Finite Element Simulation of the Acoustic Pressure Inside a Beverage Container for Non-Thermal, Ultrasound-based Pasteurization

Darren W. Branch, *dwbranc@sandia.gov*, *505-284-5843*

Purpose:

The purpose of this effort is to investigate whether large acoustic pressure waves can be transmitted inside beverage containers to enable pasteurization. Acoustic waves are known to induce large nonlinear compressive forces and shock waves in fluids, suggesting that compression waves may be capable of damaging bacteria inside beverage containers without appreciably increasingly the temperature or altering the freshness and flavor of the beverage contents. Although a combined process such as thermosonication (e.g., sonication with heating) is likely more efficient, it is instructive to compute the acoustic pressure field distribution inside the beverage container. The COMSOL simulations used two and three-dimensional models of beverage containers placed in a water bath to compute the acoustic pressure field. A limitation of these COMSOL models is that they cannot determine the bacterial lysis efficiency, rather the models provide an indirect metric of bacterial lysis based on the magnitude of the pressure field and its distribution.

Background:

The pasteurization of beer occurs after fermentation, which is at the end of the industrial production. Pasteurization typically uses a mild thermal process (60°C) to inactivate the fermenting yeast and potential microorganisms, thus extending the beer shelf-life at room temperature. Compared to sterilization, pasteurization uses minimal heat treatment, generally at a temperature below the boiling point of water. The general objective of pasteurization is to extend product shelf-life by inactivating all non-spore-forming pathogenic bacteria, most vegetative spoilage microorganisms, and fungi, as well as inhibiting or stopping microbial and enzyme activity. To be effective, pasteurization is frequently combined with another means of preservation such as concentration, acidification, chemical inhibition. Recently, non-thermal pasteurization methods have gained attention since the heat treatment processes negatively affects the original beer freshness and flavor. For example, filtration is one of the oldest non-thermal methods employed by breweries before filling (bottling/canning). However, the shelf-life of filtered beer is much shorter in comparison to thermal pasteurized beers since some spoilage organisms remain in the beer after filtration [1].

Since the conventional thermal process can negatively affect the beer flavor [2] emerging non-thermal pasteurization technologies like high pressure processing (HPP), pulsed electric fields (PEF) [3, 4], ultraviolet (UV) irradiation [5, 6], and high-power ultrasound (US) or sonication [7, 8] alone or combined with mild heating have been investigated. Acoustic waves have found widespread use for fluid manipulation [9], spore lysis [10] performing cellular membrane disruption [11-13], inducing shock waves and cavitation in fluids through remote means. For pasteurization, high-power US and sonication have been used for wines, whiskey, and spirits, where results showed that it changed the alcohol/ester balance creating an ageing effect [14]. One author did not find significant changes to the physicochemical and sensorial properties of beer for a process using thermosonication (TS) with simultaneous exposure to US and heat: 2.7 W/ml acoustic power density, temperatures of 40, 50, and 60°C, for 2 min treatment time [15]. However, higher acoustic power density (10.8 W/ml) and temperature (75°C) TS process for 20.5 s, equivalent to a 15 PU process (i.e., 1 PU is defined as 1 min treatment at 60°C [4]), developed an

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

unacceptable haze in ale and lager beers [16]. It was concluded that sonication of malted barley increased the size of the starch granules, and a better quality was obtained when malted barley was exposed to TS compared with thermally treated or untreated malted barley [17]. In most of these reports, the sonication method used an acoustic finger or transducer element inserted into a vessel where the beverage was pumped through an actively cooled vessel to limit the temperature rise of the product, see Figure 3 in [4]. Of significance, the acoustic transducers were in direct contact with the beer. Prior work suggests that the US operating conditions (i.e., power, duration, temperature) must be optimized to achieve the desired PU and physicochemical and sensorial properties of the beer [4].

In this work, a finite element analysis (FEA) was performed for the case where a beverage can was immersed in water to allow coupling of high-pressure acoustic waves through the water into the beverage can. The key questions addressed for the steady state condition were: 1) maximum acoustic pressure, and 2) the acoustic pressure distribution within the beverage can. At present, the model does not compute the pasteurization effect on a biological sample, however, the model can serve to guide the critical operating conditions and US pasteurization setup.

