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Research Paper

Numerical and experimental investigation of UV disinfection for water treatment

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HIGHLIGHTS

- UV irradiation for water treatment is numerically and experimentally investigated.
- Fluence rate E increases exponentially with the increase of UVT.
- UV dose distribution moves to a high range with increase of UVT and lamp power.
- A linear relationship is observed between fluence rate E and average UV dose D_{ave}.
- D_{ave} decreases with the increase of UVT and fluid flow rate.

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ABSTRACT

Disinfection by ultraviolet (UV) for water treatment in a UV reactor is numerically and experimentally investigated in this paper. The flow of water, UV radiation transportation as well as microorganism particle trajectories in the UV reactor is simulated. The effects of different parameters including UV transmittance (UVT), lamp power and water flow rate on the UV dose distribution and average UV dose are studied. The UV reactor performance in terms of average UV dose under these parameters is analysed. Comparisons are made between experiments and simulations on the average UV dose and reasonable agreement is achieved. The results show that the fluence rate increases exponentially with the increase of UVT. The UV dose distribution profiles moves to a high range of UV dose with the increase of UVT and lamp power. The increase of water flow rate reduces the average exposure time of microorganism particles to the UV light, resulting in the shifting of UV dose distribution to a low range of UV dose. A linear relationship is observed between fluence rate and the average UV dose. The average UV dose increases with the increase of lamp power while it decreases with the increase of UVT and water flow rate.

1. Introduction

Ultraviolet (UV) disinfection is an effective way for water treatment [1]. The central idea of this method is to use UV-C, one range of wavelength from UV light, to inactivate microorganisms for functioning and reproducing itself. UV light is able to pass through the cell wall of the microorganisms and absorbed by the protein and nucleotides so that it can disrupt the structure of DNA or RNA of the microorganism. Unlike cryptosporidium for water treatment, UV disinfection for drinking water treatment does not introduce or generate any hazardous chemical materials or by-product during the procedure. Therefore, it grows rapidly since 1985 [2]. UV disinfection for water treatment becomes more popular when the UV disinfection method was included in the Surface Water Treatment Rule by United States Environmental Protection Agency [3].

The UV disinfection system for water treatment generally consists of one or more UV lamps and a conduit or duct in which the water to be irradiated. Given the location of the UV lamps and water, UV reactors can be divided into two different types, i.e. contact and noncontact types [4,5]. Contact reactor is more popularly used. In the contact reactor, the lamps are enclosed by the cylindrical quartz sleeves. These quartz sleeves are used to separate the lamps from water. During the operation, water carried along suspended microorganisms into the reactor. These microorganisms absorb radiation during their transit in the reactor. Given the non-uniformity of the UV fluence rate field in the reactors, different microorganism absorbs different UV dose when it flows through the reactor. UV dose is the amount of UV energy per unit

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Nomenclature

a	absorption coefficient (1/m)
c_1, c_2, c_3	constant
C_D, $C_{1\varepsilon}$, $C_{2\varepsilon}$	constant
d_p	particle diameter (m)
D	UV dose (J/m^2)
E	fluence rate (W/m^2)
F	force (N)
$\vec{g}$	gravity vector (m/s^2)
G_κ	production of turbulent energy (kg/m s^3)
I	radiation intensity (W/m^2)
L	length of reactor (m)
n	refractive index
N	number of microorganisms
P	pressure (Pa)
Q	flow rate (m^3/s)
Re	Reynolds number
$\vec{s}$	direction vector (m/s)
t	time (s)
T	temperature (°C)
$\vec{u}$	velocity vector (m/s)
UVT	transmittance
x, y, z	Cartesian coordinate

Greek symbols

μ	dynamic viscosity (kg/m s)
σ	Stefan Boltzmann costant (W/m^2 K^4)
κ	kinetic energy (m^2/s^2)
ε	energy dissipation rate (m^2/s^3)
σ_κ, σ_ε	empirical constant
ρ	density (kg/m^3)

Subscripts

ave	average
p	particles
r	reference
t	turbulent flow
$*$	dimensionless

area that incident on a surface. Such UV dose absorbed by these microorganisms affects the performance of the reactor. Generally, an optimum UV dose can be calculated from the desired inactivation rate which is associated with the total and live microorganism before and after the reactor. The performance of a UV reactor is governed by many parameters including, among others, the reactor diameter, lamp arrangement, lamp power, fluid properties and fluid flow rate. Therefore, knowing the effects of these parameters on the performance of the UV reactor is important for designing an efficient UV reactor.

