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Ultraviolet (UV)-based Advanced Oxidation System for Urban Water Supplies

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Foreword

This document was drafted in accordance with GB/T 1.1-2020, *Directives for standardization – Part 1: Rules for the structure and drafting of standardizing documents.*

This document was proposed by China Association of Machinery Industry for Environmental Protection.

The drafting organizations of this document: Tsinghua University, Shandong Province City Water Supply and Drainage Water Quality Monitoring Center, Trojan Technologies (Canada), Beijing Onyx Environmental Technology Co., Ltd, Fluidsmile (Shanghai) Fluid Technology Co., Ltd, Foshan Comwin Light & Electricity Co., Ltd, Shanghai Municipal Engineering Design Institute (Group) Co., Ltd, Beijing General Municipal Engineering Design & Research Institute Co., Ltd, Research Institute for Environmental Innovation (Suzhou) Tsinghua, Pan-China Construction Group Co., Ltd, Shandong Jianzhu University, Guangzhou Municipal Engineering Design & Research Institute Co., Ltd, Tianjin University.

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Introduction

Given the severity of water pollution in China and the growing demand for high-quality water by the public, higher standards and requirements are needed for urban water supplies. Optimization and upgrade of the water treatment process are of vital importance. Advanced oxidation process (AOP) utilizes highly reactive radicals to remove contaminant compounds through degradation or mineralization. AOP has proven its benefits, such as effectiveness and versatility. Moreover, the process barely introduces byproducts. Ultraviolet (UV)-based AOP has been extensively studied in the past few decades and has emerged as a promising water treatment technology. However, even though UV AOP has gradually been adopted across the country, it still lacks practical technological guidance and regulations. Thus, the industrial development of UV AOP is still limited.

This document provides full-scale UV AOP applications for water treatment in China with theoretical information and technical guidance. Related regulations for selecting, designing, operating, and maintaining UV AOP systems for urban water supplies are described in the following content. This document aims to assist the development of UV AOP in an effort to ensure the water quality and safety for urban water supplies in China by improving the product quality, design level, and operating performance.

Ultraviolet (UV)-based advanced oxidation systems for urban water supplies

1. Scope

This document provides information on UV-based advanced oxidation process (AOP) systems for urban water supplies, including definitions and terminologies, requirements, testing, methods, inspection, labeling, packaging, transportation, storage, operation, maintenance, and safety precautions.

This document is applicable for the design, manufacturing, inspection, operation, maintenance, and safety management needs for such systems.

2. Other reference standards

The following referenced documents are indispensable for the application of this document. Note that for dated references, only the dated edition cited in this document applies. For undated references, the latest edition of the cited document (including all amendments) applies.

GB/T 191 Packaging – Pictorial Marking for Handling of Goods

GB 1616 Hydrogen peroxide for industrial use

GB 2894 Safety Signs and Guideline for the Use

GB/T 4208 Shell Protection Class (IP code)

GB 5749 Standards for Drinking Water Quality

GB/T 7782 Metering Pump

GB/T 9969 General Principles for Preparation of Instructions for Use of Industrial Products

GB 12268 List of Dangerous Goods

GB 12463 General Specifications for Transport Packages of Dangerous Goods

GB/T 13306 Plates

GB/T 13384 General specifications for packing of mechanical and electrical product

GB 15603 Rules for Storage of Chemical Dangers

GB/T 17218 Hygienic Safety Evaluation for Chemicals Used in Drinking Water Treatment

GB/T 17219 Standard for Safety Evaluation of Equipment and Protective Materials in Drinking Water System

GB/T 19837-2019 Ultraviolet (UV) Disinfection Equipment for Urban Water and Wastewater Engineering

GB/T 32091-2015 Ultraviolet Equipment for Water Disinfection – Ultraviolet Dose Testing Method

GB/T 32092 Terms of ultraviolet disinfection technology

GB 50054 Code for Design of Low Voltage Electrical Installations

GB 50160 Fire Prevention Code of Petrochemical Enterprise Design

GB 50168 Standard for Construction and Acceptance of Cable Line Electric Equipment Installation Engineering

GB 50171 Code for Construction and Acceptance of Switchboard Outfit Complete Cubicle and Secondary Circuit Electric Equipment Installation Engineering

AQ 3018 Safety Rules for Works at the District of Storage Tank for Dangerous Chemicals

AQ 3047 The Rules of Precautionary Label for Chemical in Workplace

CJJ 58 Technical Specification for Operation, Maintenance and Safety of City and Town Waterworks

CJ/T 345 Activated Carbon from Coal for Drinking Water Treatment in Municipal Water Plant

GA 1511 Public Security Requirements for Storage Sites of Potential Explosives by Chemosynthesis

SH/T 3007 Design Specification for Tank Farms of Storage and Transportation System in Petrochemical Industry

Regulation on the Safety Management of Hazardous Chemicals (Order No.344 of the State Council of the People's Republic of China)

3. Glossary

The definitions provided in GB/T 32092-2015 and the following apply to this document.

3.1. UV reactor

The equipment where the exposure of water to UV light takes place to achieve water purification, consisting of a UV reactor chamber, UV lamps, quartz sleeves, ballasts, UV intensity sensors, and cleaning systems.