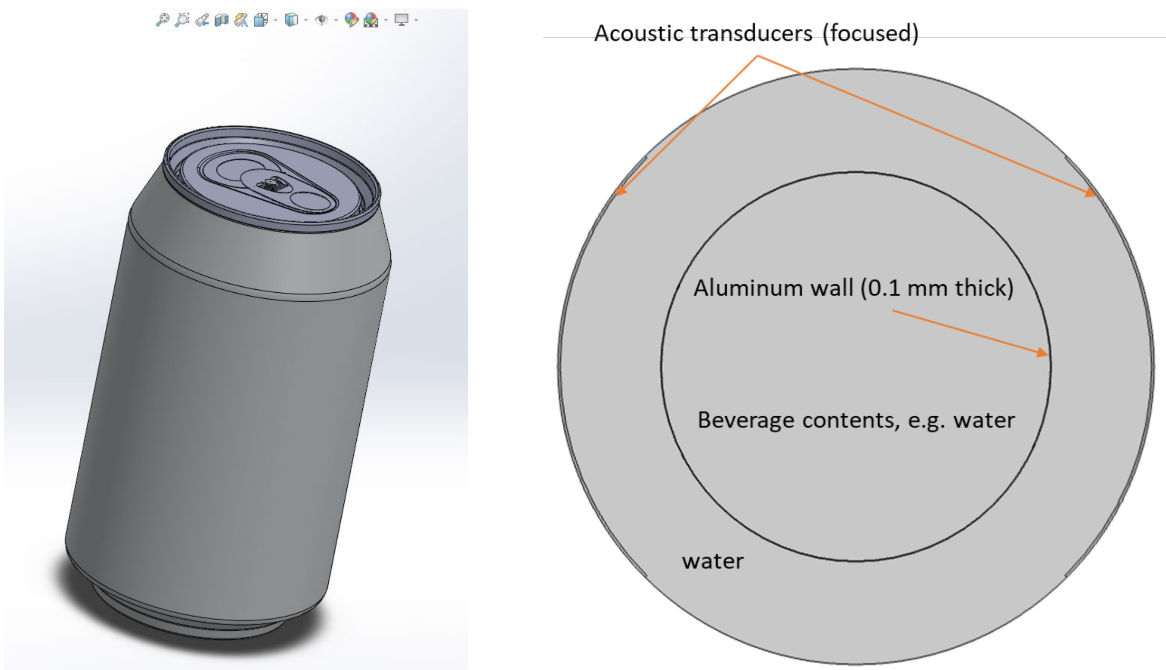

Figure 1. 2D model configuration. a) Beverage can model in SolidWorks, b) Cross-section through the center of the beverage container immersed in water with two focused acoustic transducers projecting acoustic waves toward the beverage container. The water gap was 5 mm.

Two-Dimensional FEA Model

Using COMSOL Multiphysics™, a model combining pressure acoustics, solid mechanics, and electrostatics was developed to determine the acoustic pressure that can be induced inside beverage containers immersed in water. A cylindrical piezoelectric transducer composed of PZT-5A was placed in contact with a fluid that allows acoustic waves to propagate into the beverage container. The frequency of the acoustic transducer was defined to 60kHz to represent high power commercially available transducer for this application.

