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Acoustic design aspects of megasonic reactors for oils and fat separation

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Abstract

The performance of ultrasound reactors developed to enhance oil and fat droplet separation and fractionation rely on a number of factors. These factors include the selection of transducers, the reactor geometry and dimensions, and the physical properties of the product to be processed. Ultrasound standing wave separation reactors operating in the MHz frequency range are also referred to as megasonic reactors. The separation principle is based on acoustic radiation forces following Gorkov's theory. Depending on density and compressibility, fluid droplets are splitting between nodes and antinodes in a standing wave field. The interactions between primary and secondary acoustic radiation forces and acoustic streaming determine the reactor's performance. The efficiency of the megasonic reactor strongly depends on the attenuation of the sound waves by the fluid. The sound pressure levels obtained in a large scale (up to 1.2 m) trough attached with a 600 kHz transducer were measured in water or oil bearing materials using a novel hydrophone system. Significant attenuation was observed from the midpoint of the trough through to the end when sound transmission was investigated in water, while further attenuation was observed when using palm oil sludge. Following these results, a methodology to validate megasonically enhanced oil separation from avocado and palm oil at minimum sound penetration levels at laboratory scale was developed. The combination of sound penetration data in sludges or paste supported by benchtop results will provide the information to design large scale megasonic reactors.

Keywords: ultrasound, megasonics, penetration, reactor design, sound pressure

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1 Introduction

Megasonic separation is a technology that uses high frequency (>0.4 MHz to several MHz) acoustic standing waves as the driving force to separate oil from oil bearing materials. The positioning of individual droplets or particles on pressure nodes or antinodes within the reactor may cause them to agglomerate or coalesce into larger entities rapidly. The term "megasonic" is hereafter used to distinguish this separation technology from low frequency ultrasound application in food processing, as there is a need for gentle separation processes without violent bubble collapse, which occurs during low frequency (<100 kHz) ultrasound processing. Megasonics separation has been demonstrated at industrial scale in the palm oil industry [1,2] and at laboratory to pilot scale in coconut oil, milk fat and olive oil separation processes [3].

When particles and/or oil droplets are moved together they form bands where they may aggregate or coalesce. Then, due to the increase in hydrodynamic radius of the droplets, these are more easily separated, at a faster rate of flotation, due to buoyancy forces. The acoustic separation technique is based on the action of acoustic radiation forces, resultant from a standing wave sound field, which cause particles suspended in a fluid to move towards pressure nodal or antinodal planes or regions. The creation of a stationary standing wave field is achieved by the constructive interference of the sound waves generated by the transducer and the waves reflected by an opposite solid surface (e.g. vessel wall) located at a length that is an integer multiple of the half-wavelength of the propagating sound [4].

Particles migrate towards either the pressure antinodal or nodal planes of the standing wave field, depending on the density and compressibility ratios of the particulates in the fluid. The acoustic radiation force can be observed visually as a banding effect that can cause oil droplets to be collected in individual planes within the reactor. This primary radiation force is described by Gorkov's theory [5]:

$$F_{ac} = -\frac{4\pi}{3} r^3 \mathrm{k} \mathrm{E}_{\mathrm{ac}} \phi \sin(2kx) \tag{1}$$

where *r* is the particle radius, $k = \frac{2\pi}{\lambda}$ the wave number, λ is the wavelength of sound, E_{ac} the specific energy density, *x* the distance from a nodal point of the standing wave and ϕ is the acoustic contrast factor. The contrast factor shows whether there is acoustic impedance mismatch between the fluid and either the particles or droplets, and can be calculated using:

$$\phi = \frac{5\rho_p - 2\rho_l}{2\rho_p + \rho_l} - \frac{\beta_p}{\beta_l} \tag{2}$$

where ρ is the density, β is the compressibility, and the subscripts l and p refer to the liquid medium and the particles, respectively [3]. Solid particles move towards the pressure nodes of the standing wave because its contrast factor has a positive sign, whereas oil droplets move towards the pressure antinodes as its contrast factor has a negative sign. This droplet to particle separation mechanism is further discussed by Leong et al. [5].

Leong et al. [4] provides a specific discussion of reactor configurations and design characteristics required to make this technology suitable for commercial applications in the food industry. Some key aspects to consider in designing megasonic reactors have been summarised in Figure 1, including material properties, vessel materials, transducers, sound and process parameters (frequency, amplitude, temperature, material residence time), vessel size, vessel cross section (transducer to vessel wall distance) and system type (batch, continuous).

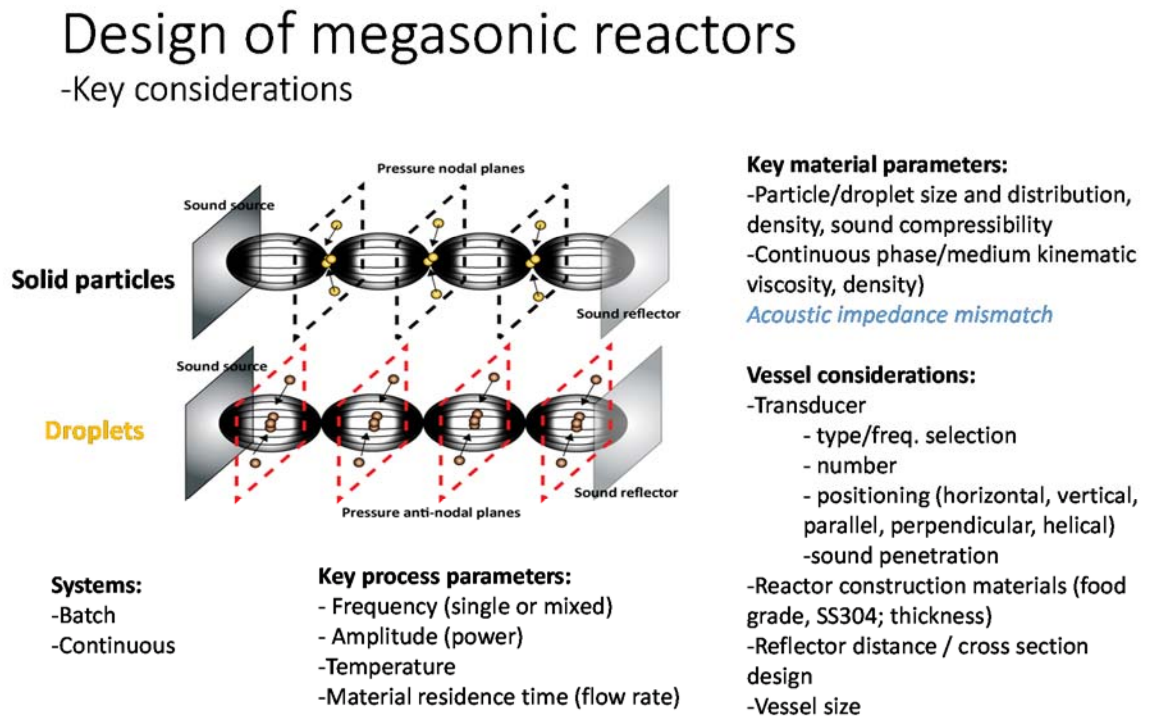

Figure 1: Key design parameters for megasonic reactors

The maximum effective distance to achieve a constant standing wave field upon reflection is limited by attenuation of the sound wave in the oil bearing material during process. If the incident sound wave becomes attenuated before it can be reflected by the opposing wall, the desired ultrasound effects on oil separation may not be achieved. For example, in the work by Leong et al. [6], transducer reflector distances greater than 85 mm were less effective in achieving skimming of milk when using dual 1 and 2 MHz frequency ultrasound. Furthermore, the minimum level of sound achievable from the sound source near the opposite reactor wall needs to be defined for an efficient design. However, little or no publication reports sound penetration information from high frequency transducer plates across water or oil bearing materials to guide reactor design decisions. Even though a standing wave is achieved across the material, the sound pressure level achieved may not be sufficient for the desired oil separation. This requires rapid methods for predicting if megasonics can predispose material for separation at achievable sound levels in large systems.

This research aims at investigating the high frequency ultrasound level achieved across water and palm oil fruit sludge in pilot and large vessels to assess future megasonic reactor designs. The laboratory scale methodology developed to evaluate oil separation effects from avocado and palm oil at minimum sound levels will be presented.

2 Materials and Methods

2.1 Fruit materials

The palm oil mill streams tested were samples of ex-screw press stream fed into a clarification tank and the underflow sludge from the clarification tank supplied by QL (Tawau, Sabah, Malaysia).

Avocados were sourced from a local supermarket (Montevideo, Uruguay) and stored in a cool room for further processing as indicated below.

2.2 Ultrasound measurement

A rugged needle hydrophone system has been developed to enable direct measurement in food materials. The system (Figure 1) is composed of a hydrophone (HNC-1000, Onda Corporation, Sunnyvale, CA, USA), a hydrophone preamplifier (20 dB, AH-2010-025, Onda Corporation, Sunnyvale, CA, USA) calibrated for measurements above 250 kHz, a glass interface, and a cooling system. The hydrophone is only usable with pure water and therefore requires an interface to protect it. It can only operate at temperatures below 50°C and therefore a cooling system has been devised to recirculate water during operation to measure materials at higher temperatures. Sound measurements were conducted via an oscilloscope and expressed as peak-to-peak voltage.

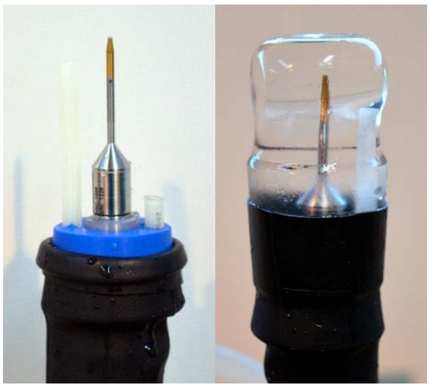

Figure 2: Hydrophone prototype design including a cooling system and glass barrier for direct measurement in food materials

A trough with a megasonic industrial transducer (600 kHz, Sonosys Ultraschallsysteme GmbH, Neuenbuerg, Germany) adjusted to one side (Figure 3a) was developed to measure the level of sound pressure achieved across its 2.4 m length. Samples were preheated and transferred to the trough. Sound measurements were taken at selected locations along the length of the trough.

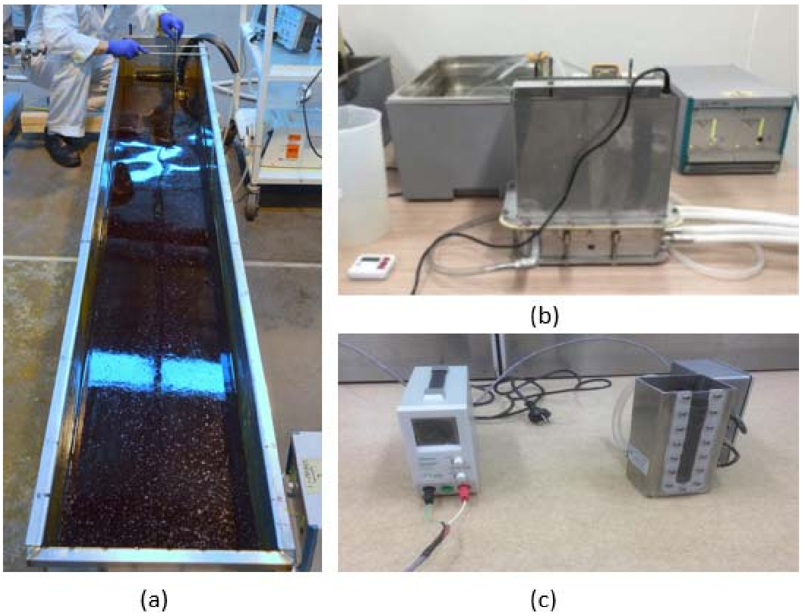

Figure 3: Megasonic devices for (a) sound penetration studies (2.4 m trough) and (b) palm oil separation studies, (c) avocado oil separation studies

2.3 Megasonic devices for oil separation assessment

A benchtop megasonic 6 L reactor (Figure 3b) was made in house with an industrial megasonic transducer including a water cooling system, transmission plates and an adjustable reflector on top surface of the sample (parallel to the transducer). This reactor was used for palm oil separation trials.

A benchtop reactor megasonic 0.5 L (Figure 3c) was made in house with two small piezo ceramic transducers operating at 1,600 kHz (nebulizer, APC International, Inc., Mackayville, PA) attached to a power regulator.

2.4 Oil separation protocols

2.4.1. Palm oil

Screw pressed palm oil fruit obtained from the process and imported into Australia (QL Plant, Malaysia) was preheated to 80°C. Heated samples were transferred to the megasonic reactor for treatment at 600 kHz (100% power, 720 W, 2 min or 10 min treatments). A control non-ultrasound sample was run in parallel for comparison. After treatment samples were transferred into 1 L measuring cylinders for settling at 80°C in an oven for various times (0 min to overnight). Oil visually separated was measured and cylinders where photographed for comparison.

2.4.2 Avocado oil

Avocado puree (Hass variety) was prepared from fresh avocados from the pulp. Water was initially added to the paste at (5:1 ratio) and the mixture was stirred for 4.5 hours at 40ºC to enable oil release. For ultrasound application, additional water was added to the mixture at 1:1 ratio and the sample was sonicated at various times at 1,600 kHz. Both control and sonicated samples were centrifuged for 15 min at 3,500 rpm. Oil yield was measured on an initial paste basis.