3.2. UV-based advanced oxidation system

The integrated system combining the UV reactor, oxidant dosing unit, and other auxiliary parts.

3.3. Off-line chemical clean (OCC)

A process to clean the lamp sleeves using a chemical cleaning solution (typically a weak acid) where the UV reactor is turned off and the lamp sleeves are removed for cleaning.

3.4. On-line mechanical clean (OMC)

A process to clean the lamp sleeves using mechanical cleaning equipment (e.g., a wiper) while the UV reactor is in operation.

3.5. On-line mechanical-chemical clean (OMCC)

A process to clean the lamp sleeves using an automatic mechanical cleaning process (e.g., a wiper) and a chemical cleaning solution while the UV reactor is in operation.

3.6. UV$_{254}$

A measurement of the amount of UV light at 254 nm absorbed through a quartz cell.

3.7. UV transmittance (UVT)

A measurement of the amount of UV light at 254 nm that passes through a 1 cm quartz cell containing the water sample compared to the amount of light that passes through a 1 cm quartz cell containing pure deionized water.

3.8. UV intensity sensor

A device used to measure the UV intensity at a point within the UV reactor.

3.9. Target contaminant

Specific contaminant needed to be removed through UV AOP (e.g., geosmin, 2-Methylisoborneol (MIB), N-Nitrosodimethylamine (NDMA), pharmaceuticals, disinfection by-product (DBPs), and other regulated organic compounds listed in GB 5749).

3.10. Target log reduction

For the target contaminant, the specific log reduction the water treatment process aims to achieve using UV AOP.

3.11. UV Dose required per log reduction (D$_L$)

The UV dose needed to achieve 1-log (90% reduction) reduction of the target contaminant. The value of D$_L$ can be determined as the inverse slope of the graph of UV dose vs. log contaminant reduction (UV dose-response curve). D$_L$ has a unit of mJ/cm^2 per log reduction.

3.12. UV reduction equivalent dose (UV RED)

The UV dose derived by entering the log reduction of the target contaminant during full-scale UV AOP testing into the UV dose-response curve that was obtained through collimated beam testing.

3.13. Oxidant

Oxidizing compounds that produce highly reactive oxidant radicals through photosensitized reactions in UV AOP systems (e.g., hydrogen peroxide, H_2O_2).

3.14. Electrical energy per order (EEO)

The electrical energy needed to reduce the concentration of a contaminant by one order of magnitude (90% reduction or 1-log reduction) in a unit volume of water. EEO has a unit of kWh m^{-3} log^{-1}.

3.15. Quenching

The process of removing residual oxidant by using a quenching agent that is more prone to react with the oxidant (e.g., H_2O_2) in UV AOP.

4. Requirements

4.1. General requirements

4.1.1. System

A UV AOP system consists of an oxidant dosing system, UV reactors, a residual quenching unit, a system control center, a power distribution center, pipelines, and other parts (Figure 1).
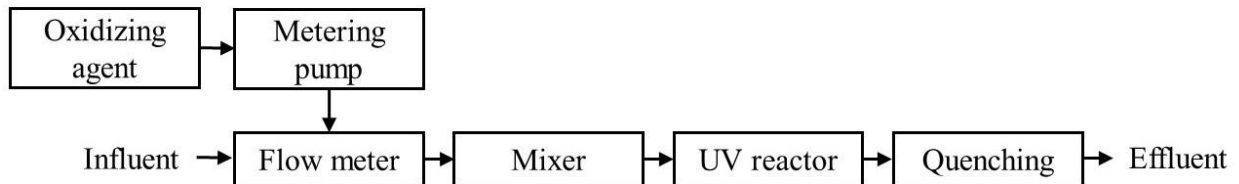

Figure 1. Schematic diagram of a UV-based advanced oxidation system.

4.1.2. UV reactor

4.1.2.1.

Each UV reactor should be equipped with UV sensors and reactor equipment protection. Given specific situations, UV reactors can also be equipped with on-line UV transmittance (UVT) analyzers, as well as on-line UV reactor cleaning systems.

4.1.2.2.

For water treatment plants (WTPs), the types of UV lamp used in UV reactors generally include low-pressure (LP) lamps, low-pressure high-output (LPHO) lamps, and medium-pressure (MP) lamps.

4.1.2.3.

The UV lamps, quartz sleeves, on-line sensors, and cleaning units should be easy to disassemble for maintenance.

4.1.2.4.

The determination of UVT and the fouling factors for quartz sleeves should comply with GB/T 19837.

4.1.2.5.

The estimation of aging factors and lamp lifetime should comply with GB/T 19837.

4.1.2.6.

The cleaning of quartz sleeves should comply with GB/T 19837.

4.1.2.7.

The use of electronic ballasts should comply with GB/T 19837.

4.1.2.8.

The reference UV sensors should be calibrated. The position of the reference UV sensors should be the same as during validation.

4.1.2.9.

To monitor UV lamp operations and to calculate UV dose, an on-line UV sensor should be provided for each lamp, or for each set of lamps.

4.1.2.10.

If water quality fluctuates with UVT value, which is an important design and operating parameter for a UV reactor, exceeds 10 percent, on-line UVT analyzers should be installed. The calibration of the on-line UVT analyzers should be verified using a spectrophotometer.

