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Insights into the scalability of magnetostrictive ultrasound technology for water treatment applications

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ABSTRACT

To date, the successful application of large scale ultrasound in water treatment has been a challenge. Magnetostrictive ultrasound technologies for constructing a large-scale water treatment system are proposed in this study. Comprehensive energy evaluation of the proposed system was conducted. The effects of chosen waveform, scalability and reactor design on the performance of the system were explored using chemical dosimetry. Of the fundamental waveforms tested; sine, triangle and square, the highest chemical yield resulted from the square wave source. Scaling up from the 0.5 L bench-scale system to the 15 L large-scale unit resulted in a gain of approximately 50% in sonochemical efficiency (SE) for the system. The use of a reactor tank with 45° inclined sides further increased SE of the system by 70%. The ability of the large scale system in removing contaminants from natural water samples was also investigated. The results revealed that the large-scale unit was capable of achieving a maximum removal of microbes and dissolved organic carbon (DOC) of 35% and 5.7% respectively at a power density approximately 3.9 W/L. The results of this study suggest that magnetostrictive ultrasound technology excited with square wave has the potential to be competitive in the water treatment industry.

1. Introduction

Ultrasound technology has gained popularity in both research and industrial investigations owing to its versatile applications. It has been extensively used in a wide range of applications such as cleaning, chemical synthesis, food processing, fuel preparation and environmental remediation [1–3]. The reason behind such a wide use of ultrasound is the attractive merits of this technology [4–6] such as;

(1) Compact size of the ultrasonic equipment
(2) Ease of installation and/or retrofitting the existing systems using ultrasound equipment
(3) Low maintenance cost
(4) Readiness of ultrasound technology to be automated
(5) Chemical-free technology

The only drawback of ultrasound technology is the relatively high energy requirements for operation, however, this is valid only for some applications where the conventional treatments require low energy compared to ultrasound. For instance, in food processing industries, ultrasound has competitive energy requirements as compared to the conventional homogenization or thermal treatments [4]. Therefore, ultrasound application in food processing has flourished in recent years with successful large-scale implementations. In some other applications such as water treatment, the conventional treatment methods (e.g. chemical disinfection) require lower operational energy than ultrasound. Hence, the application of ultrasound in water treatment practices did not receive much attention in the past few decades. Recently, the public awareness of the harmful effects of the by-products of chemical treatments on human health and the environment (e.g. production of disinfection by-products (DBPs)) have rekindled the interest in the application of ultrasound in water treatment [7]. However, the perceived high operational energy is still a major hindrance for applying ultrasound on a large-scale as a chemical-free water treatment method.

The potentially high energy demand of ultrasound application for water treatment can be reduced through optimizing ultrasonic reactor design and the operating parameters for ultrasonic processes [8]. There are plethora of design configurations proposed in the literature for improving ultrasonic performance in specific applications such as water treatment. Details regarding these designs can be found in [9]. The reactor designs suggested in the

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literature focused on improving important aspects for large-scale applications such as the uniformity of ultrasonic effects via using multiple transducers [10], capability to operate in a flow regime using Sonitube [11] and maximizing the utilization of ultrasonic energy through adapting the reflection feature in the reactors [12,13].

The effect of some of the operating parameters such as power, frequency and treatment time on the performance of ultrasound in removing water contaminants were extensively studied and the outcomes can be summarized as follows;

(i) Increasing power increases contaminants removal to a certain level after which increasing the power would have minimal or no effect on contaminants removal. This phenomenon is mainly attributed to the formation of bubbles cloud near to the irradiation source at high power levels causing scattering to ultrasound energy with shielding effects. This can be alleviated through operating ultrasound on a pulse mode [14].

(ii) Applying low frequency allows the collapsing bubbles to grow larger leading to a sever collapse with a very energetic physical effects (high pressure and temperature) [15]. Such bubble collapse conditions suit application that mainly rely on the physical effects of ultrasound such as microbial inactivation [16]. On the contrary, applying high frequency ultrasound results in gentler bubbles collapse, however, the number of collapsing bubbles is higher. Hence, the amount of chemical species produced (e.g. $OH^{\cdot}$ and H_2O_2) is higher resulting in better chemical activities [17]. Ultrasound with high chemical activities is best utilized for removing contaminants such as DOC from water. Nevertheless, DOC removal with ultrasound requires higher power and longer treatment time [18] and its removal levels are much lower than those of microbes with the same power level. Thus, it would be wise to apply frequency ranges that suit the microbial removal for water treatment application. Moreover, low frequency ultrasound is known to be more efficient in distributing the acoustic energy in large-scale reactors than high frequency ultrasound [19].

