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Configuration optimization of UV reactors for water disinfection with computational fluid dynamics: Feasibility of using particle minimum UV dose as a performance indicator

Wentao Li [a], Mengkai Li [a], James R. Bolton [b], Zhimin Qiang [a,*]

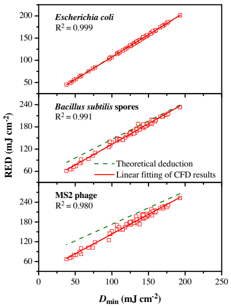
[a] *Key Laboratory of Drinking Water Science and Technology, Research Center for Eco-Environmental Sciences, University of Chinese Academy of Sciences, Chinese Academy of Sciences, 18 Shuang-qing Road, Beijing 100085, China*

[b] *Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB T6G 2W2, Canada*

HIGHLIGHTS

- D_{min} was used as a performance indicator for UV reactor configuration optimization.
- D_{min} proved to be a qualified alternative to RED for UV reactor optimal design.
- Reactor with a well-mixed flow dispersed by lamp array had the best performance.
- Disinfection capability of the optimally designed UV reactor was elevated by 47–100%.

GRAPHICAL ABSTRACT



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ABSTRACT

Computational fluid dynamics is a powerful tool for ultraviolet (UV) reactor performance evaluation, since it allows the reactor configuration optimization by comparing the performance indicator [e.g., reduction equivalent dose (RED)] of various UV reactors. In this study, a new performance indicator independent of the microbial UV dose-response curve, namely particle minimum UV dose (D_{min}), was introduced, and its feasibility was evaluated in the configuration optimization of 3-lamp UV reactors for water disinfection. Results indicate that the D_{min} could serve as an alternative to the RED in characterizing the UV reactor performance. In general, reactors with a normal (NOR) lamp position pattern (i.e., with one lamp on the top and two at the bottom) had larger D_{min} values (110–193 mW cm^{-2}) than those with a reverse (REV) lamp position pattern (i.e., with two lamps on the top and one at the bottom) (98–160 mW cm^{-2}). The largest D_{min} (193 mW cm^{-2}) was obtained in an UV reactor with a lamp relative distance (i.e., the ratio of the distance between the lamp and reactor axes to the reactor radius) of 0.4 and an inlet internal diameter of 75 mm, which could be ascribed to a well-mixed flow resulting from an optimal dispersion of the influent flow by the lamp array. The maximum disinfection flow rate of the UV reactor with the optimal configuration was elevated by 47–100% compared to those of the non-optimally designed reactors, which led to an energy saving efficiency of 32–50%.

1. Introduction

The application of ultraviolet (UV) technology in drinking water treatment is increasing rapidly worldwide because of its cost-

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* Corresponding author.
E-mail address: qiangz@rcees.ac.cn (Z. Qiang).

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Nomenclature

D_{avg}	particle average UV dose (mJ cm^{-2})
D_c	assumed particle constant UV dose (mJ cm^{-2})
D_{min}	particle minimum UV dose (mJ cm^{-2})
D_i	UV dose received by the i^{th} particle (mJ cm^{-2})
D_0	intercept of microbial UV dose-response curve on X axis (mJ cm^{-2})
D_{10}	particle 10th percentile UV dose (mJ cm^{-2})
d_r	lamp relative distance (–)
d_1	reactor internal diameter (mm)
d_2	reactor inlet or outlet internal diameter (mm)
FR	fluence rate (mW cm^{-2})
FR_{avg}	area-average fluence rate (mW cm^{-2})
ID	internal diameter (mm)
k	microbial UV inactivation rate constant (cm^2 mJ^{-1})
L_1	reactor length (mm)
L_2	lamp arc length (mm)
L_3	distance from reactor inlet to outlet (mm)
N	total simulating particle number (–)
Q	flow rate (m^3 h^{-1})
Q_{max}	maximum disinfection flow rate (m^3 h^{-1})
RED	reduction equivalent dose (mJ cm^{-2})
RSD	relative standard deviation (–)
r	reactor radius (mm)
T_{avg}	particle average retention time (s)
T_{Dmin}	particle retention time with the minimum UV dose (s)
T_{10}	particle 10th percentile retention time (s)
x	distance between the lamp and reactor axes (mm)
θ_{10}	normalized particle 10th percentile retention time (–)

