Ultraviolet germicidal irradiation

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Ultraviolet germicidal irradiation (**UVGI**) is a disinfection method that uses short-wavelength ultraviolet (UV-C) light to kill or inactivate microorganisms by destroying nucleic acids and disrupting their DNA, leaving them unable to perform vital cellular functions.[1] UVGI is used in a variety of applications, such as food, air, and water purification.

A low-pressure mercury-vapor discharge tube floods the inside of a biosafety cabinet with shortwave UV light when not in use, sterilizing microbiological contaminants from irradiated surfaces.

UV-C light is weak at the Earth's surface as the ozone layer of the atmosphere blocks it.[2] UVGI devices can produce strong enough UV-C light in circulating air or water systems to make them inhospitable environments to microorganisms such as bacteria, viruses, molds and other pathogens. UVGI can be coupled with a filtration system to sanitize air and water.

The application of UVGI to disinfection has been an accepted practice since the mid-20th century. It has been used primarily in medical sanitation and sterile work facilities. Increasingly it has been employed to sterilize drinking and wastewater, as the holding facilities are enclosed and can be circulated to ensure a higher exposure to the UV. In recent years UVGI has found renewed application in air purifiers.

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History

In 1878, Arthur Downes and Thomas P. Blunt published a paper describing the sterilization of bacteria exposed to short-wavelength light.[3] UV has been a known mutagen at the cellular level for more than one hundred years. The 1903 Nobel Prize for Medicine was awarded to Niels Finsen for his use of UV against lupus vulgaris, tuberculosis of the skin.[4]

Using UV light for disinfection of drinking water dates back to the year 1910 in Marseille, France.[5] The prototype plant was taken out of service after only a short time, due to reliability problems. In 1955, UV water treatment systems were applied in Austria and Switzerland; by 1985 about 1,500 plants were in use in Europe. In 1998 it was discovered that protozoa such as cryptosporidium and giardia were more vulnerable to UV light than previously thought; this opened the way to wide-scale use of UV water treatment in North America. By 2001, over 6,000 UV water treatment plants were operating in Europe.[6]

Over the years, UV costs have declined as researchers develop and use new UV methods to disinfect water and wastewater. Currently, several countries have developed regulations that allow systems to disinfect their drinking water supplies with UV light.

Method of operation

UV light is electromagnetic radiation with wavelengths shorter than visible light. UV can be separated into various ranges, with short-wavelength UV (UVC) considered "germicidal UV". At certain wavelengths, UV is mutagenic to bacteria, viruses and other microorganisms. Particularly at wavelengths around 260 nm–270 nm,[7] UV breaks molecular bonds within microorganismal DNA, producing thymine dimers that can kill or disable the organisms. Mercury-based lamps emit UV light at the 253.7 nm line[7] Pulsed-xenon lamps emit UV light across the entire UV spectrum. [8] Ultraviolet Light Emitting Diodes (UV-C LED) lamps emit UV light at selectable wavelengths between 255 and 280 nm.[9] It is a process similar to the effect of longer wavelengths (UVB) producing sunburn in humans. Microorganisms have less protection from UV and cannot survive prolonged exposure to it.

A UVGI system is designed to expose environments such as water tanks, sealed rooms and forced air systems to germicidal UV. Exposure comes from germicidal lamps that emit germicidal UV electromagnetic radiation at the correct wavelength, thus irradiating the environment. The forced flow of air or water through this environment ensures the exposure.

Effectiveness

The effectiveness of germicidal UV depends on the length of time a microorganism is exposed to UV, the intensity and wavelength of the UV radiation, the presence of particles that can protect the microorganisms from UV, and a microorganism's ability to withstand UV during its exposure.

In many systems, redundancy in exposing microorganisms to UV is achieved by circulating the air or water repeatedly. This ensures multiple passes so that the UV is effective against the highest number of microorganisms and will irradiate resistant microorganisms more than once to break them down.

"Sterilization" is often misquoted as being achievable. While it is theoretically possible in a controlled environment, it is very difficult to prove and the term "disinfection" is generally used by companies offering this service as to avoid legal reprimand. Specialist companies will often advertise a certain log reduction e.g., 99.9999% effective, instead of sterilization. This takes into consideration a phenomenon known as light and dark repair (photoreactivation and base excision repair, respectively), in which a cell can repair DNA that has been damaged by UV light.

