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Designing and characterizing a multi-stepped ultrasonic horn for enhanced sonochemical performance

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ABSTRACT

The commonly used ultrasonic horn generates localized cavitation below its converging tip resulting in a dense bubble cloud near the tip and limiting diffusion of reactive components into the bubble cloud or reactive radicals out of the bubble cloud. To improve contact between reactive components, a novel ultrasonic horn design was developed based on the principles of the dynamic wave equation. The horn, driven at 20 kHz, has a multi-stepped design with a cone-shaped tip increasing the energy-emitting surface areas and creating multiple reactive zones. Through different physical and chemical experiments, performance of the horn was compared to a typical horn driven at 20 kHz. Hydrophone measurements showed high acoustic pressure areas around the horn neck and tip. Sonochemiluminescence experiments verified multiple cavitation zones consistent with hydrophone readings. Calorimetry and dosimetry results demonstrated a higher energy efficiency (31.3%) and a larger hydroxyl radical formation rate constant (0.36 μM min^{-1}) compared to typical horns. In addition, the new horn degraded naphthalene faster than the typical horn tested. The characterization results demonstrate that the multi-stepped horn configuration has the potential to improve the performance of ultrasound as an advanced oxidation technology by increasing the cavitation zone in the solution.

1. Introduction

A typical ultrasonic system used to obtain cavitational effects is composed of a power supply, a transducer, and a horn (Fig. 1a) [1,2]. The horn component, typically a solid metal rod in one of a variety of tapered shapes (e.g., stepped, conical, exponential, and catenoidal) [3–8], amplifies the mechanical vibration generated by the electromechanical transducer [1,2,6,9]. Horns in common use have shrinking cross-sectional areas that concentrate energy at a small tip, resulting in a non-uniform acoustic field and localized cavitation in solution. The concentration of cavitation near the horn tip limits the degradation efficiency of a contaminant compared to more distributed cavitation zones [2,10,11]. The dense bubble cloud near the tip also limits the mass transfer of hydroxyl radical (·OH) in the reactor, consequently restricting contaminant reaction by oxidation.

Different strategies have been tested to improve the degradation efficiency of commonly used horns. These include optimizing the geometries of reactors [4,12,13], applying different operational conditions (e.g., frequency, power input, and pulsing the ultrasonic signal) [14–17], and modifying sonication media (e.g., additives and purging oxygen) [16,18–20]. A redesign of the horn configuration provides an alternative solution that potentially increases energy-emitting surfaces, reactive areas, and cavitation volumes [2,6,21].

Therefore, for this study, a horn with a multiple-step configuration and a cone-shaped tip (Fig. 1b) was designed to enhance both cavitational effects and energy efficiency. The dynamic wave equation and equivalent circuit method were used in the design and calculation processes. Performance of the new horn was evaluated by different physical and chemical methods. First, hydrophone measurements and sonochemiluminescence (SCL) imaging were conducted to demonstrate and verify how the designed horn increased energy-emitting surfaces and created multiple cavitation zones. Next, the acoustic power and ·OH yield were measured

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Nomenclature

a	displacement acceleration of micro-volume in horn rod ($m\ s^{-2}$)
A	transfer matrix for equivalent circuit
C_p	heat capacity of liquid ($J\ kg^{-1}\ K^{-1}$)
c	speed of the sound wave ($m\ s^{-1}$)
d	diameter of cylindrical element in designed horn (m)
E	Young's Modulus (Pa)
f	frequency of ultrasound (Hz)
k	angular wave number (m^{-1})
M	mass of liquid (kg)
M_p	magnification factor of ultrasonic horn
P_{ac}	calorimetrically determined acoustic power (W)
P_{to}	total electrical power consumed by generator (W)
S	cross-sectional area of any given horn along x-axis (m^2)
T	temperature of the liquid (K)
t	time (s)
u	particle displacement in the horn due to longitudinal vibration along the x-axis (m)

Greek letters

α	parameter for the equivalent circuit
ρ	density of horn material ($kg\ m^{-3}$)
σ	stress acting on any given micro-volume of the horn (Pa)
ω	angular frequency ($rad\ s^{-1}$)

through calorimetry and dosimetry experiments. Finally, sonochemical degradation of naphthalene, a polycyclic aromatic hydrocarbon (PAH), was conducted to evaluate the capability of the designed horn for use in a larger-scale advanced oxidation process (AOP). We also compared the performance of the designed horn against that of a typical horn driven at 20 kHz.

