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Rotating packed bed as a novel disinfection contactor for the inactivation of *E. coli* by ozone

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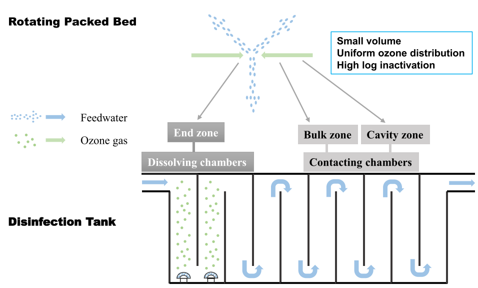
HIGHLIGHTS

- Rotating packed bed was employed as a novel disinfection contactor in this work.
- RPB showed significantly higher disinfection efficiency than conventional disinfection contactors.
- Hatta number for *E. coli* inactivation by ozone in RPB reached 7.72.
- Dissolving and contacting zones were identified in RPB.

GRAPHICAL ABSTRACT



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ABSTRACT

The intensification of mass transfer and mixing in ozone-based disinfection processes is very important in order to achieve a certain disinfection effect at a reasonable cost. This study employed rotating packed bed (RPB), an efficient process intensification device, as an ozone-disinfection contactor, and its performance on disinfection and mass transfer was evaluated by the inactivation of *Escherichia coli* (*E. coli*) and mass transfer coefficient (k_La). The ozone exposure (Ct value) and the log inactivation of *E. coli* in the RPB reached 0.0008–0.0014 min mg L^{-1} and 6.8–7.3 in phosphate buffered saline buffer, respectively. And the k_La in RPB rose from 0.030 to 0.186 s^{-1} with the increase of liquid flow rate from 10 to 60 L h^{-1}. The increase of rotation speed of the RPB enhanced the log inactivation and k_La simultaneously. It was also noted that a higher gaseous ozone concentration at the identical applied ozone dosage is favorable for the inactivation of *E. coli*. The calculation of Hatta number indicated that the inactivation of *E. coli* in RPB is a diffusion-controlled process for which RPB is well suited. Compared to the conventional bubble reactor, the achievement of high disinfection efficacy at a low Ct value in RPB revealed that RPB is an efficient ozone disinfection contactor for the inactivation of microorganisms in water.

1. Introduction

Safe and efficient disinfection processes play a key role for providing the public with clean and safe water supply (McGuire, 2006). Disinfectants and disinfection contactors are two essential

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factors in disinfection processes. Ozone is a safe and strong disinfectant and has been used for decades to disinfect drinking water, treat industrial wastewater and purify circulation water because it is able to inactivate most bacteria, viruses, spores, protozoans and algas, and remove chroma, odor and some micropollutants as well (Schaar et al., 2010). Ozone also demonstrates the capability of inactivating pathogens in high efficiency with less disinfection byproducts (DBPs) formed in water treatment (Gutierrez and Nguyen, 2012; Lee et al., 2013; Liu et al., 2015).

The ozone disinfection system requires a high solubility of ozone in view of effect and efficiency, thus an efficient transfer of ozone to water is sought in the disinfection process (USEPA, 2010). In conventional applications, the absorption and mixing of ozone with water are realized by basin/chamber contactors. Generally, the ozone transfer process conducted in the contactors must be fast and uniform, so as to satisfy the ozone consumption and guarantee a certain inactivation effect of the microorganisms. Nevertheless, conventional contactors usually exhibit the shortcomings of poor mass transfer and non-uniform mixing effects caused by short-circuiting and recirculation. Therefore, a contactor with a high efficiency of mass transfer and mixing is desirable in the ozone disinfection process.

Rotating packed bed (RPB), also known as high gravity (Higee) technology, is an innovative intensification technology for mass transfer and mixing, and has been applied to many fields such as stripping (Gudena et al., 2012), absorption (Yi et al., 2009; Zhang et al., 2011), distillation (Chu et al., 2013), nanoparticles preparation (Chen et al., 2003), effluent treatment (Wei et al., 2015), etc. By an acceleration of 1-3 orders of magnitude larger than the gravity on the earth, liquid is split and spread into fine droplets, threads and thin films by centrifugal force in the RPB, resulting in a significant intensification of mass transfer between gas and liquid. Consequently, RPB has been regarded as an ideal reactor for ozone absorption and employed in wastewater treatment for phenol degradation (Zeng et al., 2013), chroma removal (Ge et al., 2016) and biodegradability improvement of industrial effluent (Wang et al., 2017). These studies revealed that RPB can significantly enhance the ozone absorption and ozonation efficiency with a small ozone dosage and short reaction time.