4.1.2.11.

Health and safety standards for the UV reactors and related components and chemicals should comply with GB/T 17219.

4.1.3. Oxidant dosing system

4.1.3.1.

An oxidant dosing system should include units or devices for storage, adjustment, pumping, metering, and mixing for oxidants.

4.1.3.2.

The oxidant should be dosed using metering pumps. Flow meters should be installed. The use of the metering pumps should comply with GB/T 7782, and the calibration of the dosing precision should be carried out during the commissioning of the UV AOP systems.

4.1.3.3.

Health and safety standards for the selected oxidant and the corresponding dosing system should comply with GB/T17218 and GB/T 17219, respectively.

4.1.4. Quenching unit

4.1.4.1.

A quenching unit should be used to destroy the oxidant residual and should be placed downstream of the UV reactor.

4.1.4.2.

The selection of the quenching unit should be based on the properties of the oxidant used. If hydrogen peroxide (H_2O_2) is used, no residual should be detected in the effluent after quenching. If ozone or chlorine is used, the residual concentration in the effluent should comply with GB 5749.

4.2. Process requirements

4.2.1. Influent quality

For UVAOP, the UVT of the influent water should be 80% cm^{-1} or more.

4.2.2. Main process parameters

The UV and oxidant doses should meet the requirements for target contaminant removal. Typically, for a UV AOP system, the UV doses range from 200 mJ/cm^2 to 800 mJ/cm^2. If H_2O_2 is selected as the oxidant, typical doses range from 3 mg/L to 30 mg/L to achieve the target log reduction (e.g., 90% removal efficiency, or 1-log).

4.2.3. System operations

Continuous operation should be used for UV AOP.

4.3. Electrical and control system

4.3.1.

The UV AOP electric system should operate flexibly, smoothly, and with no issues.

4.3.2.

The electrical control cabinets should comply with GB 50054 and GB 50171. The electrical elements should comply with GB 50054. The wiring should comply with GB 50054 and GB 50168.

4.3.3.

To achieve the target removal of the contaminant and meet the requirements for monitoring and control, the system control center should be able to adjust the power output and oxidant dose of the UV reactor based on information including the water quality, flow rate, target contaminant reduction, and so on.

For the UV reactor, the system control center should be able to monitor the operating time, prevent overheating of the system, provide low liquid level protection, and provide cleaning and lamp failure alarms.

4.4. Equipment material and protection

4.4.1.

Equipment and components that are exposed to UV light should be made from UV-resistant materials.

4.4.2.

Metal parts of the equipment and components that are in contact with water should be made from corrosion-resistant materials.

4.4.3.

Connections of the UV lamps should be made from materials that are resistant to high temperatures.

4.4.4.

Corrosion caused by hydraulics should be prevented.

4.4.5.

Corrosion of the material of chamber caused by the oxidant should be prevented.

4.4.6.

The equipment and components should be waterproof and leakproof.

4.4.7.

The devices and piping of the oxidant dosing systems should adopt specific insulation measures based on the specific oxidant properties.

4.4.8.

Equipment surfaces should have a smooth coating without any wrinkles or scratches.

4.4.9.

The protection level of the UV reactor's electrical components above water should comply with GB/T 4208. In accordance with GB/T 4208, the outdoor and indoor electrical equipment protection levels should be at least IP65 and IP54, respectively.

5. Testing methods

5.1. Performance prediction and testing

5.1.1. Performance prediction

Before the UV AOP system's operation begins, the performance of the specific contaminant could be predicted given the UV dose per log reduction (D_L) and the UV dose of the UV reactor (or electrical energy per order (EEO)).

5.1.2. Performance testing

After the UV AOP system has been installed and commissioned, performance testing should be conducted to verify whether the system can achieve the reduction goal of the target contaminant. For details of the performance testing, see Appendix A.

5.2. Testing and determination of UV dose per log (D_L) reduction

See details in Appendix B.

5.3. Calculation and verification of the UV dose in a UV reactor

5.3.1. Theoretical UV dose

The theoretical UV dose in a UV reactor can be calculated using numerical modeling. See details in Appendix C.

5.3.2. Validated UV dose

The validated reduction equivalent dose (RED) of the UV reactor can be determined using the UV dose response curve of the target contaminant. See details in Appendix D.

5.4. Oxidant concentration

The oxidant concentration should be determined based on the specific standards. For example, if H_2O_2 is selected as the oxidant, its concentration should be tested and determined according to GB 1616.

5.5. Aging factor and lifetime of UV lamps

See details in Appendix A in GB/T 19837-2019.

5.6. UV transmittance (UVT) in the water

See details in Appendix B in BG/19837-2019.

5.7. Fouling factor of quartz sleeves

See details in Appendix B. in GB/T 32091-2015.

5.8. UV reactor protection level

The protection level of electrical system above and below water level should be determined according to GB/T 4208.

6. Inspection rules

6.1. Inspection types

Inspection includes factory inspection and other general inspections.

6.2. Factory inspection

6.2.1.

Every UV reactor should undergo factory inspections. The inspection should include the requirements mentioned in 4.1.2.3 – 4.1.2.10.

6.2.2.

The oxidant dosing unit should undergo factory inspections. The inspection should include the requirements mentioned in 4.1.3.

6.2.3.

The control center of the UV AOP system should test the digital and analog input and output functions.

6.2.4.

Upon completing the UV AOP system assembly, run the system at 1.25 times of the maximum design pressure and conduct hydrostatic pressure tests.

6.3. Other general inspections

6.3.1.

General inspections should be conducted if any of the following occur:

a) There is a change in the process
b) There is a change in the main equipment components
c) The product is sent for qualification and type approval
d) The production resumes after being suspended for over half a year
e) The production continues after one year of functional operation

6.3.2.

Sampling and testing for general inspection should meet the following requirements:

a) Among the products that passed the factory inspection, randomly sample 1 – 2 sets of equipment for type inspection.
b) General inspections should include visual inspection, routine check of the equipment protection status, UV dose, and the accuracy of the oxidant dosing system. Operation and performance testing should be conducted upon the completion of the equipment installation.

6.4. Qualification

The product is qualified only if the abovementioned inspections meet the requirements.

7. Labeling, packaging, transportation and storage

7.1. Labeling

7.1.1.

Labels should be placed at prominent locations on the UV reactor, metering pumps, and other equipment and components. For labeling standards, see GB/T 13306. The labels should include the following information:

a) Product name;
b) Product model;
c) Product number;
d) Production date;
e) Manufacturer;
f) Product total weight;
g) Main technical specifications.

7.1.2. Safety labeling

The internal and external use of safety labels should comply with GB 2894.

7.1.3. Pipe connection labeling

Labels should be placed at prominent locations for pipe interfaces.

7.2. Packaging

7.2.1.

The packaging for electromechanical equipment and components should comply with GB/T 13384.

7.2.2.

The packaging for oxidant should comply with GB 12463.

7.2.3.

The package should include the following documents:

    a) Equipment inspection certificate.

    b) Equipment user manual. The manual should comply with GB/T 9969.

    c) Equipment list.

7.2.4.

Given the specific transportation and storage conditions, the package should also provide graphic labels such as "Fragile item", "This side up", "Avoid direct sunlight", "Avoid rain", "Do not roll", "Center of gravity", etc. For graphic labeling standards, see GB/T 191.

7.3. Transportation

7.3.1.

During transportation, the packages should be handled gently with care. Do not drag, pull, or throw.

7.3.2.

During transportation, avoid rain, snow, and mechanical vibration for the UV lamps and quartz sleeves.

7.3.3.

Oxidants (e.g., H_2O_2) are hazardous chemicals. Transportation management should comply with GB 15603, GB 12268, and *Regulation on the Safety Management of Hazardous Chemicals*.

7.4. Storage

7.4.1.

The product should be stored in clean, dry, and ventilated indoor locations. Avoid corrosive gases.

7.4.2.

The storage of oxidants should comply with GB 15603. The selection of storage tank location should comply with GB 50160, GA 1511, and SHT 3007. Avoid heat sources and direct exposure to sunlight.

8. Maintenance and safety protection

8.1. Maintenance

8.1.1.

The operation, maintenance, and safety procedures for the UV AOP system should reference CJJ 58.

8.1.2.

The operating management of a UV advanced oxidation system requires professionally-trained individuals and equipment.

8.1.3.

Before the UV advanced oxidation system's operation begins, a management system (i.e., equipment list document, operation record, routine inspection, shift management, and safety inspection) should be made. Documentation should also be available on the process flow diagram, and operation and maintenance procedures for each position.

8.1.4.

Operators should be familiar with the technical indicators of the system and the operating requirements of the equipment. Operators must have technical training and conduct regular training exercises. Operators may only be permitted to operate the equipment after passing the training examination.

8.1.5.

The process flow diagram, and the operation and maintenance procedures should be placed in prominent and accessible locations. Operators are required to follow the procedures.

8.1.6.

The main equipment and components should be included in the equipment ledger. Routine inspection of the equipment, electrical appliances, and instrumentation should be carried out to verify their proper operation. Routine maintenance of the equipment, electrical components and instrumentation should also be carried out to ensure equipment reliability.

8.1.7.

The influent and effluent water quality should be regularly monitored, and the devices and instruments used for that monitoring should be properly calibrated.

8.1.8.

During operation, a frequent and regular safety check should be implemented to minimize the potential for accidents and to identify potential hazards.

8.1.9.

All personnel involved in the operation of the system should appropriately document all activities including operation, inspection, shift details, and maintenance.

8.2. Safety and protection

8.2.1.

Rigorous safety rules and regulations must be established. Supervision must be assigned to specific personnel to ensure proper safety of workers.

8.2.2.

Safety and protection procedures must be established for the power system.

8.2.3.

Facilities should be equipped with necessary firefighting equipment that complies with relevant firefighting regulations. Follow the building fire protection regulations strictly. Adequate fire separation distance must be given between buildings.

8.2.4.

Emergency eyewash stations should be provided in the storage tank area, preparation area, and dosing area for the oxidant (e.g., H_2O_2). The use of the oxidant should comply with AQ 3018 and AQ 3047.

