Ultrasonics Sonochemistry 27 (2015) 22–29

Contents lists available at ScienceDirect

Ultrasonics Sonochemistry

journal homepage: www.elsevier.com/locate/ultson

Ultrasound pressure distributions generated by high frequency transducers in large reactors

Thomas Leong [a,b], Michael Coventry [a], Piotr Swiergon [a], Kai Knoerzer [a], Pablo Juliano [a,*]

[a] *CSIRO Food and Nutrition Flagship, 671 Sneydes Road, Werribee 3030, Australia*

[b] *Mechanical and Product Design Engineering, Faculty of Science, Engineering and Technology, Swinburne University of Technology, John Street Hawthorn, Victoria 3122, Australia*

ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form 13 March 2015
Accepted 20 April 2015
Available online 25 April 2015

Keywords:
High frequency ultrasound
Reactor design
Sound penetration
Reflection
Sound pressure
Ultrasonic transducers

ABSTRACT

The performance of an ultrasound reactor chamber relies on the sound pressure level achieved throughout the system. The active volume of a high frequency ultrasound chamber can be determined by the sound pressure penetration and distribution provided by the transducers. This work evaluated the sound pressure levels and uniformity achieved in water by selected commercial scale high frequency plate transducers without and with reflector plates. Sound pressure produced by ultrasonic plate transducers vertically operating at frequencies of 400 kHz (120 W) and 2 MHz (128 W) was characterized with hydrophones in a 2 m long chamber and their effective operating distance across the chamber's vertical cross section was determined. The 2 MHz transducer produced the highest pressure amplitude near the transducer surface, with a sharp decline of approximately 40% of the sound pressure occurring in the range between 55 and 155 mm from the transducer. The placement of a reflector plate 500 mm from the surface of the transducer was shown to improve the sound pressure uniformity of 2 MHz ultrasound. Ultrasound at 400 kHz was found to penetrate the fluid up to 2 m without significant losses. Furthermore, 400 kHz ultrasound generated a more uniform sound pressure distribution regardless of the presence or absence of a reflector plate. The choice of the transducer distance to the opposite reactor wall therefore depends on the transducer plate frequency selected. Based on pressure measurements in water, large scale 400 kHz reactor designs can consider larger transducer distance to opposite wall and larger active cross-section, and therefore can reach higher volumes than when using 2 MHz transducer plates.

1. Introduction

The characterization of pressure within a sonoprocessing vessel is an important step in the design of industrial scale reactors. Several studies have documented the characterization of sonoprocessing reactors, with a focus on bath and horn-type reactors [1–3]. These systems typically use high power, low frequency ultrasound, suitable for applications such as homogenization [4], emulsification [5], extraction [6] and sonocrystallization [7].

High frequency, low power ultrasound, is typically used for applications such as cleaning of sensitive components and, more recently, in the separation of multi-component mixtures [8]. Only a limited number of studies have looked at the sound pressure characterization of high frequency transducers in the range from 400 kHz to 2 MHz. Reported studies often use sonochemiluminescence as a means to visualize the spatial and temporal distribution for cavitation in the reactor system [9–11]. Information such as the pressure distribution of transducers positioned in large-scale reactors is neither widely nor systematically documented, and differs between reactors. Further complexity is added when reflector plates are positioned in the reactor system so that standing waves are generated, as it gives rise to regions of pressure nodes and antinodes.

When considering the propagation of sound from large transducers, it should be noted that plate transducers with large surface areas rarely consist of a single transducer element, and instead are constructed from an array of piezo elements [12]. As such, the sound waves produced from each active transducer component will tend to result in interference when in close proximity to one another. Where these waves interact, the sound pressure amplitude is the combined sum of the amplitude of the individual waves.

Further away from the plate the waves travel, the more uniform the sound field should become. These two areas are called the Fresnel and the Fraunhofer zones, or more commonly known as the near field and far field, respectively. The sound waves produced

---

[*] Corresponding author.
E-mail address: Pablo.juliano@csiro.au (P. Juliano).

http://dx.doi.org/10.1016/j.ultsonch.2015.04.028

by the transducer are ‘more predictable’ and at their maximum at the area just beyond the near field, also known as the ‘natural focus’. The length of the near-field can be calculated using the equation [13]:

$$N = \frac{D^2 f}{4u} \tag{1}$$

where N is the near-field distance, D is the largest dimension of the transducer element (mm), f is the frequency of the transducer (MHz) and u is the velocity of the sound (m s^{-1}).

As these sound waves pass through a medium, they also experience a loss in energy due to absorption of the energy by the material, known as attenuation. The attenuation is dependent on the frequency of the ultrasound as well as the density and viscosity of the material, and scales as [14]:

$$\alpha \propto \frac{2}{3}\frac{\mu f^2}{\rho} \tag{2}$$

where α is the attenuation coefficient, f is the frequency of the applied ultrasound (s^{-1}), μ is the viscosity (Pa s = kg m^{-1} s^{-1}) and ρ is the density of the fluid medium (kg m^{-3}).

