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Design parameters of stainless steel plates for maximizing high frequency ultrasound wave transmission

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ABSTRACT

This work validated, in a higher frequency range, the theoretical predictions made by Boyle around 1930, which state that the optimal transmission of sound pressure through a metal plate occurs when the plate thickness equals a multiple of half the wavelength of the sound wave. Several reactor design parameters influencing the transmission of high frequency ultrasonic waves through a stainless steel plate were examined. The transmission properties of steel plates of various thicknesses (1–7 mm) were studied for frequencies ranging from 400 kHz to 2 MHz and at different distances between plates and transducers. It was shown that transmission of sound pressure through a steel plate showed high dependence of the thickness of the plate to the frequency of the sound wave (thickness ratio). Maximum sound pressure transmission of ~60% of the incident pressure was observed when the ratio of the plate thickness to the applied frequency was a multiple of a half wavelength (2 MHz, 6 mm stainless steel plate). In contrast, minimal sound pressure transmission (~10–20%) was measured for thickness ratios that were not a multiple of a half wavelength. Furthermore, the attenuation of the sound pressure in the transmission region was also investigated. As expected, it was confirmed that higher frequencies have more pronounced sound pressure attenuation than lower frequencies. The spatial distribution of the sound pressure transmitted through the plate characterized by sonochemiluminescence measurements using luminol emission, supports the validity of the pressure measurements in this study.

1. Introduction

Ultrasound is a versatile processing tool suitable for a range of industrial applications. Low frequency ultrasound (20–100 kHz), also known as power ultrasound is associated and characterized by intense physical phenomena arising from the violent collapse of bubbles due to acoustic cavitation, and is suitable for applications such as homogenization [1], emulsification [2], crystallization [3] and extraction [4]. High frequency ultrasound (~400 kHz–2 MHz) on the other hand, is usually characterized by less violent bubble collapse, making it suitable for cleaning of sensitive components [5], sonochemical modification [6] and separation of multi-component mixtures [7,8].

In some industrial applications, the process can be at very high temperatures or involve corrosive and/or toxic chemicals that may be hazardous when placed in direct contact with a transducer surface. In such applications, it is desirable for an ultrasonic transducer not to be placed in direct contact with the fluid medium. An example would be in the processing of high temperature fluids like petroleum and palm oil [9,10], as it would reduce the risk of heat damage and enable easier access for periodic cleaning and maintenance. Another example would be the treatment of toxic, non-aqueous solvents, or corrosive materials, where direct contact with maintenance crew or sensitive material has to be avoided. For products that are sensitive to harsh treatment (i.e., food, pharmaceuticals, etc.), known problems such as generation of high temperatures and release of metal particulates when transducers are positioned in direct contact with the fluid, should also be avoided.

A possible solution to these problems is placing the transducer externally to the reactor such that there is a cavity where cooling liquid can be circulated between the ultrasonic transducer and the reactor walls. This however means that the emitted sound wave has to be transmitted through an additional layer of metal (i.e., a transmission plate).

Information such as the pressure distribution of transducers positioned in large-scale systems is documented in a few selected

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studies [11]. Horn and bath-type ultrasonic systems have been well characterized. There is, however, limited information available in the public domain on the sound pressure distribution of high frequency transducer plates (>400 kHz), particularly involving transmission through a transmission plate setup.

When a sound wave encounters a solid surface such as the wall of a reactor, a part of the wave energy is reflected, while a part penetrates through the solid material [12]. Once the sound wave penetrates to the other side of the solid, a portion of the sound wave will again be reflected, and a part will be transmitted into the medium on the other side of the solid material. The extent of transmission and reflection is dependent on the properties of the materials on both sides of the boundary, i.e., liquid/solid and solid/liquid or solid/gas boundaries, with more reflection occurring at increasing density differences between the two materials.

Most of the existing literature determining transmission of sound waves through materials is devoted to the study of sound in the audible frequency range within building materials. Tadeu et al. made an experimental evaluation of the transmission of sound (0–7 kHz) in air through several solid plates of glass positioned in series. He found that transmission can be inhibited if the transmitted domains have a very big change in properties, in this case glass and air compartments [13]. Estrada et al. found different resonances in aluminium plates perforated with holes: Lattice resonances, Lamb modes and Fabry–Perot modes. In Fabry–Perot resonance only multiples of the wavelengths of the resonator can be transmitted [14].