2. Ultrasonic horn design

2.1. Design principles

Horn design theory is based on the longitudinal vibration equation of a variable cross-section rod (Fig. 2a) [1,6,9]. Microscopically, molecules in the solid rod vibrate after absorbing acoustic energy from a transducer, causes adjoining molecules to oscillate before returning to their original position due to the elastic restoring force [22–24]. The molecule displacement (u) is parallel to the direction of longitudinal sound wave propagation in the rod [25]. Macroscopically, any small volume element ($dV = S \cdot dx$) in the variable cross-section rod forming the horn (Fig. 2a) repeats the same vibration and transmits the oscillation to the next micro-element when the stresses of the acoustic waves are uniformly distributed over the rod's cross section. Based on Newton's Second Law, a dynamic equation of vibration for the small volume element (dV) can be developed such that [6,21]:

$$\frac{\partial(S \cdot \sigma)}{\partial x} dx = S \cdot \rho \frac{\partial^2 u}{\partial t^2} dx \quad (1)$$

where S is cross-sectional area (m^2), $\sigma = E\frac{\partial u}{\partial x}$ is stress (Pa), E is Young's Modulus (Pa), ρ is density of horn material ($kg\ m^{-3}$), and t is time (s). The left side of Eq. (1) is the force, $F = S \cdot \sigma$, acting on the small volume element, dV. On the right side of Eq. (1), $S \cdot \rho \cdot dx = dm$, where dm is the mass of the micro-element, and the expression $\frac{\partial^2 u}{\partial t^2} = a$, where a is the displacement acceleration.

Usually, simple harmonic vibration in steady-state mode is used to describe vibration in a micro-element [23,24]. Eq. (1) can be modified to:

$$\frac{\partial^2 u}{\partial x^2} + \frac{1}{S} \cdot \frac{\partial S}{\partial x} \cdot \frac{\partial u}{\partial x} + k^2 u = 0 \quad (2)$$

where $k^2 = \frac{\omega^2}{c^2}$, $k = \frac{2\pi}{\lambda}$ is the angular wavenumber, $\omega = \frac{2\pi}{T} = 2\pi f$ is the angular frequency, and $c = \left(\frac{E}{\rho}\right)^{\frac{1}{2}}$ is the propagation velocity of the longitudinal wave within the horn rod.

For a cylindrically shaped horn rod, the area of its cross section remains unchanged; thus, $\frac{\partial S}{\partial x} = 0$. Therefore, Eq. (2) simplifies to:

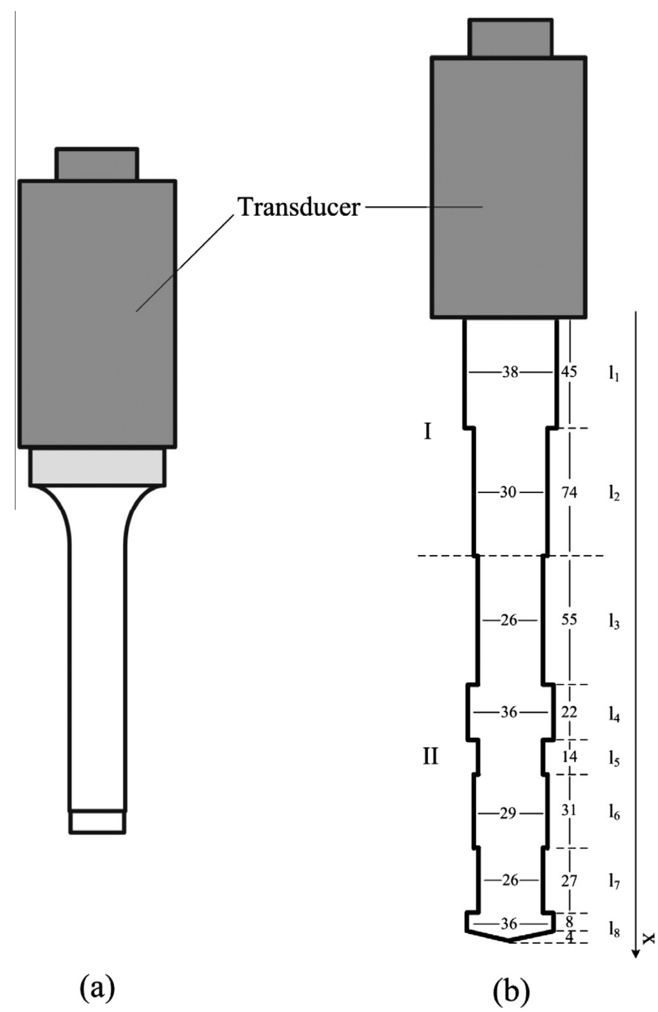

Fig. 1. Configurations of a typical horn (a) and the designed horn (b; I – the transitional section; II – the reactive section; all measurement numbers in mm).

$$\frac{\partial^2 u}{\partial x^2} + k^2 u = 0 \quad (3)$$

The solution of Eq. (3) for any single-element cylindrical horn is:

$$u = A\cos\ kx + B\sin\ kx \quad (4)$$

With Eq. (4), displacement (u) and the parametric constants A and B can be calculated using the following boundary conditions: