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Experimental and numerical study of cavitating flow with suction in a mixing reactor for water treatment

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HIGHLIGHTS

- The flow and mixing patterns of cavitating flow with OASs suction were investigated.
- Experimentally studies indicate the cavitation zone was extended by OASs suction.
- Numerical calculations demonstrate that cavitation collapse promoted mixing process.
- The $C_{v,w}$ analyses reveal a high mixing degree of OASs and cavitating flow.

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ABSTRACT

Hydrodynamic cavitation technology, as well as its collaborative technologies, have been widely studied in advanced oxidation processes (AOPs) for the engineering application of water treatments. Cavitation evolution process, which could be greatly changed by the injection (or suction) in cavitating flow, might significantly affect the efficiency of water treatment. However, few interests have been focused on the flow and mixing pattern of cavitating flow with injection. In this study, the interactions (including flow and mixing pattern) between cavitating flow and oxygen active species were investigated in a hydrodynamic cavitation mixing reactor. A visible experimental set-up was designed to capture the cavitation flow and mixing phenomena in this reactor. Besides, three-dimensional numerical simulations were conducted to gain further insight into the distribution of oxygen active species (OASs) in the reactor using commercial CFD code. Experimental results show that the change of cavitation structure might be related with the OASs suction. Numerical simulations demonstrated that vortices due to cavitation collapse caused the OASs mixing with the cavitating flow. Moreover, the lower the pressure ratio, the lower value of weighted coefficient variation of OASs volume fraction at outlet, resulted in better mixing quality. The findings of this work could offer theoretical supports for using hydrodynamic cavitation technologies over a wide range of applications in water pollution control.

1. Introduction

Water pollution problems, either fresh water or sea water, are serious issues for global ecological environment and human society. With rapid growth of population and economy, the increasing discharges of municipal and industrial wastewater effluent without proper treatment cause serious pollution on drinking water resource [1]. For the marine environment, with the development of international shipping and trade, microorganism invasion caused by ballast water discharges can not only destroy the ecological balance, but also do harm to human health and block the growth of local and global economy [2,3]. The increasingly serious water-related issues prompt researchers to develop effective techniques to remove chemical pollutants and harmful microorganisms in water, and finally to meet the conventional requirements of water quality.

Advanced oxidation processes (AOPs) have been reported to effectively solve the problems of water pollution [4–6]. Hydroxyl radical (·OH), the core of AOPs, can rapidly degrade pollutants and kill harmful

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microorganisms owning to its strong oxidation potential (E^0 = 2.80 V) and high chemical reaction rate ($k \sim 10^9 M^{-1} s^{-1}$) [7]. Among the AOPs, cavitation technology, possessing the advantages of generating extreme temperatures (up to 5000 °C inside cavitation bubble and up to 2000 °C at the bubble–liquid interface) and pressures (approx. 500–1000 bar) that contribute to ·OH formation and chemicals oxidation [8], has been widely studied for water treatment [9]. There are several methods to trigger cavitation [10], such as turbulent flow, fast moving particles, laser, and ultrasonic irradiation. However, most of them only generate cavitation in laboratory scale, which limit their practical applications.

Hydrodynamic cavitation (HC), caused by the pressure gradients of water, makes the scale-up applications [11,12] possible, via reactors with various geometry [13,14] like Venturi tube, orifice plate, liquid whistle, and rotating device [15]. Many studies have been conducted to investigate hydrodynamic cavitation numerically and experimentally [16–19]. HC produced by Venturi device has been proved to be effective in the oxidative degradation of chemical pollutants, such as p-nitrophenol [20] and ibuprofen [21]. In addition, many studies have indicated that hydrodynamic cavitation combining with other AOPs results in a significant improvement of water treatment efficiency [22]. Čehovin et al. [23] reported that HC enhanced the removal of dissolved organic carbon in combination with ozone, hydrogen peroxide and UV-based AOPs. Mohan [24] injected ozone into cavitating flow and reported that the combination of HC with ozone is better than the individual process for the degradation of dye effluent.

Gas or/and Liquid injection (or suction) into cavitating flow could influence the inception, growth and collapse of cavitation [25–28], which might essentially affect ·OH formation and the efficiency of water treatment. To better apply the hybrid HC in water treatment, researchers have made great efforts in investigating the interaction between cavitation and injection. Tomov et al. [29] showed that structure of cavitating flow can be deeply modified by bubble injection. Wu et al [30] reported that the utilization rate of ozone was significantly improved by suction-cavitation. Sayyaadi et al. [28] and Wu [31] investigated the injection effects on the chemical reaction efficiency in a suction-cavitation system. Most of the existing researches about the interaction between cavitation and injection overwhelmingly only focused on the efficiency and mechanism of chemical reaction, however, with a lack of attention to the flow and mixing pattern of cavitating flow with injection.