Appendix A

UV-based AOP System Performance Testing

A.1   Target contaminant

The analysis methods should be determined according to the target contaminant in the UV AOP system. During performance testing, the target contaminant at the reactor influent should be spiked to reach a specific concentration.

A.2   Testing of influent

Important background water quality parameters should be measured, including UVT, TOC/DOC, pH, temperature, conductivity, TSS, TDS, alkalinity, etc. If the influent contains chemical disinfectants (e.g., chlorine), inactivators such as sodium thiosulfate could be applied. Note that the residual should not affect the UVT of water.

A.3   Commissioning of UV system

Once the operation begins, adjust the valves or pumps to reach the target flow rate. Make sure that the target flowrate does not change by over 5% during sampling.

A.4   Oxidant dosing and analysis

The dosing of the oxidant should be determined based on parameters including the target contaminant concentration, the target log reduction, flow rate, etc. Calculate the required volume of the liquid and use a metering pump for controlled delivery of the oxidant.

For the measuring of oxidant concentration, refer to the related standard method.

A.5   System stability and mixing analyses

A.5.1   Stability testing

The stability of the system should be tested prior to sampling. The test could be done by first estimating the hydraulic residence time (HRT) based on the liquid volume and flowrate. Next, a UV-absorbing chemical is injected into the flow (e.g., coffee, lignin sulfonic (LSA), or humic acid) at t_0. Calculate the ratio of the UVT in the influent and effluent at every HRT interval. The time to reach steady state (defined as ST) is when the ratio reaches 1. Note that ST should be determined for each operating flow rate.

A.5.2   Mixing

A.5.2.1   Mixing in influent

Inject the target contaminant or UV-absorbing compound (as mentioned above) into the water (when the UV lamps are turned off). Adjust the flow rate to the minimum and maximum values to be used for the

tests. After the system reaches steady state, measure both the UVT (or UV_{254}) and probe compound concentration at the inlet and the outlet. The standard deviation of the average UVT (or UV_{254}) or the probe compound concentrations at different locations should not exceed 5 percent of the mean value. The standard deviation of each replicate (all samples should be taken in triplicates) should not exceed 5%.

A.5.2.2 Mixing in effluent

Inject the target contaminant or UV-absorbing compound (as mentioned above) into the water (when the UV lamps are turned off). Adjust the flow rate to the minimum and maximum values to be used for the tests. After the system reaches steady state, measure both the UVT (or UV_{254}) and probe compound concentration at the outlet and the end of the drainage hose. The standard deviation of the average UVT (or UV_{254}) or the probe compound concentrations at different locations should not exceed 5 percent of the mean value. The standard deviation of each replicate (all samples should be taken in triplicates) should not exceed 5%.

A.6 Sampling

A.6.1 Sampling time

All samples should be collected after the system is stable.

A.6.2 Requirements

Samples should be collected at both influent and effluent. Multiple water samples should be collected for the testing of target contaminants, water quality, and oxidant concentrations. Record the start and finish time during sampling.

Avoid exposure to UV light during effluent sampling.

Test technicians are required to record the following data: sample ID, flow rate, lamp power, operating current, UV intensity, sensor location, sampling time, and temperature.

A.6.3 Storage and transportation

Samples should be stored at 4°C. The testing of water quality and oxidant concentrations should be undertaken by the technician and conducted in-situ. The samples for the testing of target contaminants should be delivered to the corresponding chemical analysis laboratory.

A.7 Test data analysis

The above-mentioned procedure can be used to calculate the contaminant removal efficiency, *RE*, under specific oxidant dose, UV dose, and water quality conditions. The removal of the contaminant is defined as:

$$RE = \frac{C_o - C}{C_o} \times 100\%$$
<div align="right">A.1</div>

where:

RE is the removal of target contaminant

C_0 is the target contaminant concentration prior to the UV AOP treatment ($\mu g/L$)

C is the target contaminant concentration after the UV AOP treatment ($\mu g/L$)

The system performance is determined by whether the contaminant removal efficiency meets the set goal.

Appendix B

Testing and determination of the UV dose per log reduction (D_L)

B.1 Target contaminant

The analysis method for the contaminant should be selected based on the target contaminant in the UV AOP system. The target contaminant concentration should consider the range of that in the given influent water.

B.2 Collimated Beam Apparatus

A collimated beam apparatus is used to develop a UV dose-response curve (Figure B.1). The collimated beam apparatus includes a UV lamp (LP or MP) enclosed in a cylinder. A tube with a diameter of 6 – 9 cm and a length of 30 – 60 cm is connected at the center of the bottom of the cylinder, allowing the UV light to be delivered to the water sample surface with a near zero-degree angle of incidence and homogeneity across the surface area.

Approximately 40 – 50 mL of water sample is irradiated in a Petri dish that has a diameter of 50 – 90 mm. To ensure homogeneity of UV exposure of the contaminant, the sample should be mixed using a magnetic stirrer. The rate of mixing should be controlled to avoid vortices.

