Ultraviolet Sterilizes Drinking Water With Renewable Energy Systems

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ABSTRACT

High operating costs for conventional water sterilization techniques preclude their application in numerous water supply systems in developing countries. Ultraviolet (UV) disinfection, using 254 nm radiation, appears to be a cost-effective and appropriate alternative to chlorination, reverse osmosis, or ozone treatment for certain projects. Problems associated with the design and operation of UV sterilizers are presented. Their flexibility facilitates integration with an overall treatment system. Low power consumption, portability, and increasing availability of low cost, long life, 12 volt direct current UV lamps lend themselves to renewable energy or hybrid power supplies.

INTRODUCTION

Pathogens proliferate in the surface and groundwater supplies of most communities in developing countries. Although several techniques of sterilization of drinking water have been used in water supply projects, chiefly chlorination, the vast majority of the world's rural populace continues to consume contaminated water. Reluctance to disinfect water by conventional means may be attributed to economic and aesthetic considerations. Boiling water is simply too expensive, given the price of wood or charcoal in Asia, Africa, and South America. Reverse osmosis is not cost-effective except for highly saline raw water. Chlorine dosages required for eradication of certain micro-organisms, for example streptococcus lactis, result in foul tasting water, to say nothing of the high operating costs of dosing either toxic chlorine or ozone. For small scale, decentralized water treatment projects, a sterilization system is sought that requires low maintenance, is portable for application in remote areas, and that is flexible enough to be incorporated into an integrated water supply system.

Disinfection of drinking water by irradiation (with 254 nanometer wavelength UV) may be feasible for certain applications, primarily where either raw water quality (pH and temperature), or the strong taste of treated water disallow chlorination. However, chlorination provides a distinct

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advantage over UV treatment in the establishment of free chlorine residual to combat recontamination in the distribution network (Oliver and Carey, 1976, p. 2619). However, as mentioned above, the use of UV for small projects (without extensive distribution systems) obviates the need for a residual agent.

The manufacture of commercially available UV lamps with low power consumption and increased life (Zhang and Mee, 1986) allows a wide range of applications. Of particular interest is the use of UV with solar photovoltaic, wind, or microhydropower generators.

FUNDAMENTALS

Ultraviolet radiation may be subdivided into three types: UV-A, or longwave (400-330 nm); UV-B, or mediumwave (330-270 nm); and UV-C, or shortwave (270-200 nm). The lethal effect of UV varies with wavelength, peaking between 250 and 260 nm for all organisms. Micro-organisms, in particular, are susceptible to 254 nm UV-C radiation.

Fortunately, the earth's ozone layer attenuates virtually completely this band of the spectrum. Window glass, even cloth, block localized UV-C. The intensity of radiation in a given medium falls away exponentially with distance from the source, according to Beer's law:

$$I(r) = I_o e^{-kr}$$

where I_o is the incident radiation intensity, k the extinction coefficient, and r the penetration distance. Typical values of k (in cm^{-1}) range from 0.007-0.01 for distilled water to 0.3-0.4 for strained sewage effluent, with k for drinking water from 0.02-0.1 (Masschelein, 1983, p. 211). Factors affecting k include turbidity, color and ion concentrations. Evidently, pretreatment of water greatly increases penetration of UV.

The germicidal action of 254 nm radiation results from inactivation of the micro-organism's DNA. Bacteria and certain viruses may be eradicated through brief exposure to UV, though higher organisms (Daphniae, Euglena, etc.) and algae require significantly higher doses. Table 1 lists the UV dosage required for 90 percent and 99.99 percent extinction of various micro-organisms (Groocock, 1984, p. 168; Angehrn, 1984, p. 111; Masschelein, 1983, p. 218).

	254 nm dosage (mJ/cm^2) for:	
Organism	90% extinction	99.99%
Salmonella enteritidis	4.0	25
Salmonella typhimurium	8.0	25
Shigella paradysenteriae	1.7	20
Streptococcus lactis	6.2	25
Vibrio cholerae	3.4	25
Polio (virus)	3.2	25

Table 1:
UV dosage required for extinction of commonly occurring micro-organisms (WHO, 1984, p. 3).

DESIGN

Typical exposure time ranges from 3 seconds to several minutes, depending on sterilizer design and proximity of water to the UV source. The most common source of UV-C radiation is the uncoated mercury vapor lamp, which releases a high intensity spike at 253.7 nm. Hot cathode and cold cathode types are available; of the two, hot cathode lamps are preferable, due to higher optical efficiency, optimal lamp temperature of 40 degrees C (compared with 500 degrees C for the cold cathode variety), and longer overall life. Both types are available commercially as tube lamps. In 1980, the antimony vapor lamp was developed with higher efficiency, though costs are high and availability limited.

Design of the irradiation chamber is based on one of three flow regimes: turbulent, laminar, or well-mixed batch processing. With the aid of impellers, and sleeves (to encase the lamp and allow immersion in a pressurized conduit), maximum exposure of pathogens to radiation is achieved under turbulent flow conditions. Generally the encased UV source fits longitudinally inside the chamber of circular cross section, with room for one or more impellers. It is assumed under such conditions, that all micro-organisms pass against the sleeve, minimizing penetration distance. However, determining exposure time at that distance may be problematic.