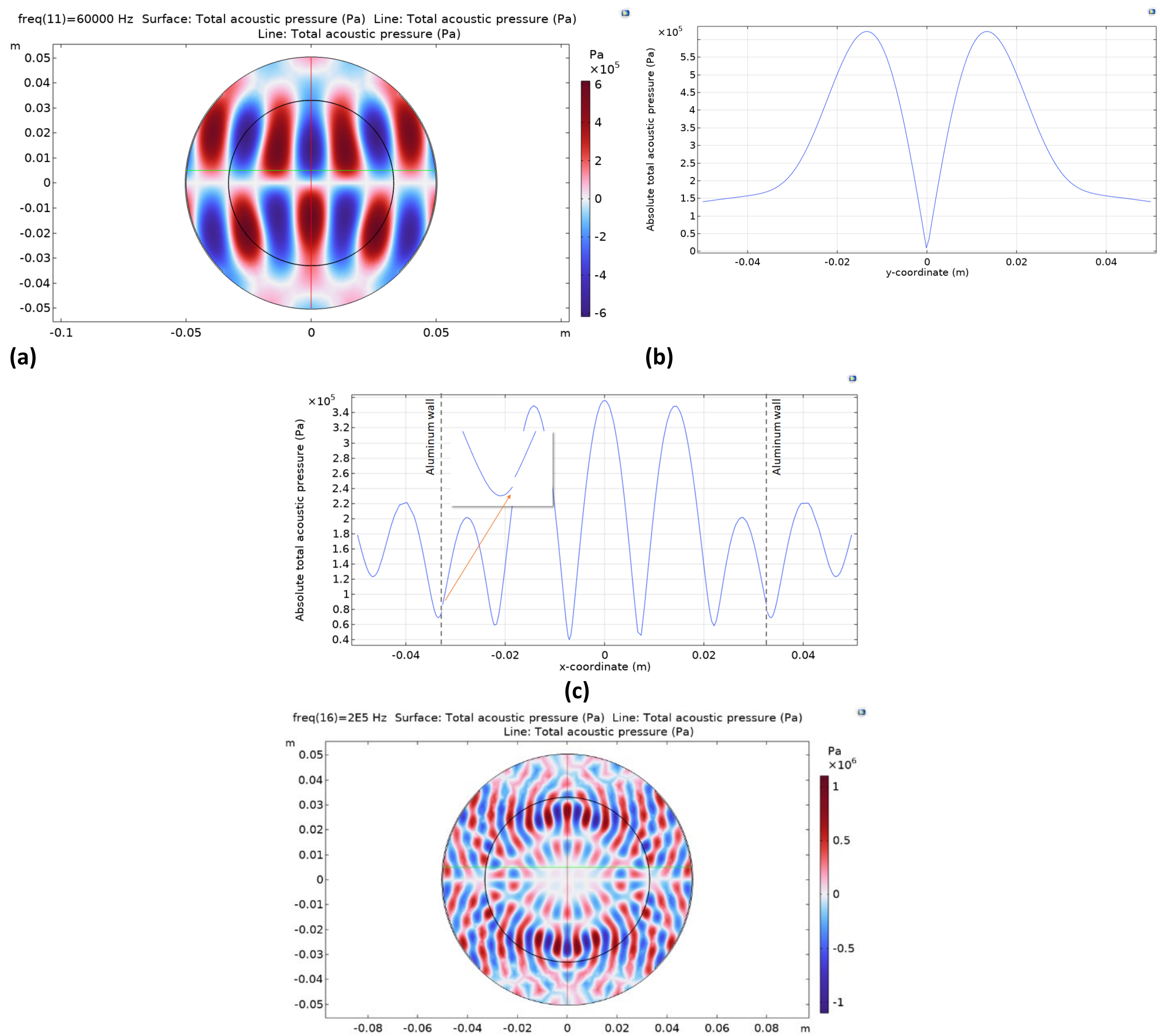

Figure 2. Two cylindrical transducers, a) Total acoustic pressure in water and beverage can domain at 60 kHz, b) Total acoustic pressure measured along the y-axis (red), c) 5 mm above the x-axis (green). Inside the aluminum wall, the acoustic pressure is not defined and instead there is a jump in the pressure across the boundary, and d) total acoustic pressure in the water and beverage can at 200 kHz transducer frequency.

To reduce memory requirements, a 2D model was developed to capture the acoustic generation and wave propagation through an aluminum beverage can. For the simulation the diameter of an aluminum can was taken as 6.62 cm with a wall thickness of 0.1 mm. Two cylindrical transducers were defined on the outer boundary in contact with water that partially encompassed the aluminum can (Figure 1). In Figure 2a and 2b, the spatial dependence of the acoustic pressure is shown at 60 kHz. Since the acoustic velocity in water is ~1500 m/s, the acoustic wavelength in the water domain is 25 mm, which easily passes through the thin aluminum (i.e., 0.1 mm) of the beverage can with very little phase shift or noticeable attenuation (Figure 2c). Higher frequency transducers will produce more nodes within the can. The maximum acoustic pressure achieved for a 1,000 V drive potential was ~600 kPa. Since the acoustic pressure varies more strongly along the x-direction due to the locations of the transducers but not exactly along the x-axis, a

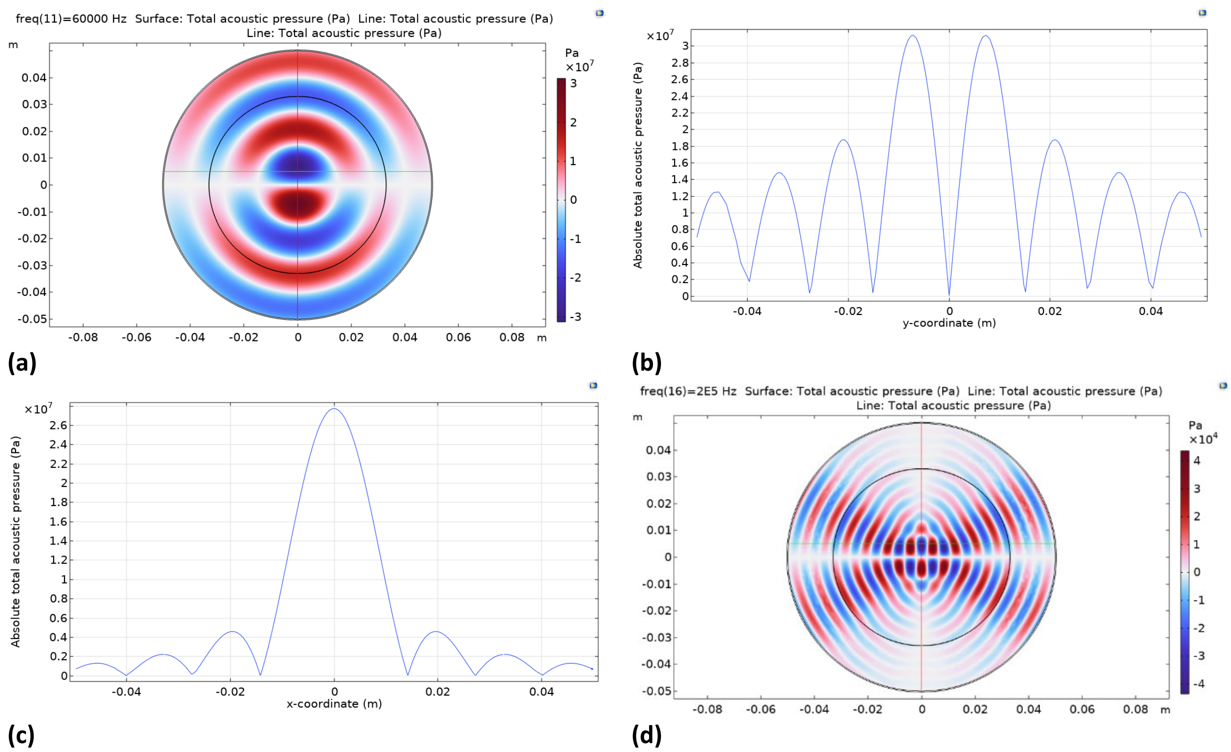

Figure 3. A piezoceramic tube transducer. a) total acoustic pressure in water and beverage can domain at 60 kHz, b) Total acoustic pressure measured along the y-axis (red) 60kHz, c) 5 mm above the x-axis (green) at 60 kHz, and d) Total acoustic pressure in water and beverage can domain at 200 kHz.

line was defined 5 mm above the x-axis to compute the acoustic pressure along this line (Figure 2c). In Figure 2d, acoustic transducers at 200 kHz would produce more pressure nodes as well as more sonication cycles per second and thus presumably more efficient bacterial lysis.

A piezoceramic tube transducer (Figure 3) was placed around the beverage can immersed in water. A large piezoceramic tube transducer would be more difficult to manufacturer; however, it provides additional insight into the acoustic pressure distribution within the beverage can. In this case, for a 1,000 V drive potential, the acoustic pressure variation reaches a value up to ~10 MPa. If the material yield of PZT- 5H can be maintained at this high drive level (e.g., pulse with a low duty cycle), the circular tube transducer would provide about 10x higher acoustic pressure inside the beverage can. As for manufacturing, Boston Piezo Optics Inc. is known to produce piezoceramic tube transducers up to 2 cm in diameter, which is too small for this application. Piezo Technologies Inc. supplies high power acoustics transducers from 20 kHz to 20 MHz and may be able to manufacturer a piezoceramic tube transducer with a radius of ~ 4 cm. Thus, individual transducer elements would likely be required to form a circular transducer array around the beverage can.

Three-Dimensional FEA Model

A 3D model was developed to explore the acoustic pressure that can be transmitted into an aluminum beverage can. The model of the can was simplified to reduce complexity of the FEA mesh. However, the overall size of the aluminum can is identical to a standard beverage can, having a radius of 3.31 cm, height of 12.2 cm, and wall thickness of 0.1 mm. In Figure 4, the FEA simulation shows the acoustic pressure at 60 kHz. At 60 kHz in water, the acoustic wavelength is 25 mm or about 3.8x longer than the radius of the