The exposure time can be controlled via a shutter mechanism. The average intensity is measured using a calibrated radiometer.
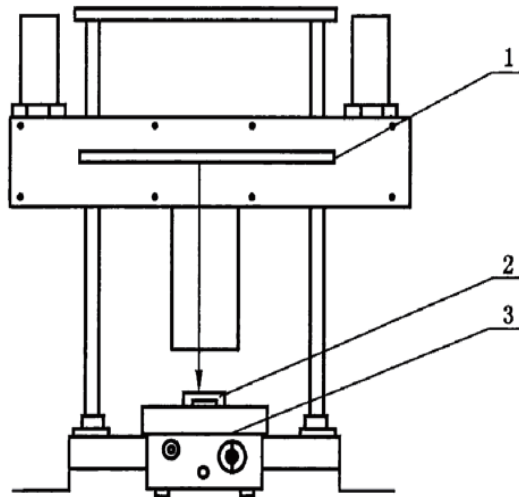

Figure B.1 Collimated Beam Apparatus (1. UV lamp; 2. Petri dish containing water sample to be tested; 3. Magnetic stirrer)

B.3 Test procedure

B.3.1

Before testing starts, switch on the UV lamp and pre-heat the lamp for 30 min to ensure that the UV light emission is stable.

B.3.2

If a LP lamp is used, measure the A_{254} of the sample. If a MP lamp is used, measure the absorbance at wavelengths from $200 - 300$ nm (A_{200} -A_{300}).

B.3.3

Place the water sample into a Petri dish. Draw ticks every 0.5 cm in x- and y-axes from the center of the light circle projected by the collimated beam. The calibration level is at the top surface of the water.

B.3.4

Use the radiometer to measure the irradiance at 0.5 cm increments across the x-axis (+x, -x) and the y-axis (+y, -y). The ratio of the average irradiance across the water surface to the irradiance measured at the center is defined as the Petri factor (P_f).

B.3.5

For a LP lamp, the UV dose can be calculated by the following equation:

$$D = E_s P_f (1 - R) \frac{L}{d + L} \left(\frac{1 - 10^{a_{254}d}}{a_{254}d ln(10)} \right) t \qquad \text{B.1}$$

where:

D = UV dose (mJ/cm^2)

E_s = UV irradiance at the center of the Petri dish at the height of the sample surface (mW/cm^2)

P_f = the Petri Factor, unitless

R = Reflectance at the air/water interface. A value of 0.025 is used in this document

L = Distance from lamp center to the water surface (cm)

d = Depth of the water sample in the Petri dish (cm)

a_{254} = UV absorbance at 254 nm (cm^{-1})

t = Exposure time (s)

B.3.6

For an MP lamp, a Sensor Factor, S_f, is introduced for correction and can be calculated by:

$$S_f = \frac{S_{254}}{\sum i \ N_{\lambda_i} S_{\lambda_i}} \qquad\qquad \text{B.2}$$

where:

S_f – the UV sensor sensitivity at 254 nm divided by the weighted average of that at 200 – 300 nm

S^{254} – the UV sensor sensitivity at 254 nm

N – Normalized relative photon flux at wavelength λ_i

S – the UV sensor sensitivity at wavelength λ_i with a range of 200 – 300 nm

The UV dose can then be calculated by the following equation:

$$D = E_c P_f S_f (1 - R) \frac{L}{d + L} \sum_i N_{\lambda_i} \frac{1 - 10^{a_i d}}{a_i d \ln(10)} t \qquad\qquad \text{B.3}$$

where:

D = UV dose (mJ/cm^2)

E_s = UV irradiance at the center of the Petri dish at the height of the water sample surface (mW/cm^2)

P_f = the Petri Factor, unitless

R = Reflectance at the air/water interface. A value of 0.025 is used in this document

L = Distance from lamp center to the water surface (cm)

d = Depth of the water sample (cm)

a_i = UV absorbance at wavelength λ_i nm (cm^{-1})

t = Exposure time (s)

B.3.7

Alternatively, given a target UV dose, the required exposure time can be calculated using Equation B.1or B.3.

B.3.8

Prepare the test sample with the target contaminant and specific dose of oxidant.

B.3.9

Center the Petri dish (with the test sample) under the collimating tube. Switch on the magnetic stirrer. Unblock the collimating tube using a shutter. After the desired exposure time, block the light from the collimating tube. Add an oxidant quenching agent immediately as soon as the target exposure time has elapsed. Collect the treated sample and measure the concentration of the target contaminant. Each test should be conducted in triplicate.

B.3.10

Use Equation

$$RE_{log} = \log\left(\frac{C_0}{C}\right)$$ <div style="text-align:right">B.4</div>

where:

RE_{log} = log reduction of contaminant

C_0 = Target contaminant concentration in the test sample before UV exposure ($\mu g/L$)

C = Target contaminant concentration in the test sample after UV exposure ($\mu g/L$)

B.3.11

Plot RE_{log} as a function of UV dose. D_L is the reciprocal of the slope of the curve.