3 Results and Discussion

3.1 Sound penetration in water

Figure 4 demonstrates the attenuation of sound in water in a trough across a 1,200 mm distance. Sound level was greatly reduced with distance across the trough up to 1,000 mm (Figure 4a). The highest sound level was measured at 200 mm from the transducer giving a voltage, as measured by the hydrophone, of about 3.2 V. Sound pressure gradually decreased to a voltage of about 1 V.

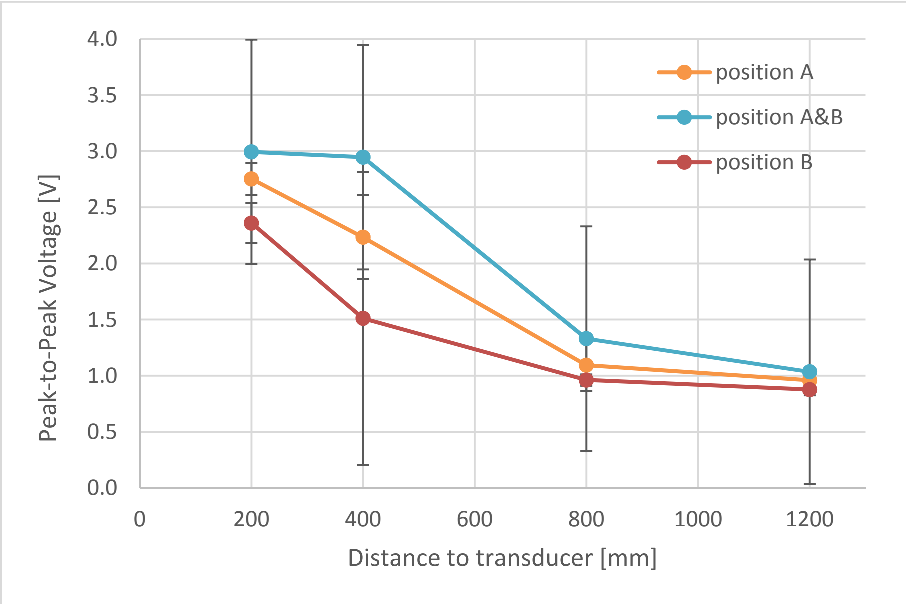

Figure 4: Sound penetration in water across an industrial size trough using a 600 kHz industrial plate transducer (regions of the twin plate transducer are defined as: A – left region; A&B central region; B – right region).

3.2 Sound penetration in palm oil sludge

The sludge from pressed fruit material was composed of 35% oil, 53% water and 12% solids. Sound pressure in the sludge was significantly attenuated at 200 mm from 3 V to 1 V compared to water (compare Figures 4 and 5). The sound profile obtained in the oil sludge had a similar pattern to that in water at reduced sound levels. Voltages of 0.3-0.4 V were measured near the end of the trough. Sound detection at the end of trough provides an opportunity to design vessels with increased cross-sectional areas by increasing the transducer-wall distance. A larger cross-section will enable to pass greater volumes through the vessel, which will provide longer residence times. This work is relevant for the current industrial design operating in the palm oil industry. However, the impact of lower sound levels measured half way beyond the transducer-wall distance on oil separation is unknown. Therefore, the next sections address rapid methods to assess the performance of megasonics on oil bearing materials at reduced sound levels.

