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A computational study of the effect of lamp arrangements on the performance of ultraviolet water disinfection reactors

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HIGHLIGHTS

- Effects of lamp arrangement on water disinfection reactor performance were analyzed.
- Water flow rate and lamp arrangement have complex effects on reactor performance.
- Parallel-type reactors perform better than perpendicular-type.
- Good reactors should have high average UV fluence rate.
- Operating conditions should provide low particle residence time standard deviation.

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ABSTRACT

Ultraviolet (UV) disinfection is an environmentally friendly water treatment technology. Effects of different lamp arrangements on UV disinfection reactor performance have not been well-studied. In this work, the UV disinfection performance of reactors with various lamp arrangements was analyzed on a common basis. Computational fluid dynamics (CFD) simulation software FLUENT was used to simulate microorganism particle motion in different UV water disinfection reactors. Applying the Monte-Carlo method, the reactor performance was assessed based on microorganism log reduction under constant UV dosage. Results for different lamp arrangements show that increasing number of lamps did not improve reactor performance despite more homogeneous UV fluence rate distribution. The lamp located directly below the water outlet retains particles inside the reactor for a longer time, thus enhancing reactor performance especially at low water flow rates.

1. Introduction

Due to absence of hazardous chemicals added or generated during water treatment process, Ultraviolet (UV) disinfection technology is attracting much research interest (Hijnen et al., 2006). Since its cost is still higher than conventional disinfection processes such as chlorination (Wolfe, 1990), researchers have devoted much effort to find more efficient design for UV disinfection reactors. Utilization of light radiation of longer wavelength by addition of a photocatalyst such as TiO_2 has attracted much of the attention (Hoffmann et al., 1995; Li et al., 2008; Pan et al., 2010). Kinetics of UV disinfection process has also been discussed to provide basis for reactor optimization (Alpert et al., 2010; Ballari et al., 2010; Grabowska et al., 2012). Arrangement of light source is another important aspect of UV disinfection reactor design. Although there have been a few studies on various arrangements of light source (Ray, 1999; Taghipour, 2004; Chen et al., 2011; Baranda et al., 2012), comparison of different lamp arrangements on a common basis is absent in the literature.

UV water disinfection reactors, or photocatalytic water disinfection reactors, can be classified into three types according to the light source arrangement: *external*, *distributive* and *immersive* reactors (Ray, 1999). In the *external* type, the light source is placed outside the reactor. Light has to pass through the reactor wall (which is normally quartz glass for good UV transmission) to reach the water body. The UV intensity and evenness of UV fluence rate (UV-FR) in this kind of reactors are normally lower than that in the other two types for the same power consumption. Currently, most of external type water treatment reactors utilize solar radiation so that there is no capital cost or operating cost for the light source (Malato et al., 2007). In the *distributive* type also, the light source is outside the reactor. Light transmission media such as glass rods or optical fibers are added to distribute light inside the reactors. The distributive type reactor usually has higher and more uniform UV

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radiation inside the reactor than the external type reactor. However, the light incident angle has to be chosen carefully, and maintenance and operation of such reactors are complicated.

The *immersive* type reactor has UV lamps placed inside the reactors. This kind of reactors utilizes more UV radiation output than the other two types. Most industrial UV disinfection water reactors are of this type (US-EPA, 1999). Therefore, only immersive type reactors were analyzed in this work. Various ways of placing lamps inside the reactors have been explored by researchers, such as a row or a matrix of lamps placed perpendicular to the water flow direction (Chiu et al., 1999; Taghipour, 2004), or single or multiple lamps placed horizontal/parallel to the reactor axis (Elyasi and Taghipour, 2006; Sozzi and Taghipour, 2006a, b), both via experiments and simulations. Different lamp arrangements have different UV-FR distribution and water flow profile inside the reactors, affecting the reactor performance in a complex way. Placing the lamp parallel to the reactor axis utilizes more lamp emission, but the UV fluence rate is much lower at the two reactor ends and near the reactor outer wall (Xu et al., 2013). Placing the lamp matrix perpendicular to the reactor axis provides a more uniform UV-FR distribution in the radiation zone, but there is nearly no UV radiation outside the radiation zone. Each of the studies cited in this paragraph focuses on only one or two types of lamp arrangement. In this work, different lamp arrangements were compared on common basis through simulations.