Herein, we studied the performance of RPB as an ozone disinfection contactor by the inactivation of *Escherichia coli* (*E. coli*) in water and the mass-transfer study. *E. coli* is commonly used as an indicator organism to assess the effectiveness of water disinfection (Li et al., 2017b, 2017c). The effect of rotation speed and applied ozone dosage (AOD) on *E. coli* inactivation was investigated. Ozone exposure in the RPB was determined and contrast experiments with a bubble reactor were also conducted. Furthermore, k_La and Hatta number (Ha) were measured and calculated to evaluate the gas-liquid mass transfer efficiency of the RPB. To the best of our knowledge, employment of RPB as a disinfection contactor has not been reported previously.

2. Materials and methods

2.1. Preparation of E. coli suspension and water samples

E. coli (CICC 10389) was cultured at 37 °C, 180 rpm in nutrient broth for 12 h. The LB nutrient broth was made up of 0.5% beef extract (BR, AOBOX Biotechnology, China), 1% peptone (BR, AOBOX Biotechnology, China) and 0.5% NaCl (AR, Beijing Chemical Works, Beijing, China). Then the cells were harvested by a centrifuge (3000 rpm, 5 min at room temperature) and washed 3 times in 1:10 diluted phosphate buffered saline (PBS, pH = 7.4). The pellet was re-suspended to 5 mL with the concentration of *E. coli* ~10^9 CFU mL^{-1}. Five hundred microliters of the suspension were mixed with 1 L of 1:10 diluted and autoclaved PBS to prepare the simulated water samples with an *E. coli* concentration of ~10^6 CFU mL^{-1}. In addition, the glucose (AR, Beijing Chemical Works, China) was used as the source of COD in the simulated water. All the water samples were used and tested within 2 h after the preparation and collection.

2.2. Experimental setup and procedures for inactivation

2.2.1. Contactors

The RPB consists mainly of a packed rotor, a casing and a liquid distributor, and the bubble reactor is made up of a glass column and a gas diffuser. The parameters of these two reactors are given in Table S1 in the supplementary materials.

In the contrast experiment, the RPB was operated at a continuous flow of the ozone gas and water, while the bubble reactor was on a semi-batch mode with a continuous flow of the ozone gas and a certain volume of water contained in the reactor. The gas flow rate and liquid treatment capacity (liters per minute) were the same for the two reactors.

2.2.2. Experimental setup and procedures

Fig. 1 shows the inactivation system with the RPB as the contactor. One liter of *E. coli* water sample was prepared and stored in a flask autoclave in advance. Ozone gas was produced by an ozone generator (3S-A10, Tonglin High-Tech Technology Co. Ltd., Beijing, China), which used dried air as supply source, and the gaseous ozone concentration was monitored by an ozone concentration analyzer (3S-J5000, Tonglin High-Tech Technology Co. Ltd., Beijing, China).

The ozone gas and *E. coli* water were introduced into the RPB via the gas inlet and liquid inlet respectively and contacted countercurrently in the packing of the rotor to absorb ozone into the water. After the gas-liquid contact in the RPB, the gas stream exited the RPB and was monitored by another ozone concentration analyzer (UV-100, Limicen Ozone R&D Center, Guangzhou, China) prior to handled by an ozone destructor. Water samples were collected with the autoclaved bottles once water flowed out of the RPB, and the aqueous ozone concentration was detected with an aqueous ozone detector (DOZ5500, Clean Instruments, USA). Besides, the water samples were collected after starting running the experiment for 45 s, and the collected samples were used for the *E. coli* surviving test within 30 min.

For inactivation tests with the bubble reactor, the gas setup in the RPB experiments was also employed and the gas pipeline was connected with the aeration stone located at the bottom of the bubble reactor. However, the liquid setup of the RPB was unnecessary due to the semi-batch operating mode of the bubble reactor.

2.3. Analytical and calculation methods

2.3.1. Ozone exposure

Ozone exposure, also defined as Ct value, was calculated to evaluate the inactivation efficacy of ozone contactors (USEPA, 2010). The t_{10} method is commonly employed to calculate the Ct value, which is obtained by multiplying the residual ozone concentration by time that should be corrected by the "baffling factor" for nonideal flow (Zhang et al., 2016), while the continuous stirred tank reactor (CSTR) method, which assumes that the ozone contactor is composed of a series CSTRs, is recommended for the contactors that have significant back mixing or when no tracer data is available. Since the degree of back mixing in the RPB is equal to two CSTRs in series (Guo, 1996), the CSTR method was employed for the Ct value calculation in the RPB, where "C" was the aqueous ozone concentration at the outlet of the RPB, and "t" is defined as