In this paper, the flow and mixing patterns of cavitating flow that coupling with a gas suction of oxygen active species (OASs) were investigated, for the purpose of industrially applying hydrodynamic cavitation and OASs in water treatments, the combination of which had been proved to have great advantages in ·OH formation and microorganism inactivation [32–35]. To figure out the interaction between cavitating flow and OASs suction, visual experiments were carried out to observe the cavitating flow region at various pressure ratios in a Venturi-type hydrodynamic cavitation reactor. The distribution of OASs in this reactor were captured with three-dimensional numerical simulation. Moreover, the weighted coefficient variation of OASs volume fraction was calculated to evaluate the mixing degree of OASs and water. The experimental and numerical results can provide basic data and reference for engineering application of OASs combined with hydrodynamic cavitation in water treatment.

2. Experimental and numerical preparation

2.1. Experimental system

An experimental system was developed to investigate the mixing and flow pattern in a hydrodynamic cavitation mixing (HCM) reactor, as shown in Fig. 1. In this system, high concentration of oxygen active species (OASs) in gaseous state, including O_2^+, $O(^1D)$, O, O_2^-, $O_2(a^1\Delta_g)$, and O_3, were produced from O_2 (95%) by an atmospheric pressure non-equilibrium plasma reactor [36], and then were sucked into the HCM reactor. Water procured from tank A via a centrifugal pump (A003538, Toshiba, Japan) flowed through the HCM reactor and then was collected in tank B. The inner diameter of the cylindrical water pipe in the developed system was 16 mm. The water flow was monitored by a rotor flowmeter, while the flow rate of OASs was controlled by a float flowmeter. Two absolute pressure sensors (CYYZ11, Starsensors, China) in the range of 0–1.0 MPa were located at both ends of the HCM reactor to record the inlet pressure P_{in} and outlet pressure P_{out}. Another absolute pressure senor (CYYZ11, Starsensors, China) was placed between the float flowmeter and the orifice plate of HCM reactor to monitor the suction pressure P_s.

2.1.1. Plasma reactor

A flat-plate plasma reactor (shown in Fig. 2) developed in our lab was used to generate OASs in this experimental system, in which a high voltage electrode made from silver material was covered by two α-Al_2O_3 (99% of mass fraction) dielectric layers, and two discharge gaps of 0.5 mm were formed between the two dielectric layers and two stainless steel ground electrodes [36]. The discharge area of the plasma reactor is 157 × 118 mm^2. The temperature of cooling water that passes through the ground electrode was maintained at 5–10 °C.

2.1.2. HCM reactor

HCM reactor in the experimental system was transparent horizontal with a structure of Venturi tube, which was made of transparent material (Plexiglas) and designed for the purpose of investigating the interaction between cavitating flow and suction flow. Fig. 3 shows the geometry sketch of internal structure of HCM reactor. The HCM reactor mainly compose of three portions including constriction, throat and diffusion. The total length of the HCM reactor is 75 mm, and the length of construction and throat is 10 mm and 3 mm, respectively. The diameter of inlet and outlet is 12 mm, and the diameter of throat is 4 mm. An orifice plate is located between the constriction portion and throat portion in the HCM reactor and connected with a suction tube. The orifice plate has a diameter of 6 mm and a length of 1 mm, while the diameter of the suction tube is 0.8 mm. OASs was sucked into the HCM reactor from the plasma reactor through the suction tube. The plasma reactor connected to the suction tube via a hosepipe.

2.2. Cavitation experiments

Two sets of experiments (cavitating flow without OASs suction, cavitating flow coupling with OASs suction) were carried out to study the flow and mixing pattern. In the first case, only water flowed through the HCM reactor, and the cavitation phenomenon in HCM reactor was observed. In the second case, water flowed through the HCM reactor. Meanwhile, OASs in gaseous state approximately at atmospheric pressure were sucked into the reactor via the suction tube with a suction flow rate of 0–3.0 L/min. During the experiments, the inlet pressure (P_{in}) was chosen to be 0.5 MPa and was kept constant. The outlet pressure (P_{out}) was changed via the needle valve and set range from 0.2 to 0.45 MPa. In this study, pressure ratio (P_r) was used to describe the operation condition that can be expressed as following:

$$P_r = \frac{P_{out} - P_{sat}}{P_{in} - P_{sat}} \quad (1)$$

where the saturation vapor pressure (P_{sat}) in operating conditions is 3200 Pa at 25 ± 1 °C.

The cavitating flows generated in both cases were observed using a SLR camera (EOS 6D, Canon, Japan) with exposure time of 1/4000 s, while the flow was continuously illuminated from backside by a high power white LED (LED260C, Godox, China).