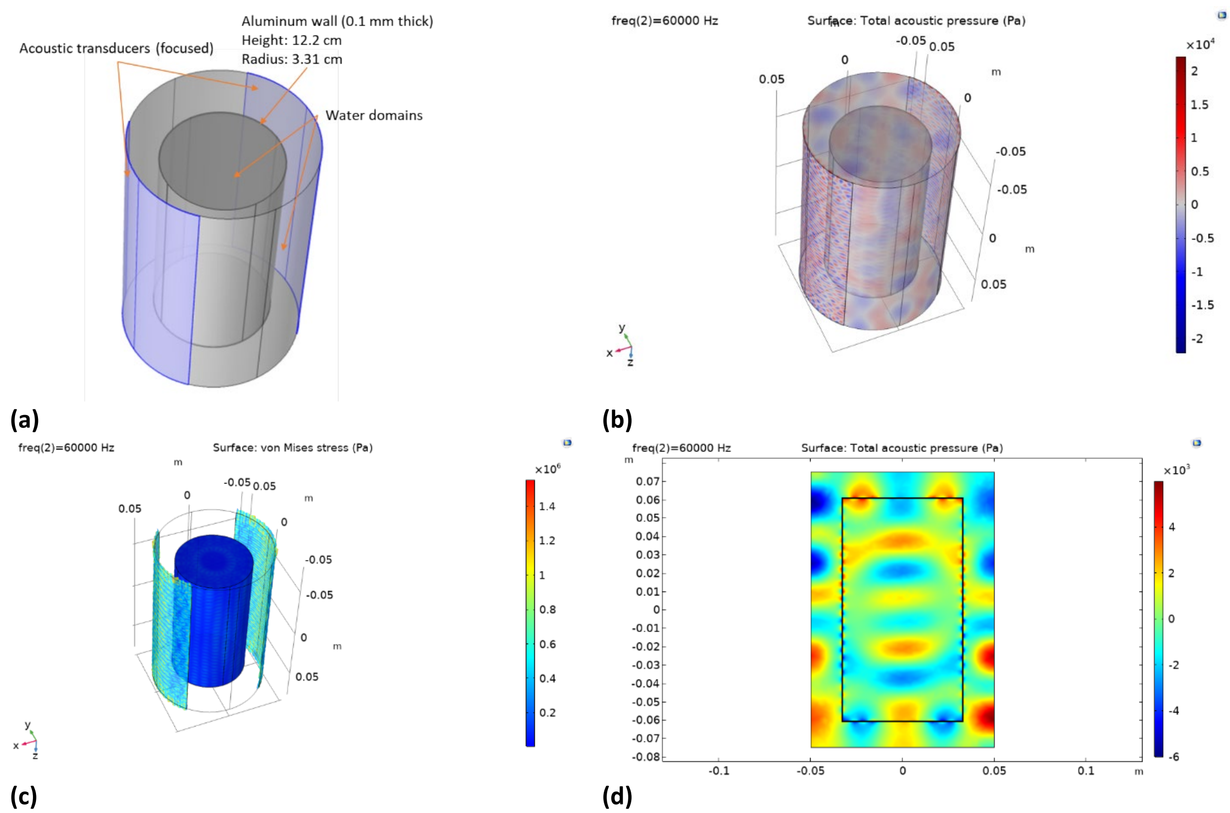

Figure 4. 3D FEA analysis at 60 kHz transducer frequency. a) 3D FEA of a water filled beverage can immersed in water with two acoustic transducers facing the can, b) Total acoustic pressure, c) von Mises stress, and d) YZ cut plane showing acoustic pressure perpendicular to the acoustic transducer faces.

beverage can, which limits the number of pressure nodes in the can. It would be more advantageous to produce additional nodes within the beverage can, suggesting that the acoustic transducer frequency should be increased to at least 200 kHz. In Figure 5, the acoustic drive frequency was increased to 200 kHz. The acoustic pressure increases to 1 MPa with multiple nodes across the cross-section of the beverage can. This analysis suggests that a transducer operating ~200 kHz would more efficiently destroy bacteria in the beverage can. Though the acoustic loss scales approximately as the frequency squared, the frequency is sufficiently low that the acoustic losses are negligible. A 5 mm gap between the transducer and the beverage can is a very thin water gap, limiting acoustic losses in the gap.

Conclusions:

2D and 3D COMSOL models were developed to compute the acoustic pressure fields in the water domain that surrounds the beverage can as well as inside the can. The models showed that lower frequency acoustic transducers (i.e., 60 kHz) may not provide the required acoustic pressure for bacterial lysis since they do not produce enough pressure nodes inside the beverage can, which is due to the longer wavelength in water. Increasing the transducer frequency to 200 kHz produced far more acoustic nodes inside the beverage can along with more sonication cycles per second. A piezoceramic tube transducer produced acoustic pressure nodes with cylindrical symmetry compared to the focused transducers. Transducer frequencies at 200 kHz produced acoustic pressure variation ~1 MPa, which is likely sufficient to destroy or lyse bacteria. Future experimental studies are needed to determine which transducer