Appendix C

Calculation of average dose in a UV reactor

C.1 Theoretical formula of UV dose in a flow-through reactor

C.1.1 LP/LPHO lamp

For a collimated beam (using LP/LPHO lamp), $L/(d+L) = 1$, and given the UV irradiance entering the water $E_e = E_s P_f (1-R)$, Equation B.1 can be simplified as:

$$D = E_e \frac{1 - 10^{a_{254}d}}{a_{254}d \ln(10)} t \qquad \text{C.1}$$

Or, if P_e is the total radiant power entering the water over a total area of A, then $E_e = P_e/A$:

$$D = \frac{P_e}{A} \frac{1 - 10^{a_{254}d}}{a_{254}d \ln(10)} t \qquad \text{C.2}$$

For a batch reactor, the volume of the reactor $V = A \times d$, therefore:

$$D = \frac{P_e}{V} \frac{1 - 10^{a_{254}d}}{a_{254}d \ln(10)} t \qquad \text{C.3}$$

Given the above formula, the UV dose is a function of the radiant power entering the water (P_e), the path length which the UV light traverses in the water (d), the volume (V), the exposure time (t), and the UV absorption coefficient (a). Note that the UV dose is independent of area (A).

For a non-uniform batch reactor that has multiple path lengths, the UV dose is given as:

$$D = \sum_{d_1}^{d_n} \frac{P_e F_i}{V} \frac{1 - 10^{a_{254}d}}{a_{254}d \ln(10)} t \qquad \text{C.4}$$

where:

D = UV dose of an LP lamp (mJ/cm^2)

V = Volume of the water (cm^3)

P_e = Radiant power entering the water (mW)

d = path length (cm)

F_i = the fraction of UV with path length d_i

a_{254} = UV absorbance at 254 nm (cm^{-1})

For a flow-through reactor, the flow rate $Q = V/t$, according to equation C.4:

$$D = \sum_{d_1}^{d_n} \frac{P_e F_i}{Q} \frac{1 - 10^{a_{254}d}}{a_{254}d\ln(10)} \qquad \text{C.5}$$

where:

D = UV dose of an LP lamp (mJ/cm^2)

Q = Flow rate (cm^3/s)

P_e = Radiant power entering the water (mW)

d = path length (cm)

F_i = Fraction of UV with path length d_i

a_{254} = UV absorbance at 254 nm (cm^{-1})

C.1.2 MP lamp

When using a UV reactor that uses MP lamps (MPUV), the UV dose can be calculated by integrating the UV dose at the different associated UV wavelengths. For instance, for a MPUV/H$_2$O$_2$ reactor, the UV dose is calculated as the integral of the dose, weighted by the H$_2$O$_2$ absorption coefficient relative to that at 254 nm, by the associated wavelength. Similar to UV dose in UV disinfection reactors, D$_L$ is independent of the lamp spectral output, the UV transmittance, and the path length that UV traverses in an MPUV reactor. Therefore, the UV dose for a batch reactor can be calculated by summing that over all given wavelengths:

$$D_{H_2O_2} = \sum_{\lambda=200nm}^{300nm} \sum_{d_1}^{d_n} \frac{P_{e\lambda} r_\lambda F_i}{V} \frac{1 - 10^{a_\lambda d_i}}{a_\lambda d\ln(10)} t \qquad \text{C.6}$$

where:

$D_{H_2O_2}$ = H$_2$O$_2$ weighted UV dose in an MPUV reactor (mJ/cm$_2$)

$P_{e\lambda}$ = Total radiant power at wavelength λ entering the water (mW)

r_λ = Relative absorption coefficient of the oxidant (e.g., H$_2$O$_2$) or photoactive species at wavelength λ to that at 254 nm. Note that if the quantum yield of the oxidant or photoactive species varies with UV wavelength, r_λ should be multiplied by the relative quantum yield at wavelength λ to that at 254 nm.

V = Volume of the water (cm^3)

d = Path length (cm)

F_i = Fraction of UV with path length d_i

a_λ = UV absorbance at wavelength λ (cm^{-1})

For a flow-through MPUV/H$_2$O$_2$ reactor, the UV dose can be calculated by:

$$D_{H_2O_2} = \sum_{\lambda=200nm}^{300nm} \sum_{d_1}^{d_n} \frac{P_{e\lambda} r_\lambda F_i}{Q} \frac{1 - 10^{a_\lambda d_i}}{a_\lambda d \ln(10)} \qquad \text{C.7}$$

where:

$D_{H_2O_2}$ = H$_2$O$_2$ weighted UV dose in an MPUV reactor (mJ/cm$_2$)

$P_{e\lambda}$ = Total radiant power at wavelength λ entering the water (mW)

r_λ = Relative absorption coefficient of the oxidant (e.g., H$_2$O$_2$) or photoactive species at wavelength λ to that at 254 nm. Note that if the quantum yield of the oxidant or photoactive species varies with UV wavelength, r_λ should be multiplied by the relative quantum yield at wavelength λ to that at 254 nm.

Q = Flow rate (cm^3/s)

d = Path length (cm)

F_i = Fraction of UV with path length d_i

a_λ = UV absorbance at wavelength λ (cm^{-1})

C.2   Path length

The path length distribution in a UV reactor can be calculated from the reactor geometry. Due to internal reflection and refraction by the quartz tube, all UV light emitted from the quartz sleeve is estimated to be an arc approximately +/- 45 degree to normal.

C.3   Numerical modeling of UV reactor

The results using the aforementioned collimated beam or batch reactor testing do not address the non-uniform UV dose distribution in a full-scale UV reactor. Therefore, for a full-scale UV reactor, the UV dose should be calculated through numerical modeling.