In the ultrasonic frequency range (64–359 kHz), Boyle et al. examined the transmission through steel plates where water was the liquid on both sides of the plates [12,15]. They showed that transmission reaches a maximum when the thickness of the plate is a multiple of half the wavelength of the sound wave [15]. This theory was confirmed by Boyle et al. in the above mentioned range for a system with no impedance mismatch between the two sides of the plate. Boyle et al. also derived a ratio that calculates the proportion of the incident sound energy reflected when the wave is normal to a parallel partition that is infinitely extended (i.e., thickness is much less than the other dimensions) [15]. The result obtained is expressed in the following equation:

$$R = \frac{\left(\frac{V\rho}{V_1\rho_1} - \frac{V_1\rho_1}{V\rho}\right)^2}{4cot^2\frac{2\pi l}{\lambda_1} + \left(\frac{V\rho}{V_1\rho_1} + \frac{V_1\rho_1}{V\rho}\right)^2} \tag{1}$$

where R is the ratio of the energy reflected, V is the velocity of sound in the incident medium, V_1 is the velocity of sound in the material of the partition, ρ is the density of the incident medium, ρ_1 is the density of the material of the partition, l is the thickness of the partition and λ is the wavelength of sound (within the partition).

If $l = \frac{n\lambda_1}{2}$, then $R = 0$.

Eq. (1) also shows that the thickness of the plate influences the transmission of the sound energy. A thicker plate may have lower impedance on the system than a thinner plate if the reflection ratio calculated by Eq. (1) reaches a minimum (this occurs when the denominator approaches a maximum). In this study, the only parameters of this equation that were varied are the thickness of the plate and the wavelength (i.e., the frequency). Therefore, the only term to consider is the circular function. A minimum in the reflection occurs when the following term approaches infinity:

$$\lim_{l\to x} cot^2\frac{2\pi l}{\lambda} = \infty \tag{2}$$

This term can be rearranged to get the ideal transmission at:

$$x = n\frac{\lambda}{2} \tag{3}$$

in which n is an integer. Thus, if the plate thickness equals a multiple of half of the wavelength, the impedance of the plate approaches 0. On the other hand if:

$$x = a\frac{\lambda}{4} \tag{4}$$

in which a is an odd integer, then:

$$\lim_{l\to x} cot^2\frac{2\pi l}{\lambda} = 0 \tag{5}$$

and the reflection ratio approaches a finite maximum.

From these considerations, a thickness ratio d/λ can be devised, where d is the plate thickness and lambda is the wavelength of the sound wave. The transmission reaches a maximum every time the thickness ratio is reaching a multiple of 0.5.

From a strictly mathematical point, it should be noted that if the plate thickness equals zero times the wavelength (i.e., no transmission plate) there will be maximum transmission.

While this holds true for an infinitesimal small transmission distance, it should be noted that even in the absence of a steel plate, the sound pressure decreases through attenuation, i.e., it is partially absorbed by the liquid it passes through. This decay is dependent on the properties of the sound wave and the surrounding fluid. Higher frequencies have a higher attenuation while traveling through fluids such as water [16]. Stokes [17] gives the following equation for calculating the attenuation coefficient:

$$\alpha = \frac{2\mu(2\pi f)^2}{3\rho_m c^3} \tag{6}$$

where μ is the viscosity of the fluid, ρ_m is the density of the fluid, c is the speed of sound in the medium and f is the frequency.

Given the robustness of stainless steel in various reactor design applications, this study will experimentally extend the investigations and experimental validations made by Boyle et al. [12] into the ultrasonic frequency range of 400 kHz–2 MHz. In addition to determining the transmission behavior, the spatial distribution sound pressure transmitted through the steel plate will be characterized using sonochemiluminescence and hydrophone pressure measurements. An improved understanding of the penetration of the ultrasound after transmission through the steel plate will provide valuable information for the design of ultrasonic reactors that make use of transmission plate configurations. Other factors influencing the transmission of ultrasound through stainless steel plates, such as the distance of the plate from the transducer, the thickness of the plate, and the distance of the measuring device from the transducer will also be studied.

Note that for practical reasons in this study, the angle of incidence is maintained at a constant 90°. It is known that transmission behavior is also dependent on the angle of incidence as Takahashi et al. [18] and Fay and Fortier [19] have shown.

2. Materials and methods

2.1. Transducers

The transducers utilized in this study were submersible plate transducers (SONOSYS Ultraschallsysteme GmbH, Neuenbuerg, Germany) with nominal frequencies of 400 kHz, 1, and 2 MHz. The active area of the transducers tested were 110 × 75 mm (for the 400 kHz system) and 100 × 100 mm (for the 1 and 2 MHz system).

2.2. Hydrophones

Two different hydrophones were used for the different ranges of frequencies investigated. A needle hydrophone (HNC-1000, Onda, Sunnyvale, CA, USA) was used to measure pressure levels for the systems operating at a frequency of 1 and 2 MHz. Pressure levels for the lower frequency system operating at 400 kHz were mea-