Laminar flow irradiation allows for more precise calculation of exposure time, for minimum intensity occurs at the maximum distance. This may lead to simpler design and less expensive fabrication, and facilitates maintenance. Several designs are conceivable. A shallow, rectangular channel conveys water under a longitudinally placed lamp set at the focus of a parabolic reflector of the same length as the lamp. Baffles ensure mixing. Or, an encased, sinuous lamp (requiring custom fabrication) is immersed in a shallow rectangular channel. Finally, the standard tube lamp may be placed perpendicular to flow to act as a round-crested weir. In this last alternative, exposure time will be very brief; yet penetration distance will be no greater than critical depth.

A batch processing irradiation chamber may be considered. Variations could incorporate any of the design alternatives mentioned above. However, automated valves allow inflow and outflow, and would certainly increase power consumption, and consequently, cost.

Safety factors must be considered for several aspects of lamp operation. UV output is a function of: 1) time after startup, 2) applied voltage, 3) lamp temperature, and 4) lamp age. Characteristically, a warmup period of several minutes should be allowed before the UV lamp reaches 100 per cent of its rated output. For hot cathode lamps, UV output is roughly proportional to applied voltage, for the 90 to 110 percent of nominal applied voltage range (Masschelein, 1983, p. 209). Output may drop to 70 percent of the rated maximum at operating temperatures below 5 degrees C (Masschelein, 1983, p. 210). Optimal operating temperature is

40 degrees C. . Output drops with age. After several thousand hours of operation, the lamp may be producing only 75 percent of the maximum rated output (Angehrn, 1984, p. 112). It is recommended that lamps operating eight hours per day be replaced at least once a year.

Control circuitry should be considered to detect lamp failure. As the mercury vapor lamp emits visible radiation in addition to UV-C, inexpensive photo cells, or calcium sulphide elements whose electrical resistance varies with incident light intensity, may serve this purpose. In a prototype sterilizer designed and tested by the author, such photo cells were coupled with a relay switch that closed a solenoid valve at the inlet to the laminar flow irradiation chanber. Additionally, a simple timer opened the valve several minutes after startup to allow the lamp to warm up.

OPERATION

Several auxiliary systems may be applied to augment the operation of the UV source. In addition to the sleeves and reflectors discussed above, chemical "sensitizers" can be added to the water to enhance the action of UV on organics in the untreated water. Chief among these are hydrogen peroxide (Malaiyandi, *et al.*, 1980, p. 1135), and TiO_2 in the anastase phase (Carey and Oliver, 1980, p. 157). H_2O_2 is consumed during treatment, though TiO_2 can be recovered. Application of sensitizers necessitates dosing and recovery systems whcih increase both the complexity of design and the total cost.

The use of sleeves, reflectors, and sensitizers has implications for the fabrication and operation of UV sterilizers. Since window glass does not transmit UV-C, sleeves must be made of quartz. Optical quartz with high transmittance at 254 nm is prohibitively expensive--a single sleeve may run several tens of times the cost of the lamp alone. Additionally, immersed lamps must then be periodically cleaned of organic buildup, which may pose particular problems in the case of enclosed, turbulent flow, pressurized devices.

Lamps suspended above the water should make use of reflectors in order to maximize the available radiation. However, reflectance varies with wavelength. It has been found that highly polished Alzak reflectors have high reflectance at 254 nm. Aluminized mylar has poorer reflectance, to say nothing of degradation of mylar films under intense UV radiation.

To improve the efficiency of pathogen eradication, designers may wish to consider two types of pretreatment: filtration and ion-exchange. It is noted above that turbidity, color, and the presence of ions reduce the penetration of UV-C in water. Pre-filtration would lower the indices of turbidity and color, and may be a necessary process in the overall treatment. Ion-exchange resins reduce the concentration of dissolved ions, thus improving the efficiency of UV treatment.

The application of UV sterilizers in developing countries raises several hardware problems. Lamps commercially available in industrialized countries may have to be imported. Transportation of delicate components (lamps and quartz sleeves) is likely to be costly. Finally, periodic replacement of various components requires some technical expertise.

CONCLUSION

UV sterilization of drinking water offers several unique advantages over conventional techniques (chlorination, reverse osmosis, and ozone treatment) and may actually be more appropriate for application under certain conditions. Compared to chlorine and ozone, UV requires less maintenance, is not toxic, is considerable faster, and is less dependent on water quality (considering suspended matter, temperature, and pH). Installation is less elaborate for UV systems than for any of the three mentioned above, and for a small scale project, operating costs are lower.

Mercury vapor lamps are inexpensive and consume 4 to 64 watts (GE, p. 2). Control circuitry requires an additional 10 to 50 percent of power. The prototype constructed and tested by the author used a 15 W lamp (General Electric G15 T8) to treat 2.0 liters per minute (of unfiltered water), achieving over 99 percent eradication of micro-organisms. The estimated operating cost was U.S.$ 0.045 per 1000 liters (1985 energy prices).

Currently, both AC and DC lamps are available. Without the use of DC/AC inverters, a DC lamp could be run directly from battery storage, powered by solar photovoltaic, wind, or microhydropower generators, possibly in conjunction with a diesel hybrid system. For example, a photovoltaic array with batteries and voltage regulator, sized for a 15 W system operating 8 hours per day, would cost less than U.S.$ 1000 for Cameroon, West Africa or India (1986 prices, which will fall). The initial outlay plus operating costs for a complete treatment system using UV sterilization for small scale applications is significantly less that for a comparable conventional system.

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