Numerical modeling of a UV reactor includes a UV light intensity distribution (LID) model and a computational fluid dynamics (CFD) model. Based on optics and the laws of geometry, LID models calculate the UV radiation in a reactor, characterize the spatial distribution of the fluence rate, and derive the UV dose. Commonly used LID models include MPSS, MSSS,LSI, RAD-LSI, and DO.

CFD is a technique for numerically solving the fluid dynamics, and can be used to compute the trajectory of the contaminant and hydraulics in a UV reactor. For a full-scale UV reactor, the geometry is divided into millions of CFD cells. For a MPUV reactor, the UV dose should be weighted based on the oxidant (e.g., H_2O_2) or the target contaminant. UV intensity modeling (UVI) is used to calculate the hydrogen peroxide (or other photoactive species) weighted UV dose, D_{H2O2}, in each CFD cell. The hydrogen peroxide weighted UV dose at each cell can be obtained by:

$$D_{H_2O_2} = \sum_{\lambda=200nm}^{300nm} E_\lambda r_\lambda t \qquad \text{C.8}$$

where:

$D_{H_2O_2}$ = hydrogen peroxide weighted UV dose in each CFD cell (mJ/cm^2)

E_λ = Total UV irradiance (fluence rate) at wavelength λ (mW/cm^2)

r_λ = Relative absorption coefficient of hydrogen peroxide (or other photoactive species) at wavelength λ to that at 254 nm

t = residence time of the water in the CFD cell (s)

Appendix D

Validation of UV dose in a UV reactor

D.1 Testing Scope and controlled variables

D.1.1 Testing Scope

D.1.1.1

Determination of the log reduction of the target contaminant in the UV AOP.

D.1.1.2

Determination of the UV dose-response curve of the target contaminant using collimated beam apparatus

D.1.1.3

Data analysis and the calculation of the required UV dose

D.1.2 Controlled variables

During testing, the main variables that are being measured, controlled and recorded are: flow rate, velocity, target contaminant concentration, oxidant dose, background water matrix, UV intensity, lamp arrangement and status, inlet and outlet piping configurations, and other important equipment operating factors.

D.1.2.1

The UV manufacturers should provide information such as the aging/fouling factors and the validated UV dose results for the UV reactor.

D.1.3 Operating conditions

In a UV AOP system, D_L is dependent on the oxidant dose and water matrix. The validation of reduction equivalent dose (RED) should be verified using at least three different oxidant doses. Water matrix factors such as TOC/DOC, pH, and alkalinity, may have a significant impact on the log removal efficiency of the target contaminant. Operating conditions should be adjusted given specific UV systems.

D.2 Target contaminant selection

The target contaminant selections for water treatment processes could consider one or more organic contaminant compounds. Accordingly, the analysis method should be selected to reflect the target contaminants. The target contaminant concentration should consider the range of that in the given influent water.

D.3   Equipment requirements

D.3.1

The hydraulics in the selected piping system should not be more optimal than that in real operations, ensuring a conservative estimation of the delivered UV dose.

D.3.2

Influent and effluent sampling ports should have appropriate bend connections to the UV AOP system.

D.3.3

The UV lamp descriptions should include information such as lamp model, operating specifications, dimensions, pressure level, emission spectrum, photoelectric conversion rate, manufacturer names, etc. The UV lamps used for testing should have a minimum number of operating hours of 100h, making sure that stable UV irradiation can be produced. A safety cut-off switch should be applied to prevent overheating if MP lamps are used.

D.3.4

During operation, the difference between the UVT analyzer measurement and the UVT measured by a calibrated spectrophotometer, at the same location, should be less than 10%.

D.4   Validation process

D.4.1   General requirements

Given different applications, the log removal curve should be determined under specific conditions including the target contaminant, oxidant, background water matrix, and UV intensity. The UV dose-response curve should be determined in a laboratory environment using a collimated beam apparatus. The validated UV dose of a UV AOP system is determined using the removal performance measured in the UV AOP system and the UV dose-response curve determined in the laboratory.

D.4.2   Testing of influent

See A.2 in Appendix A.

D.4.3   Commissioning of UV system

See A.3 in Appendix A.

D.4.4   Oxidant dosing and analysis

See A.4 in Appendix A.

D.4.5   System stability and mixing analyses

See A.5 in Appendix A.

D.4.6   Sampling

See A.6 in Appendix A.

D.4.7   Collimated beam testing

The abovementioned testing is carried out at full-scale. The collimated beam testing should be conducted in a laboratory to determine the UV dose-response curve of the target contaminant using the same oxidant dose and water samples. The detailed procedure and requirements are described in Appendix B.

D.4.8   Data analysis

D.4.8.1   Log removal of target contaminant

Based on the testing results of the water sample, use Equation B.4 to calculate the log removal of the target contaminant under given conditions.

D.4.8.2   Collimated beam testing

Based on the collimated beam testing results, determine the UV dose-response curve at the specific oxidant dose and water quality conditions.

D.4.8.3   Determination of validated UV dose

Based on the results described above, the validated UV dose of a UV AOP, RED, can be determined by matching the log removal of the target contaminant to the UV dose-response curve.