavelength is a fundamental descriptor of electromagnetic energy, including light that refers to a distance in a line of advance of a wave from any point to a similar point on the next wave. It corresponds to the distance travelled by the wave during one cycle. It is the velocity of light divided by equivalent frequency of oscillation associated with a photon. A wavelength is typically measured in angstroms or nanometres [nm]. Ultraviolet (UV) radiation is a form of electromagnetic radiation with wavelengths between the blue region of the visible light and the X-ray region.

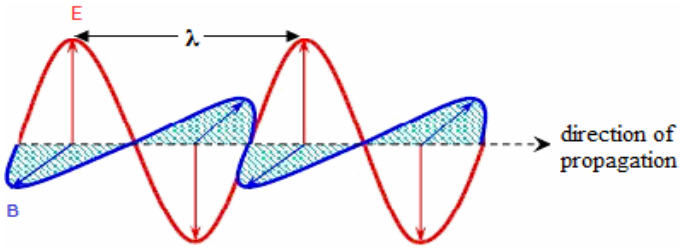

Fig. 1. *Electromagnetic radiation* [13]

The International Commission on Illumination (CIE) divided the UV spectrum into three wavelength bands primarily due to biological effects. The 315-400 nm wavelength band is designated as UV-A (near UV), 280-315 nm is designated as UV-B (middle UV), and 100-280 nm as UV-C (far UV). Wavelengths below 180 nm are of little practical biological significance since the atmosphere readily absorbs them [3].

In other scientific papers the UV spectrum is divided into four regions: vacuum UV (100 to 200 nm), UV-C (200 to 280 nm), UV-B (280 to 315 nm) and UV-A (315 to 400 nm).

As UV light propagates from its source, it interacts with the materials it encounters through absorption, reflection, refraction, and scattering.

Absorption is the transformation of light to other forms of energy as it passes through a substance. UV absorbance of a substance varies with the wavelength (λ) of the light. Unlike absorption, the phenomena of refraction, reflection, and scattering change the direction of UV light, but the UV light is still available to disinfect microorganisms.

Refraction (Figure 2) is the change in the direction of light propagation as it passes through the interface between one medium and another.

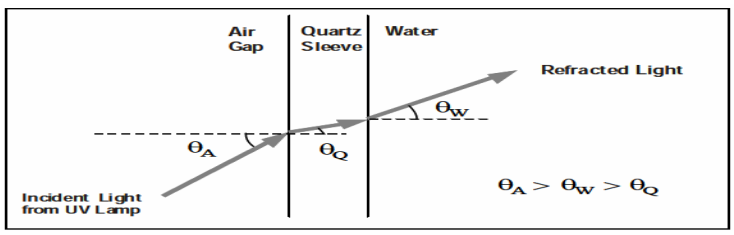

Fig. 2. *Refraction of Light* [11]

Reflection is the change in direction of light propagation when it is deflected by a surface (Figure 3). Reflection may be classified as specular or diffuse. Specular reflection occurs from smooth polished surfaces and follows the Law of Reflection (the angle of incidence is equal to the angle of reflection). Diffuse reflection occurs from rough surfaces and scatters light in all directions with little dependence on the incident angle. In UV reactors, reflection will take place at interfaces that do not transmit UV light (e.g., the reactor wall) and also at UV transmitting interfaces (e.g., the inside of a lamp sleeve). The type of reflection and intensity of light reflected from a surface depends on the material of the surface.

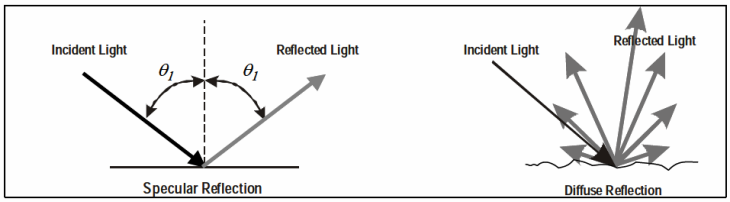

Fig. 3. *Reflection of light* [11]

Scattering of light is the change in direction of light propagation caused by interaction with a particle (Figure 4). Particles can cause scattering in all directions, including toward the incident light source (back-scattering). Scattering of light caused by particles smaller than the wavelength of the light is called Rayleigh scattering. Rayleigh scattering depends inversely on wavelength to the fourth power ($1/\lambda^4$) and thus is more prominent at shorter wavelengths. Particles larger than the wavelength of light scatter more light in the forward direction but also cause some backscattering that is relatively independent of wavelength.