When sound waves encounter a boundary such as a steel plate, part of the energy is reflected back to the transducer. The remaining energy will pass through the plate. Recent work investigating the transmission of sound pressure through steel plate boundaries (where water was located on both sides of the boundary) at ultrasonic frequencies between 400 kHz and 2 MHz has been reported by Michaud et al. [15]. To date, however, no studies have characterized the sound pressure distributions across the length of a reactor system at these frequencies in vessels up to 2 m in length.

This study therefore focuses on understanding the effective operating distance of plate-type transducers that operate in large-scale reactor systems by measuring the sound pressure decline over long distance, the distribution of sound pressure within the active area over these distances and the influence of sound wave reflection on the sound pressure uniformity.

The performance of transducers operating at mid (400 kHz) and high (2 MHz) ultrasonic frequencies at these distances should be evaluated to understand the working limitations in larger reactor systems. Information pertaining to sound pressure distributions will enable calculation of maximum reactor transducer to wall distances in large scale operating volumes, which will help determine the optimum number of transducers required for the design of a reactor and minimizing capital costs entailed. It will therefore enable improvements in future designs to maximize reactor performance in the effective ultrasound processing regions.

2. Materials and methods

2.1. Experimental setup

A stainless steel chamber with dimensions of 350 mm × 350 mm × 2100 mm and a wall thickness of 2 mm was used for all experiments unless otherwise stated. The chamber itself may exhibit resonance modes at certain frequencies. These resonant frequencies can be estimated by assuming that the chamber is a ‘1-D room’ with closed ends using:

$$f_R = \frac{nc}{2L} \tag{3}$$

where n is an integer corresponding to the mode of vibration, c is the speed of sound in the fluid and L is the characteristic length of the chamber.

Transducers were mounted on one end of the chamber as shown in Fig. 1a. The top of the chamber was open to the air to facilitate maneuvering of the hydrophone measurement system.

The transducers utilized in this study were submersible plate transducers (SONOSYS Ultraschallsysteme GmbH, Neuenbuerg, Germany) with nominal frequencies of 400 kHz and 2 MHz. The active areas of the transducers are 110 mm × 75 mm and 100 mm × 100 mm for the 400 kHz and the 2 MHz transducers, respectively. The transducers were operated at a nominal electrical power load of 50% (~120 W for the 400 kHz system, and ~128 W for the 2 MHz system) unless otherwise stated. Preliminary tests performed at power settings of 50% and 100% showed no difference in the trends of sound penetration and uniformity for these transducers (results not shown). Note that although the power settings are similar, the actual acoustic energy delivered and hence sound pressure measured for the 2 different frequencies are quite different in magnitude. The testing chamber was filled with tap water at ambient temperature at 20 ± 5 °C and left to equilibrate at this temperature for several hours prior to each experiment.

Two different hydrophones were used for the two frequencies investigated. A needle hydrophone (HNC-1000, Onda, Sunnyvale, CA, USA) was used to measure sound pressure levels for the 2 MHz transducer. The sound pressure level for the lower frequency (i.e., 400 kHz) was measured with an ultra-broad-band spherical hydrophone (TC-4034, Reson, Slangerup, Denmark). The peak-to-peak signals were recorded with an oscilloscope (GDS-1102, GW Instek, Taipei, Taiwan) and converted to sound pressure levels using Eq. (3).

$$p = 20 \cdot \log_{10}(V_{rms}) - \mathrm{OCV} \tag{4}$$

where V_{rms} is the root mean square voltage determined from the peak-to-peak values measured, and OCV is the open received circuit voltage (read off a hydrophone calibration chart supplied by the manufacturer). Trials were carried out in a silent environment with no or minimal interference into the measuring system. Note that both hydrophones used in this study measured a baseline noise of 8 ± 4 mV when no ultrasound was applied, which is much lower than values measured at the center of the vessel and may contribute up to an additional 0.3 kPa (Reson) or 3 kPa (Onda) to the calculated pressure data. This value was not subtracted from the final values reported. Noise from the surrounding environment was minimized by averaging a minimum of 16 sweeps in the oscilloscopes.

Where required, a stainless steel plate with the same cross sectional area as the vessel and thicknesses of 3 mm, was positioned in the chamber at distances of 500 mm, 1000 mm, 1500 mm and 2000 mm from the transducer to determine the influence of reflectance to the sound pressure distribution. In such a setup, water was located on one side of the reflector plate and air on the other (Fig. 1a).

2.2. Hydrophone measurements

All hydrophones were soaked for a minimum of 20 min in the water of the testing tank prior to beginning measurements. The hydrophone was positioned directly in front of the transducer pointing at its active face (Fig. 1b). A minimum of three readings were recorded at selected locations inside the chamber, with the first few readings discarded until stabilized readings were obtained. The hydrophone was positioned at various distances along the x-axis between 55 and 1955 mm (Fig. 1b). The spacing between each measurement point was 10 mm between 55 and 155 mm, 20 mm between 155 and 255 mm, 100 mm between 255 and 955 mm and 400–500 mm between 955 and 1855 mm. Unless otherwise stated, the sound pressure with distance for each