The effectiveness of this form of disinfection depends on line-of-sight exposure of the microorganisms to the UV light. Environments where design creates obstacles that block the UV light are not as effective. In such an environment, the effectiveness is then reliant on the placement of the UVGI system so that line of sight is optimum for disinfection.

Dust and films coating the bulb lower UV output. Therefore, bulbs require periodic cleaning and replacement to ensure effectiveness. The lifetime of germicidal UV bulbs varies depending on design. Also, the material that the bulb is made of can absorb some of the germicidal rays.

Lamp cooling under airflow can also lower UV output; thus, care should be taken to shield lamps from direct airflow, or to add additional lamps to compensate for the cooling effect.

Increases in effectiveness and UV intensity can be achieved by using reflection. Aluminum has the highest reflectivity rate versus other metals and is recommended when using UV.

One method for gauging UV effectiveness in water disinfection applications is to compute UV dose. The U.S. EPA publishes UV dosage guidelines for water treatment applications.[10] UV dose cannot be measured directly but can be inferred based on the known or estimated inputs to the process:

- Flow rate (contact time)
- Transmittance (light reaching the target)
- Turbidity (cloudiness)
- Lamp age or fouling or outages (reduction in UV intensity)

In air and surface disinfection applications the UV effectiveness is estimated by calculating the UV dose which will be delivered to the microbial population. The UV dose is calculated as follows:

UV dose (http://www.americanairandwater.com/uv-definitions/index.htm) $\mu Ws/cm^2$ = UV intensity $\mu W/cm^2$ x Exposure time (seconds)

The UV intensity is specified for each lamp at a distance of 1 meter. UV intensity is inversely proportional to the square of the distance so it decreases at longer distances. Alternatively, it rapidly increases at distances shorter than 1m. In the above formula the UV intensity must always be adjusted for distance unless the UV dose is calculated at exactly 1m from the lamp. Also, to ensure effectiveness the UV dose must be calculated at the end of lamp life (EOL is specified in number of hours when the lamp is expected to reach 80% of its initial UV output) and at the furthest distance from the lamp on the periphery of the target area. In some applications coating is applied to the lamp to make it shatterproof. The coating is Fluoro Ethylene Polymer which completely encapsulates the lamp and contains the shards and mercury in case of accidental breakage. The coating decreases the UV intensity up to 20%.

To accurately predict what UV dose will be delivered to the target the UV intensity, adjusted for distance, coating and end of lamp life, will be multiplied by the exposure time. In static applications the exposure time can be as long as needed for an effective UV dose to be reached. In case of rapidly moving air, in AC air ducts for example, the exposure time is short so the UV intensity must be increased by introducing multiple UV lamps or even banks of lamps. Also, the UV installation must be located in a long straight duct section with the lamps perpendicular to the air flow to maximize the exposure time.

These calculations actually predict the UV fluence (http://www.americanairandwater.com/uv-definitions/) and it is assumed that the UV fluence will be equal to the UV dose. The UV dose is the amount of germicidal UV energy absorbed by a microbial population over a period of time. If the microorganisms are planktonic (free floating) the UV fluence will be equal the UV dose. However, if the microorganisms are protected by mechanical particles, such as dust and dirt, or have formed biofilm a much higher UV fluence will be needed for an effective UV dose to be introduced to the microbial population.

Inactivation of microorganisms

The degree of inactivation by ultraviolet radiation is directly related to the UV dose applied to the water. The dosage, a product of UV light intensity and exposure time, is usually measured in microjoules per square centimeter, or equivalently as microwatt seconds per square centimeter ($\mu W \cdot s/cm^2$). Dosages for a 90% kill of most bacteria and viruses range from 2,000 to 8,000 $\mu W \cdot s/cm^2$. Larger parasites such as cryptosporidium require a lower dose for inactivation. As a result, the U.S. Environmental Protection Agency has accepted UV disinfection as a method for drinking water plants to obtain cryptosporidium, giardia or virus inactivation credits. For example, for one-decimal-logarithm reduction of cryptosporidium, a minimum dose of 2,500 $\mu W \cdot s/cm^2$ is required based on the U.S. EPA UV Guidance Manual published in 2006.[11]:1–7

Strengths and weaknesses

Advantages

UV water treatment devices can be used for well water and surface water disinfection. UV treatment compares favorably with other water disinfection systems in terms of cost, labor, and the need for technically trained personnel for operation. Water chlorination treats larger organisms and offers residual disinfection, but these systems are expensive because they need special operator training and a steady supply of a potentially hazardous material. Finally, boiling of water is the most reliable treatment method but it demands labor, and imposes a high economic cost. UV treatment is rapid and, in terms of primary energy use, approximately 20,000 times more efficient than boiling.

Disadvantages

UV disinfection is most effective for treating high-clarity, purified reverse osmosis distilled water. Suspended particles are a problem because microorganisms buried within particles are shielded from the UV light and pass through the unit unaffected. However, UV systems can be coupled with a pre-filter to remove those larger organisms that would otherwise pass through the UV system unaffected. The pre-filter also clarifies the water to improve light transmittance and therefore UV dose throughout the entire water column. Another key factor of UV water treatment is the flow rate—if the flow is too high, water will pass through without sufficient UV exposure. If the flow is too low, heat may build up and damage the UV lamp.[12]

A disadvantage of UVGI is that while water treated by chlorination is resistant to reinfection (until the chlorine off-gasses), UVGI water is not resistant to reinfection. UVGI water must be transported or delivered in such a way as to avoid reinfection.

Safety

In UVGI systems the lamps are shielded or are in environments that limit exposure, such as a closed water tank or closed air circulation system, often with interlocks that automatically shut off the UV lamps if the system is opened for access by human beings.

For human beings, skin exposure to germicidal wavelengths of UV light can produce rapid sunburn and skin cancer. Exposure of the eyes to this UV radiation can produce extremely painful inflammation of the cornea and temporary or permanent vision impairment, up to and including blindness in some cases. UV can damage the retina of the eye.

Another potential danger is the UV production of ozone, which can be harmful to health. The U.S. Environmental Protection Agency designated 0.05 parts per million (ppm) of ozone to be a safe level. Lamps designed to release UVC and higher frequencies are doped so that any UV light below 254 nm wavelengths will not be released, to minimize ozone production. A full-spectrum lamp will release all UV wavelengths, and will produce ozone when UVC hits oxygen (O_2) molecules.

UV-C radiation is able to break down chemical bonds. This leads to rapid aging of plastics, insulation, gaskets, and other materials. Note that plastics sold to be "UV-resistant" are tested only for UV-B, as UV-C doesn't normally reach the surface of the Earth. When UV is used near plastic, rubber, or insulation, care should be taken to shield said components; metal tape or aluminum foil will suffice.

The American Conference of Governmental Industrial Hygienists (ACGIH) Committee on Physical Agents has established a TLV for UV-C exposure to avoid such skin and eye injuries among those most susceptible. For 254 nm UV, this TLV is 6 mJ/cm² over an eight-hour period. The TLV function differs by wavelengths because of variable energy and potential for cell damage. This TLV is supported by the International Commission on Non-Ionizing Radiation Protection and is used in setting lamp safety standards by the Illuminating Engineering Society of North America. When TUSS was planned, and until quite recently, this TLV was interpreted as if eye exposure in rooms was continuous over eight hours and at the highest eye-level irradiance found in the room. In those highly unlikely conditions, a 6.0 mJ/cm² dose is reached under the ACGIH TLV after just eight hours of continuous exposure to an irradiance of 0.2 μW/cm². Thus, 0.2 μW/cm² was widely interpreted as the upper permissible limit of irradiance at eye height.[13]

Uses

Air disinfection

UVGI can be used to disinfect air with prolonged exposure. Disinfection is a function of UV intensity and time. For this reason, it is not as effective on moving air, or when the lamp is perpendicular to the flow, as exposure times are dramatically reduced. Air purification UVGI systems can be free-standing units with shielded UV lamps that use a fan to force air past the UV light. Other systems are installed in forced air systems so that the circulation for the premises moves microorganisms past the lamps. Key to this form of sterilization is placement of the UV lamps and a good filtration system to remove the dead microorganisms.[14] For example, forced air systems by design impede line-of-sight, thus creating areas of the environment that will be shaded from the UV light. However, a UV lamp placed at the coils and drain pans of cooling systems will keep microorganisms from forming in these naturally damp places.

ASHRAE covers UVGI and its applications in indoor air quality and building maintenance in "Ultraviolet Lamp Systems", Chapter 16 of its 2008 Handbook, *HVAC Systems and Equipment*. Its 2011 Handbook, *HVAC Applications*, covers "Ultraviolet air and surface treatment" in Chapter 60.

Water disinfection


A portable, battery-powered, low-pressure mercury-vapor discharge lamp for water sterilization.

Ultraviolet disinfection of water is a purely physical, chemical-free process. Even parasites such as *cryptosporidia* or *giardia*, which are extremely resistant to chemical disinfectants, are efficiently reduced.[15] UV can also be used to remove chlorine and chloramine species from water; this process is called photolysis, and requires a higher dose than normal disinfection. The sterilized microorganisms are not removed from the water. UV disinfection does not remove dissolved organics, inorganic compounds or particles in the water.[16] However, UV-oxidation processes can be used to simultaneously destroy trace chemical contaminants and provide high-level disinfection, such as the world's largest indirect potable reuse plant in New York which opened the Catskill-Delaware Water Ultraviolet Disinfection Facility on 8 October 2013. A total of 56 energy-efficient UV reactors were installed to treat 2.2 billion US gallons (8,300,000 m^3) a day to serve New York City.[17]

It used to be thought that UV disinfection was more effective for bacteria and viruses, which have more-exposed genetic material, than for larger pathogens that have outer coatings or that form cyst states (e.g., Giardia) that shield their DNA from UV light. However, it was recently discovered that ultraviolet radiation can be somewhat effective for treating the microorganism Cryptosporidium. The findings resulted in the use of UV radiation as a viable method to treat drinking water. Giardia in turn has been shown to be very susceptible to UV-C when the tests were based on infectivity rather than excystation.[18] It has been found that protists are able to survive high UV-C doses but are sterilized at low doses.

Developing countries

A 2006 project at University of California, Berkeley produced a design for inexpensive water disinfection in resource deprived settings.[19] The project was designed to produce an open source design that could be adapted to meet local conditions. In a somewhat similar proposal in 2014, Australian students designed a system using chip packet foil to reflect solar UV radiation into a glass tube that should disinfect water without power.[20]

Wastewater treatment

Ultraviolet in sewage treatment is commonly replacing chlorination. This is in large part because of concerns that reaction of the chlorine with organic compounds in the waste water stream could synthesize potentially toxic and long lasting chlorinated organics and also because of the environmental risks of storing chlorine gas or chlorine containing chemicals. Individual wastestreams to be treated by UVGI must be tested to ensure that the method will be effective due to potential interferences such as suspended solids, dyes, or other substances that may block or absorb the UV radiation. According to the World Health Organization, "UV units to treat small batches (1 to several liters) or low flows (1 to several liters per minute) of water at the community level are estimated to have costs of US$20 per megaliter, including the cost of electricity and consumables and the annualized capital cost of the unit."[21]

Large-scale urban UV wastewater treatment is performed in cities such as Edmonton, Alberta. The use of ultraviolet light has now become standard practice in most municipal wastewater treatment processes. Effluent is now starting to be recognized as a valuable resource, not a problem that needs to be dumped. Many wastewater facilities are being renamed as water reclamation facilities, whether the wastewater is discharged into a river, used to irrigate crops, or injected into an aquifer for later recovery. Ultraviolet light is now being used to ensure water is free from harmful organisms.

Aquarium and pond

Ultraviolet sterilizers are often used to help control unwanted microorganisms in aquaria and ponds. UV irradiation ensures that pathogens cannot reproduce, thus decreasing the likelihood of a disease outbreak in an aquarium.

Aquarium and pond sterilizers are typically small, with fittings for tubing that allows the water to flow through the sterilizer on its way from a separate external filter or water pump. Within the sterilizer, water flows as close as possible to the ultraviolet light source. Water pre-filtration is critical as water turbidity lowers UVC penetration. Many of the better UV sterilizers have long dwell times and limit the space between the UVC source and the inside wall of the UV sterilizer device.[22]

Laboratory hygiene

UVGI is often used to disinfect equipment such as safety goggles, instruments, pipettors, and other devices. Lab personnel also disinfect glassware and plasticware this way. Microbiology laboratories use UVGI to disinfect surfaces inside biological safety cabinets ("hoods") between uses.

Food and beverage protection

Since the U.S. Food and Drug Administration issued a rule in 2001 requiring that virtually all fruit and vegetable juice producers follow HACCP controls, and mandating a 5-log reduction in pathogens, UVGI has seen some use in sterilization of juices such as fresh-pressed apple cider.