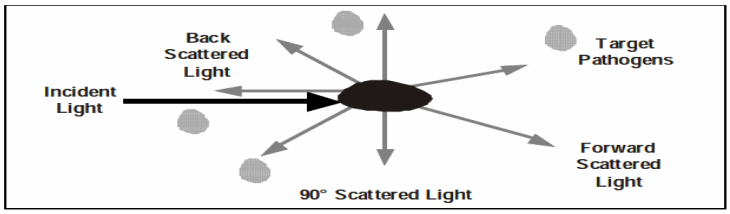

Fig. 4. *Scattering of Light* [11]

UV radiation exposure is typically quantified in terms of an irradiance **E** [W/m^2] for continuous exposure, or in terms of a radiation exposure **H** [J/m^2] for time-limited exposure. In different cases UV can be an alternative to the chlorination of drinking water because unlike chemical disinfectants, UV leaves no residual that can be monitored to determine UV dose and inactivation credit. The UV dose depends on the UV intensity (measured by UV sensors), the flow rate, and the UV transmittance (UVT).

• ***Terms and definitions***

UV Dose - the UV energy per unit area incident on a surface, typically reported in units of mJ/cm^2 or J/m^2. The UV dose received by a waterborne microorganism in a reactor vessel accounts for the effects

on UV intensity of the absorbance of the water, absorbance of the quartz sleeves, reflection and refraction of light from the water surface and reactor walls, and the germicidal effectiveness of the UV wavelengths transmitted.

***UV Absorbance* (*A*)** - a measure of the amount of UV light that is absorbed by a substance (e.g., water, microbial DNA, lamp envelope, quartz sleeve) at a specific wavelength (e.g., 254 nm). This measurement accounts for absorption and scattering in the medium (e.g., water).

***UV Absorbance at 254 nm* (A_{254})** - a measure of the amount of UV light that is absorbed by a substance at 254 nm. A_{254} is measured using a spectrophotometer with 254 nm incident light and is typically reported on a per centimetre [cm^{-1}] basis.

***Required Dose* (D_{req})** - the UV dose in units of mJ/cm^2 needed to achieve the target log inactivation for the target pathogen.

***Validated Dose* (D_{val})** - the UV dose in units of mJ/cm^2 delivered by the UV reactor as determined through validation testing. The validated dose is compared to the Required Dose (D_{req}) to determine log inactivation credit.

Calculated Dose - the RED calculated using the dose-monitoring equation that was developed through validation testing.

UV Dose-Response - the relationship indicating the level of inactivation of a microorganism as a function of UV dose.

UV Irradiance - the power per unit area incident to the direction of light propagation at all angles, including normal.

UV Intensity - the power passing through a unit area perpendicular to the direction of propagation.

UV Transmittance (UVT) - a measure of the fraction of incident light transmitted through a material (e.g., water sample or quartz). The UV Transmittance is usually reported for a wavelength of 254 nm and a path length of 1 cm. If an alternate path length is used, it should be specified or converted to units of cm^{-1}. UV Transmittance is often represented as a percentage and is related to the UV absorbance (A_{254}) by the following equation (for a 1 cm path length): $\% T = 100 \cdot 10^{-A}$.

Gas Discharge - a mixture of non-excited atoms, excited atoms, cations, and free electrons formed when a sufficiently high voltage is applied across a volume of gas. Most commercial UV lamps use mercury gas discharges to generate UV light.

Germicidal Effectiveness - the relative inactivation efficiency of each UV wavelength in an emission spectrum. This value is usually approximated by the relative absorbance of DNA at each wavelength.

Reduction Equivalent Dose (RED) - the UV dose derived by entering the log inactivation measured during full-scale reactor testing into the UV dose-response curve that was derived through collimated beam testing. RED values are always specific to the challenge microorganism used during experimental testing and the validation test conditions for full-scale reactor testing [4].

• ***UV light sources***

UV light sources are characterized by the mercury vapor pressure inside the lamp, and the relative UV energy they produce. UV light sources primarily come as low-pressure or medium/high-pressure lamps. Low-pressure lamps produce virtually all of their UV output at a wavelength of 254 nm, very close to the peak germicidal effectiveness curve of 264 nanometres [10]. These lamps are available in ozone producing or non-ozone producing and they are used in small systems. The peak wavelength for the non ozone producing germicidal lamp is 253.7 nm and the peak wavelength for ozone producing germicidal lamps is 253.7 nm and 185 nm.