The performance of the UV reactor can be investigated experimentally. A detailed summary for experimental study of UV disinfection for water treatment can be found in the work of Hijnen et al. [1]. Generally, experimental study of UV reactor performance requires large scale test facility and expensive high-resolution equipment to provide convincible data. Besides, the operating cost of the UV reactor is substantial. Experimental study, although expensive, is still a desired and straightforward way to evaluate the performance of one UV reactor. Janex et al. [6] tested the effect of water quality and hydraulic characteristics on the performance of the UV reactor. They concluded that the performance of the UV reactor is affected by its geometry and the type of microorganism in the water. With the development of the dyed microspheres method [7], it makes the measurement of UV dose distribution in a UV reactor possible. This serves as potential evaluation platform for the UV reactor performance, leading to a better and more in-depth understanding of the UV reactor. Blatchley et al. [7] used the dyed microspheres to measure the UV dose distribution in a large scaled UV reactor. Their experimental results agreed well with their simulation results. Zhao et al. [8] used fluorescence microspheres to measure the UV dose distribution in a UV reactor. They investigated different orientations of the inlet pipe, i.e. straight and elbow inlet pipe on the UV dose distribution. They concluded that no significant difference is observed for different inlet pipe configurations.

Generally, the study of UV reactor is complex as it involves with fluid flow, UV radiation transport as well as microorganism movements. One of the important factors which affect the UV reactor performance is the flow path of the microorganisms. Fluid flow in the reactor is usually highly turbulent. It makes the trajectories of the microorganisms complex and unpredictable. In view of this, numerical simulations play an essential complementary role in understanding various processes involved in the reactor. It can provide useful detailed insights. Numerical simulation of UV process in a reactor is extensively studied. Chiu et al. [9] numerically studied the effects of the reactor geometry on the UV dose distribution as well as microbial inactivation. They have evaluated the reactor with different side walls including wavy side wall and baffled side wall. The results showed that both of these two geometries have high UV dose distribution. A three-dimensional numerical model was built by Munoz et al. [10] to simulate the full scale UV reactor. They have investigated the sensitivity of particle numbers on the reduction equivalent dose (RED). RED is another factor which is used to evaluate the UV reactor performance. The model was applied to simulate different operating mode of the lamps as well as arrangements of the lamps and baffles. Their results showed that RED is very sensitive to the particle numbers injected into the reactor. Different reactor requires different number of particles to achieve a stable solution. In addition to the experimental study for the orientation of the inlet pipe on the UV dose distribution by Zhao et al. [8], they also performed numerical simulation to compare with their experimental data. Their numerical simulation predicted higher RED compared with experimental data. Xu et al. [11] developed a three-step UV fluence rate and fluid dynamics (TURF) model to simulate fluid flow, radiation and microorganism movements in the UV reactor. Their simulation is performed based on the commercial software of FLUENT ANSYS platform. The model was applied to study the effect of water flow rate, reactor size and shape as well as the lamp arrangements [12] on the UV reactor performance. The results showed that these parameters have complex effect on the microbial inactivation.

Although there exist extensive studies of UV disinfection for water treatment in the literature, however, the performance of a UV water treatment reactor is reactor, water content and operation condition specific. For example in terms of water content, even for the same reactor, the performance depends on both the type and quantity of the micro-organisms. Generalizing the findings from these studies for design and operation of a new reactor is therefore uncertain.

Given the wide range of possible water content and operation conditions, lab-scaled experimentation is expansive and time consuming. Besides, scaling-up the results of a lab-scaled experiment for use in an actual reactor is not straight forward. On the other hand, sole numerical study, though much less expensive, may