(iii) Increasing treatment time increases contaminants removal with ultrasound. However, microbes' removal with ultrasound is likely to follow an exponential trend and increasing the treatment time after a certain limit would have a little effect on the removal levels.

The less explored ultrasonic operating parameter is the effect of the waveform used for exciting ultrasonic transducers on the performance of ultrasound. Only limited studies have investigated this aspect [20].

When considering the scale-up of ultrasound technology, the way through which ultrasound waves are generated becomes important. There are three types of transducers based on the mechanisms of generating ultrasound waves; liquid-driven, magnetostrictive and piezoelectric transducers [21]. The last two types are the most common ones. The vibration generated in magnetostrictive transducers is due to the contraction and expansion of the ferromagnetic core material caused by the change in the magnetic field around it (induced by electric current). The vibration of the piezoelectric transducers emanates from the change in the dimensions of the crystalline material when exciting it with electrical current. Table 1 shows a comparison between the characteristics of the magnetostrictive and piezoelectric transducers.

Despite the clear advantages of magnetostrictive transducers (Table 1), there have been hardly any thorough investigations conducted on the use of this type of transducers for water treatment applications on a large-scale. In this work, we attempted to provide some insights into the application of magnetostrictive ultrasonication for water treatment focusing on the effects of waveform, scalability and reactor design on the performance of ultrasound. New design for ultrasonic reactor that adopted the notions of multi-transducers and reflection feature was proposed and tested in this study. Energy and chemical characterisations of the designed ultrasonic system were conducted. The potency of the system in removing contaminants from natural water was also examined. The targeted contaminants were total coliform and DOC. The change in DOC structure was studied through single wavelength and UV ratios analysis at 254 and 280 nm and ratios of 254/204, 250/365 and 254/436. Absorbance at 254 and 280 nm was applied to detect change in humification and aromaticity, respectively. UV ratios of 254/204, 250/365 and 254/436 were measured to track changes in oxygen containing aromatic functional groups, molecules size and the ratio of UV absorbance to color forming moieties of DOC [7]. Absorbance at 250 nm represents small sized molecules of DOC, whereas absorbance at 365 nm represents large sized molecules.

Table 1
Characteristics of piezoelectric and magnetostrictive transducers (information adapted from [22–24].

Piezoelectric transducers	Magnetostrictive transducers
1. Relatively inexpensive	1. Higher capital outlay than piezoelectric transducers
2. Small and light	2. Heavy and bulky
3. Cannot withstand high temperature >150 °C	3. Tolerant of high temperatures >250 °C
4. Susceptible to mechanical impact	4. Extremely resistant to mechanical impacts
5. Age quickly	5. Have a prolonged working life >∼20 years
6. Have relatively lower strain in static conditions as compared to Terfenol-D	6. New alloy core (e.g. Terfenol-D) has large field-induced strain in static conditions
7. Good coupling coefficient (slightly lower than Terfenol-D)	7. Superior coupling coefficient
8. Good dynamic strain (lower than that of Terfenol-D at resonance)	8. Dynamic strain of Terfenol-D is higher than the piezoelectric transducers at resonance

2. Materials and methods

2.1. Ultrasonic system

The experimental setup used in this work is illustrated in Fig. 1a. The setup is comprised of three parts; ultrasonic system, power amplifier and associated signal source and the cooling system. The ultrasonic system consists of two Terfenol-D ultrasonic magnetostrictive transducers (CU18A, Etrema Products, Inc.) each connected to a titanium horn (∅ = 19 mm). The frequency range of the transducers used is 0–20 kHz. The transducers were mounted on a detachable acrylic top cover of a custom made metal tank. The features and dimensions of the tank are shown in details in Fig. 1b. The maximum capacity of the tank is 17 L, however the applied working volume in this work was 15 L. The tank was designed with base inclines of 45° to reflect the waves emitting from the horns to the center of the tank, thus obtaining a good distribution of ultrasonic events in the liquid. The tank was designed with two acrylic windows on the longitudinal sides of the tank. The two purposes of the acrylic windows were to precisely locate the depth of the sampling point in the irradiating liquid and to observe the sonication events during operation. The acrylic top cover has three openings. The two openings close to the edges (∅ = 32 mm) were used as an access for the ultrasonic horns and