Typically, UV light is generated by applying a voltage across a gas mixture contained within a lamp envelope. The gas

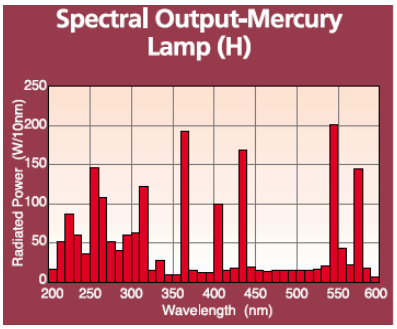

Fig. 5. *Typical spectral output from a Mercury Lamp* [12]

is temporarily excited by the discharge and then returns to a lower energy state, resulting in the discharge of photons.

In operating lamps, elemental mercury (from pure or amalgamated mercury) is vaporized in the presence of an inert gas. The concentration of mercury in the vapor phase is controlled predominantly by temperature. At typical low-pressure (LP) and low-pressure-high-output (LPHO) lamp operating temperatures, only a small portion of the liquid (pure) or solid (amalgam) mercury is vaporized. However, at typical medium-pressure (MP) lamp temperatures (600 to 900 ºC), mercury is present primarily in the vapor phase due to the high operating temperatures. A main characteristic of a UV lamp is the spectral output (Figure 5) which represents the radiant output of a lamp versus wavelength. It is displayed in a variety of ways, but most commonly as a graph or chart of output watts plotted against wavelength. The appearance of the plot will vary dramatically, depending on the wavelength resolution used. A technique of normalizing is to integrate spectral power over 10 nanometer bands, to reduce the difficulty of quantifying the effects of line emission spectra [8].

The specific wavelengths of light emitted from photons discharge depend on the elemental composition of the gas and the power level of the lamp. The light output from mercury-based UV lamps depends on the concentration of mercury atoms, which is directly related to the mercury vapor pressure [6]. In low-pressure (LP) UV lamps, mercury at low vapor pressure and moderate temperature (40 ºC) produces essentially monochromatic (one wavelength) UV light at 253.7 nm. In medium-pressure (MP) UV lamps, a higher vapor pressure, and higher operating temperature (600...900 ºC) is used to increase the frequency of collisions between mercury atoms, which produces UV light over a broad spectrum (polychromatic) with an overall higher intensity. They are capable of treating significant flow volumes and lower quality water.

In comparison, low-pressure lamps perform safely and efficiently and they are the better option for use in UV sterilization (Figures 6 and 7).

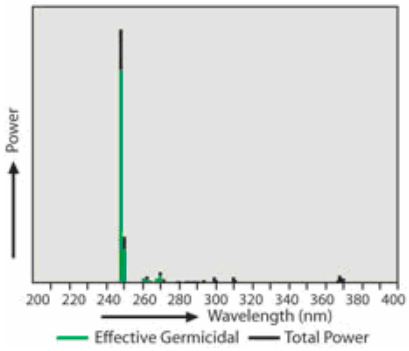

Fig. 6. *LP mercury lamp relative spectral power distribution curve* [10]

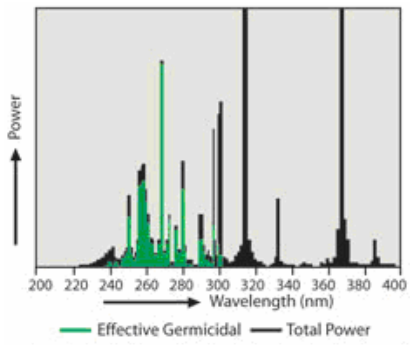

Fig. 7. *MP/HP mercury lamp relative spectral power distribution curve* [10]

Since the very beginnings of mercury lighting it has been realised that a significant portion of the energy radiated by all mercury discharges is in the ultraviolet part of the spectrum. In the case of the low pressure discharge, more than half of the total energy supplied is radiated in the short-wave UV region at 253.7 nm. High pressure lamps radiate about 10% of their energy in the long-wave UV region at 365.0 nm, but an appreciable amount is also radiated at shorter wavelengths. These lamps are very poor producers of usable germicidal wavelengths [5].

In 1995, approximately 98% of all UV systems being used to disinfect wastewater used low-pressure (LP) mercury vapor lamps. In the mid-1990s, UV disinfection systems with medium-pressure lamps were introduced into the UV disinfection market and were shortly followed by LP, high-intensity and pulsed UV technologies in the late 1990s. These advances in lamp technologies continued to fuel the growth of UV for wastewater applications.

• ***Principles***

UV disinfection is a physical process that achieves disinfection by inducing photochemical changes within microorganisms, and unlike other disinfectants, UV light does not inactivate microorganisms by chemical reaction.

Since most microorganisms are affected by radiation around 260 nm, UV-C light is in the appropriate range for germicidal activity. UV light inactivates microorganisms by damaging their nucleic acid, thereby preventing them from replicating (Figure 8). For UV light to effectively inactivate a microorganism, the DNA must absorb energy from an appropriate range of the electromagnetic spectrum.