effectiveness in inactivating *Cryptosporidium* and *Giardia* [1] and great potential for micro-pollutant removal when used in combination with other chemicals [2,3]. Although UV disinfection has not yet been commonly adopted in drinking water treatment plants in China, its use for secondary water supply in communities with high-rise buildings has already become widespread owing to an encouraging policy [4]. The performance of a UV reactor for water disinfection (i.e., disinfection efficiency) depends on the fluence received by microorganisms while traveling through the reactor and is highly related to the radiation and flow fields inside the reactor chamber. In cases when the flow rate (Q) and water UV transmittance are constant, the fluence rate (FR) distribution and hydrodynamics inside the reactor chamber are determined only by the reactor configuration. Hence, by comparing the effective fluences delivered by UV reactors with various configurations, one can sort out the optimal configuration with the largest effective fluence for a constant lamp power input, so as to increase the maximum disinfection flow rate (Q_{max}) and reduce the specific energy consumption as well.

The effective fluence of a UV reactor can be measured with biodosimetry [5], chemical dosimetry [6], or other suitable methods [7]; however, these measurements are practicable only for manufactured reactors, which are too costly to be applied for reactor design. Computational fluid dynamics (CFD) has recently been used to evaluate the UV reactor performance, and an integrated CFD simulation of UV disinfection reactors includes the simultaneous modeling of flow field, radiation field and microbial transportation and inactivation [8–9]. The behavior of microorganisms inside a UV reactor can be mimicked by releasing micro simulating particles at the reactor inlet, and the fluence received by each particle is calculated with a complied user-defined function [10]. Then, particle fluences can be converted to equivalent survival microbial concentrations using an appropriate microbial UV dose-response curve, and the accumulative survival microbial concentration at the reactor outlet is finally converted to an effective fluence which is known as the reduction equivalent fluence or reduction equivalent dose (RED) [10]. The microbial inactivation ratios or RED values of UV disinfection reactors predicted by CFD simulations have generally agreed with the measured results from biodosimetry [9–12].

The RED is a widely accepted performance indicator for UV reactors for water disinfection and the optimal reactor configuration can be obtained by comparing the RED values of UV reactors with various configurations. However, to obtain the RED, a specific UV dose-response curve of a certain challenge microorganism must be given at first and two conversions are needed as mentioned above. Besides, the RED depends highly on the microbial UV dose-response curve that is obtained from bench-scale microbial UV inactivation experiments with a *quasi*-collimated beam apparatus. Different RED values will be generated from the same simulation when using varied experimental microbial UV dose-response curves [13]. Therefore, it is difficult to compare the results among studies that usually employ various microbial UV dose-response curves and sometimes even disparate challenge microorganisms. On that account, efforts have been made to search alternative performance indicators for UV disinfection reactors. Wols et al. [14] found a strong linear correlation ($R^2 = 0.99$) between the disinfection efficiency (expressed in log-inactivation of microorganisms) and D_{10} (the 10th percentile dose in the UV dose distribution). Xu et al. [15] found that the disinfection efficiency was correlated to the normalized standard deviation of particle radial displacement. Nonetheless, all these findings were based on simulations with low corresponding RED values (<50 mJ cm^{-2}). The target RED for reactor design will be considerably higher because both lamp aging and sleeve fouling have to be accounted for while still achieving a required minimum UV dose (i.e., 40 mJ cm^{-2}) [16]. Other potential performance indicators include θ_{10} [17], D_{min} and D_{avg} [14]. θ_{10} is the normalized particle 10th percentile retention time, that is, the time when the first 10% of the micro simulating particles exit the reactor normalized by the theoretical mean retention time of all particles. θ_{10} has often been used as an indicator for short-circuiting in reactors [17]. D_{min} and D_{avg} are the particle minimum UV dose and the particle average UV dose, respectively; which are the characteristic parameters of the UV dose distribution just like D_{10} (Fig. S1). All these potential performance indicators have an advantage over the RED in being independent of the microbial UV dose-response curve. In addition, by evaluating their feasibilities in characterizing the UV disinfection reactor performance, one can determine the dominant parameter affecting the reactor performance so as to efficiently optimize the reactor configuration.

In this study, the configurations of 3-lamp UV reactors for water disinfection were optimized focusing on the lamp arrangement and the inlet size by using CFD simulations. In this optimization process, a new and simple performance indicator, D_{min}, was introduced, and its feasibility in characterizing the UV disinfection reactor performance was verified both theoretically and experimentally. The effects of the lamp arrangement and the inlet size on the reactor performance were clarified by analyzing the FR distribution and hydrodynamics, and the optimal configuration