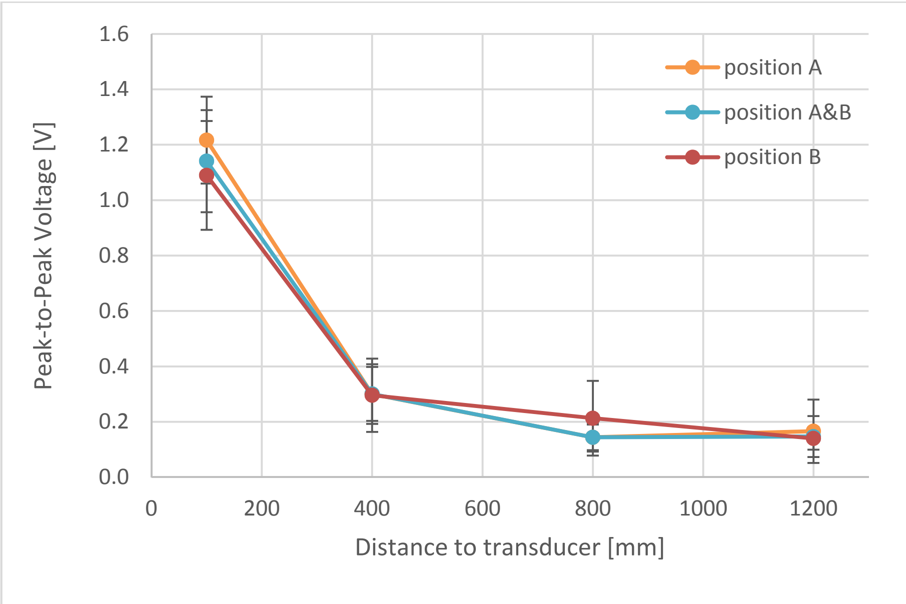

Figure 5: Sound penetration in an industrial size trough using a 600 kHz industrial plate transducer (regions of the twin plate transducer are defined as: A – left region; A&B central region; B – right region).

3.3 Oil recovery assessment in palm oil

The rapid method was able to demonstrate additional palm oil separation from the sludge after megasonic processing. Figure 6 shows the untreated and megasonically treated sludges in their respective decantation cylinders. Additional oil separation was seen before starting decantation (Figure 6, 0 min). Further decantation made the difference in oil separation between the untreated control and the megasonically treated sludge more pronounced.

Figure 6: Decantation cylinders with untreated and megasonic (600 kHz) treated samples at 0 min, 15 min and 3 h at 80°C (left cyldinder – sonicated control; right cylinder – non-sonicated control).

3.4 Oil recovery assessment in avocado oil

The process developed for avocado pastes showed higher oil separation after megasonic processing using 1,600 kHz. Water addition was required to achieve additional oil separation in megasonically treated paste. The viscosity of the paste was too low to enable sufficient sound penetration through the paste, and dilution of the paste with water provided better conditions for sound transmission. These assumptions require further validation with sound penetration data. Once the optimum oil removal conditions were identified after water addition, 5 min sonication was sufficient to detect an impact of sound treatment for additional oil recovery, while further sonication time provided similar oil recovery values.

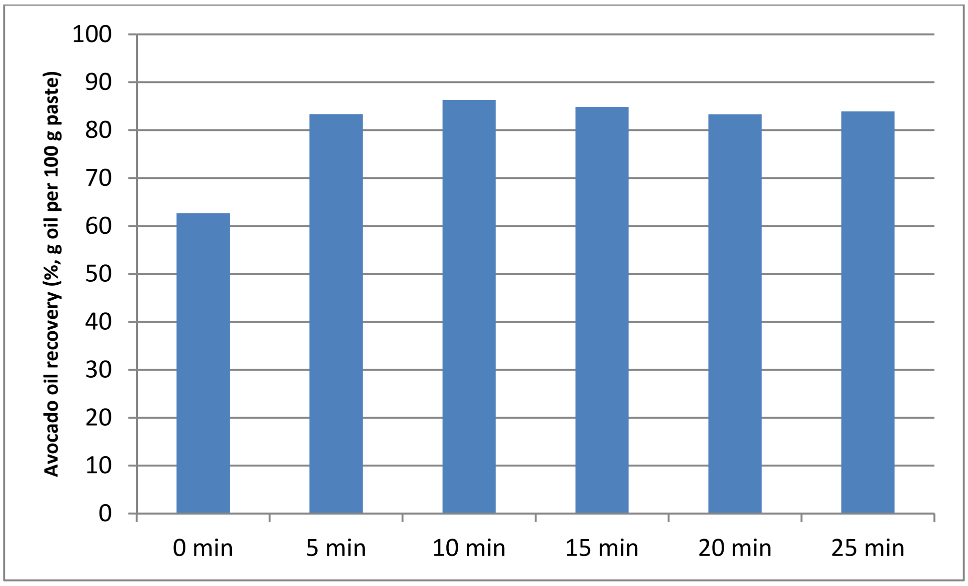

Figure 7: Oil recovered before and after sonication of avocado water mixture at 1,600 MHz for 5-25 min.

4 Conclusions

A new hydrophone measurement device enabled, for the first time, obtaining sound measurements at high frequency in oil bearing materials. The unit is suitable for characterisation of large scale reactors. Data of sound penetration across palm oil sludge has shown that sound can penetrate at least 1,200 mm, albeit causing greater attenuation than water. This information is critical for new reactor designs, particularly for the construction of larger reactors with increased ultrasound residence time and efficiency. Laboratory scale methodologies developed to evaluate oil separation effects from avocado and palm oil have proven useful to rapidly assess effects on oil separation and will enable further research to evaluate the impact of megasonic at minimum sound levels.

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