CFD software FLUENT was used to simulate UV water disinfection reactors with different lamp arrangements operating under different conditions. Lamps were placed either parallel or perpendicular to the reactor axis. The number of lamps was also varied in order to analyze its effect on reactor performance. The simulation methodology is described in Section 2. Results are presented and discussed in Section 3. Effects of lamp arrangement on UV-FR field inside the reactors are presented in Section 3.1, followed by lamp arrangement effects on water flow profile in Section 3.2, and reactor performance comparison in Section 3.3. Relationship between variables of interest is discussed in Section 3.4. Findings of this work are summarized in the Conclusions section.

2. Reactors and their simulation procedure

The reactors in this work were simulated in FLUENT using the TURF (Three-step UV fluence Rate and Fluid dynamics) methodology described in our previous work (Xu et al., 2013). The only difference is the lamp arrangement in the simulated reactors.

2.1. Reactor specifications

In order to compare on a common basis, all the reactors considered in this work had the same dimensions: a cylinder with 50 cm in length and 4.45 cm in radius. A single-lamp annular reactor with an inner radius (the outer radius of the quartz jacket housing the lamp) of 1.125 cm was chosen as the reference reactor. In different reactors, the lamps were placed to be either perpendicular or parallel to the reactor axis. In this work, each reactor was named according to the number and direction (PER for perpendicular and PAR for parallel), as well as orientation (A and B for different reactors with the same number and direction of lamps) of the lamps, as shown in Fig. 1. For example, 4-PAR-A means Type A of the reactor with 4 lamps placed parallel to the reactor axis. The only difference between Type A and Type B is that, in Type A reactors, there is at least one lamp right under the water inlet and outlet. In parallel reactors, the centres of the lamps are located right in the middle between centre of the reactor and the reactor wall. The distance between neighbouring lamps is constant for all lamps. In Type A perpendicular reactors, there is one lamp right under the water inlet and another directly below the water outlet. The rest of the lamps are distributed evenly between these two lamps. In Type B perpendicular reactors, the lamps are distributed evenly between two ends of the reactors along its central axis. The internal volumes of all reactors were kept the same as the reference reactor by varying the radius of quartz jackets housing the UV lamps, as indicated by the numbers in Fig. 1.

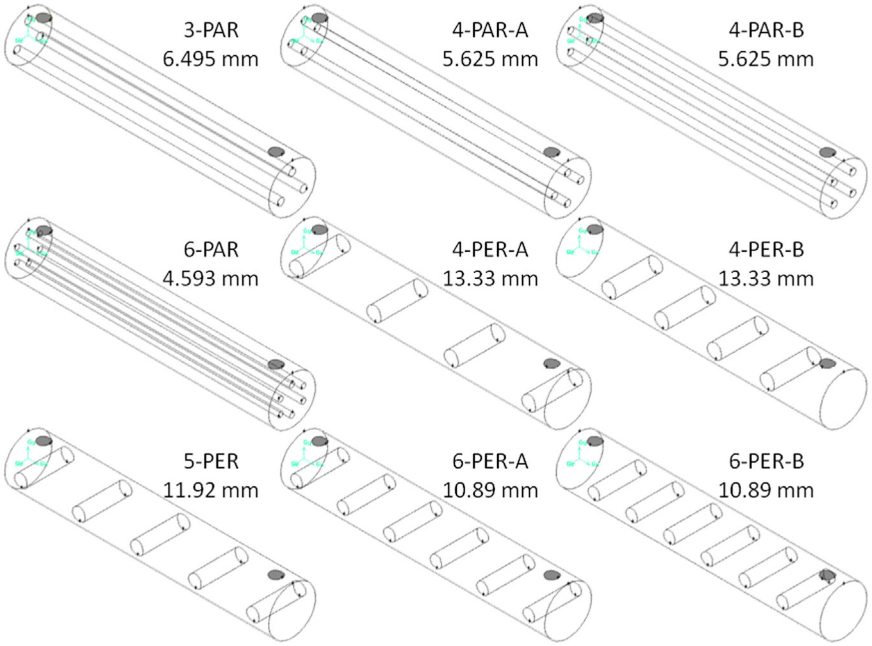

Fig. 1. Reactor layouts studied in this work; inlet and outlet nozzles are shown as small shaded circles on top of the large cylindrical surface.