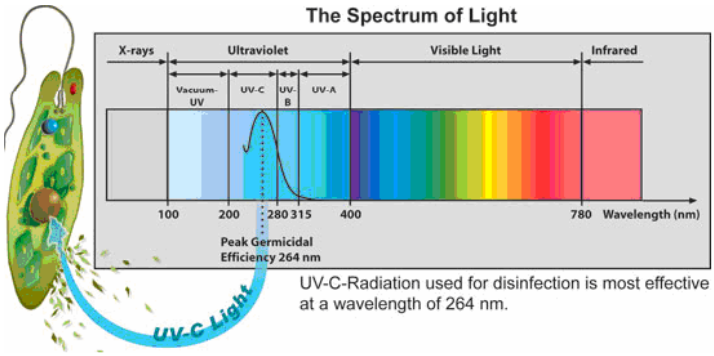

Fig. 8. *The peak germicidal effectiveness curve* [10]

To be most effective for disinfection, the spectral output of a germicidal UV lamp should match the absorption spectrum of the target organism's genome.

As UV light penetrates bacteria, viruses, and other microorganisms, the energy is absorbed by the organism's nucleic acids, causing structural damage [3].

UV light penetrates and permanently alters the DNA of the microorganisms in a process called *thymine dimerization.* The microorganisms are "inactivated" and rendered unable to reproduce or infect.

The log inactivation (log I) determines the magnitude reduction in concentration using the following equation:

$$\log I = \log I \cdot (N_0/N), \qquad (1)$$

where: N_0 - challenge microorganism concentration in influent sample, in pfu/mL or cfu/mL; N - challenge microorganism

concentration in corresponding effluent sample, in pfu/mL or cfu/mL [4].

The level of inactivation of typical bacterial indicator organisms can be demonstrated using the equation below:

$$N = N_0 \cdot e^{-I \cdot t}, \quad (2)$$

where: N - organism concentration following UV exposure; N_0 - initial organism concentration; I - UV intensity at a wavelength of 253.7 nm, and t - exposure time. The degree of inactivation by ultraviolet radiation is directly related to the UV dose applied to the water. The relationship between the UV dose and destruction achieved of a target microorganism is shown in Table 1.

Significant research has been done in the past years to determine the log inactivation of various pathogens. The UV dose requirement to reach the percent removal of various pathogens is shown in Table 2.

Dose/Destruction relationship [7] Table 1

Dose [mJ/cm^2]	Reduction in number of live microorganisms
5.4	90.0%
10.8	99.0%
16.2	99.9%
21.6	99.99%
27.0	99.999%

UV Dose Requirements (*mJ/cm^2*) [9] Table 2

Target Pathogens	Log inactivation							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	15	22
Giardia	1.5	2.1	3.0	5.2	7.7	11	15	22
Virus	39	58	79	100	121	143	163	186

- ***The use of UV radiation for disinfecting the water used in food industry***

In an increasingly regulated and safety-conscious market, the bottled water and beverage industries have to meet ever more stringent standards of quality. Microbial growth due to contaminated water supplies or sugar syrups and flavorings can cause discoloration, off-flavors and shortened shelf-life, as well as increasing the risk of infection to consumers. The threat of contamination is further increased as manufacturers respond to consumer demand for a reduction in chemical additives. Effective microbial disinfection of the whole production process is therefore essential [5].

Since some processes (e.g food and beverage industries) are unable to tolerate chlorine, the advantage of using UV for water treatment over other methods (mainly chemical) is that there is no residual chemical or hazardous by product at the end of the process. Unlike chemical biocides, UV-C light does not introduce toxins or residues into water and does not alter the chemical composition, taste, odor or pH of the fluid being disinfected. This feature is especially important in the bottled water and beverage industries where the chemical dosing of incoming process water can cause off-flavors and alter the chemical properties of the final product.

3. Conclusions

- Ultraviolet (UV) disinfection is now an accepted technology for inactivation of a variety of waterborne pathogens in wastewater and drinking water.

• UV light is a natural, cost effective, environmentally friendly and non-thermal disinfection process which can be used for multiple purposes in water and air treatment, but is primarily employed as a disinfection process that inactivates microorganisms without chemicals and harmful side effects.

• Currently, the most widely utilized UV lamp technologies employed for the disinfection of wastewater and drinking water throughout the world are low-pressure (LP), low-pressure-high-output (LPHO), and medium pressure (MP) mercury vapor lamps.

Acknowledgements

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