Technology

Lamps


A 9 W germicidal lamp in a compact fluorescent lamp form factor

Germicidal UV for disinfection is most typically generated by a mercury-vapor lamp. Low-pressure mercury vapor has a strong emission line at 254 nm, which is within the range of wavelengths that demonstrate strong disinfection effect. The optimal wavelengths for disinfection are close to 270 nm.[11]:2–6

Lamps are either amalgam or medium-pressure lamps. Low-pressure UV lamps offer high efficiencies (approx 35% UVC) but lower power, typically 1 W/cm power density (power per unit of arc length). Amalgam UV lamps are a higher-power version of low-pressure lamps. They operate at higher temperatures and have a lifetime of up to 16,000 hours. Their efficiency is slightly lower than that of traditional low-pressure lamps (approx 33% UVC output) and power density is approximately 2–3 W/cm. Medium-pressure UV lamps have a broad and pronounced peak-line spectrum and a high radiation output but lower UVC efficiency of 10% or less. Typical power density is 30 W/cm^3 or greater.

Depending on the quartz glass used for the lamp body, low-pressure and amalgam UV emit radiation at 254 nm and also at 185 nm, which has chemical effects. UV radiation at 185 nm is used to generate ozone.

The UV lamps for water treatment consist of specialized low-pressure mercury-vapor lamps that produce ultraviolet radiation at 254 nm, or medium-pressure UV lamps that produce a polychromatic output from 200 nm to visible and infrared energy. The UV lamp never contacts the water; it is either housed in a quartz glass sleeve inside the water chamber or mounted external to the water which flows through the transparent UV tube. Water passing through the flow chamber is exposed to UV rays which are absorbed by suspended solids, such as microorganisms and dirt, in the stream.[23]

Light emitting diodes (LEDs)


Compact and versatile options with UV-C LEDs

Recent developments in LED technology have led to commercially available UV-C LEDs. UV-C LEDs use semiconductors to emit light between 255 nm-280 nm.[9] The wavelength emission is tuneable by adjusting the material of the semiconductor. The reduced size of LEDs open up options for small reactor systems allowing for point-of-use applications and integration into medical devices.[24] Low power consumption of semiconductors introduce UV disinfection systems that utilized small solar cells in remote or Third World applications.[24]

Water treatment systems

Sizing of a UV system is affected by three variables: flow rate, lamp power, and UV transmittance in the water. Manufacturers typically developed sophisticated Computational Fluid Dynamics (CFD) models validated with bioassay testing. This involves testing the UV reactor's disinfection performance with either MS2 or T1 bacteriophages at various flow rates, UV transmittance, and power levels in order to develop a regression model for system sizing. For example, this is a requirement for all drinking water systems in the United States per the EPA UV Guidance Manual.[11]:5-2

The flow profile is produced from the chamber geometry, flow rate, and particular turbulence model selected. The radiation profile is developed from inputs such as water quality, lamp type (power, germicidal efficiency, spectral output, arc length), and the transmittance and dimension of the quartz sleeve. Proprietary CFD software simulates both the flow and radiation profiles. Once the 3D model of the chamber is built, it is populated with a grid or mesh that comprises thousands of small cubes.

Points of interest—such as at a bend, on the quartz sleeve surface, or around the wiper mechanism—use a higher resolution mesh, whilst other areas within the reactor use a coarse mesh. Once the mesh is produced, hundreds of thousands of virtual particles are "fired" through the chamber. Each particle has several variables of interest associated with it, and the particles are "harvested" after the reactor. Discrete phase modeling produces delivered dose, head loss, and other chamber-specific parameters.

When the modeling phase is complete, selected systems are validated using a professional third party to provide oversight and to determine how closely the model is able to predict the reality of system performance. System validation uses non-pathogenic surrogates such as MS 2 phage or *Bacillus subtilis* to determine the Reduction Equivalent Dose (RED) ability of the reactors. Most systems are validated to deliver 40 mJ/cm^2 within an envelope of flow and transmittance.

To validate effectiveness in drinking-water systems, the method described in the EPA UV Guidance Manual is typically used by the U.S., whilst Europe has adopted Germany's DVGW 294 standard. For wastewater systems, the NWRI/AwwaRF Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse protocols are typically used, especially in wastewater reuse applications.[25]

See also

- Portable water purification
- Sanitation
- Sanitation Standard Operating Procedures
- Solar water disinfection

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External links

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- [State UVGI publications by W. J. Kowalski] (http://www.engr.psu.edu/iec/)
- Residential and Commercial UVGI systems with detailed UV-C indoor air treatment information (http://www.negativeiongenerators.com/ultraviolet.html)
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- This page was last modified on 13 December 2016, at 15:33.
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