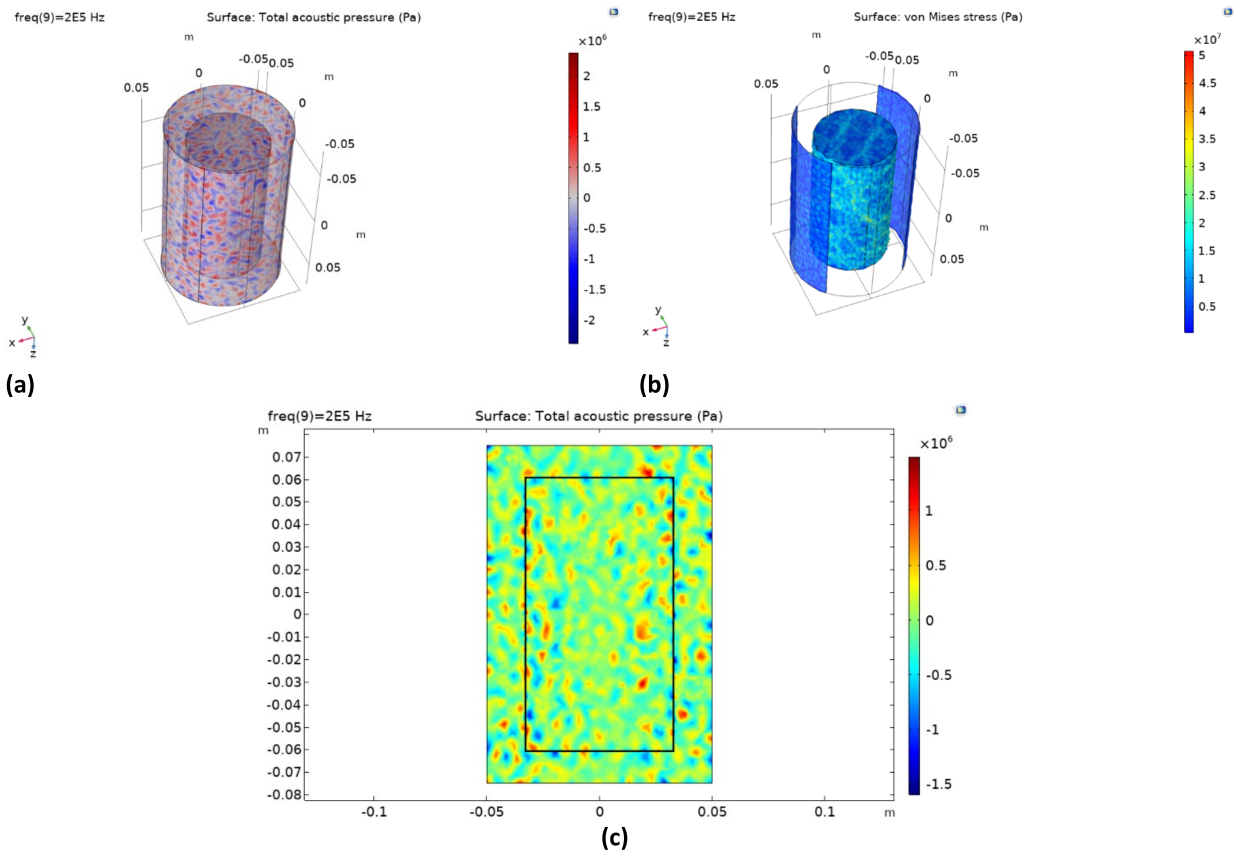

Figure 5. 3D FEA analysis at 200 kHz transducer frequency. a) Total acoustic pressure, b) von Mises stress, and c) YZ cut plane showing acoustic pressure perpendicular to the acoustic transducer faces.

geometry and drive frequencies are optimum for cellular membrane disruption and ultimately pasteurization.

Acknowledgements

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

References:

[1] N. S. Curtis, "European Brewery Convention," *J. Inst. Brewing,* vol. 74, no. 4, pp. 330–333, 1968.

[2] E. A. Milani and F. V. M. Silva, "Ultrasound assisted thermal pasteurization of beers with different alcohol levels: Inactivation of Saccharomyces cerevisiae ascospores," *Journal of Food Engineering,* vol. 198, pp. 45-53, 2017.

[3] M. Walkling-Ribeiro, O. Rodríguez-González, S. H. Jayaram, and M. W. Griffiths, "Processing temperature, alcohol and carbonation levels and their impact on pulsed electric fields (PEF) mitigation of selected characteristic microorganisms in beer," *Food Research International,* vol. 44, no. 8, pp. 2524-2533, 2011.

[4] E. A. Milani and F. V. M. Silva, "Pasteurization of Beer by Non-Thermal Technologies," (in English), *Frontiers in Food Science and Technology,* Review vol. 1, 2022-March-30 2022, doi: 10.3389/frfst.2021.798676.

[5] G. Lu, C. Li, P. Liu, H. Cui, Y. Yao, and Q. Zhang, "UV inactivation of microorganisms in beer by a novel thin-film apparatus," *Food Control,* vol. 21, no. 10, pp. 1312-1317, 2010.

[6] A. Quintero-Ramos, Churey, J. J., Hartman, P., Barnard, J., and Worobo, R. W., "Modeling of Escherichia coli Inactivation by UV Irradiation at Different pH Values in Apple Cider," *J. Food Prot.,* vol. 67, no. 6, pp. 1153–1156, 2004.

[7] A. Sulaiman, M. J. Soo, M. Farid, and F. V. M. Silva, "Thermosonication for polyphenoloxidase inactivation in fruits: Modeling the ultrasound and thermal kinetics in pear, apple and strawberry purees at different temperatures," *Journal of Food Engineering,* vol. 165, pp. 133-140, 2015.

[8] E. Ugarte, H. Feng, S. E. Martin, and K. R. Cadwallader, "Inactivation of Escherichia coli with Power Ultrasound in Apple Cider," *J. Food Sci.,* vol. 71, no. 2, pp. 102–108, 2006.

[9] G. Zhang, K. Hashimoto, and M. Yamaguchi, "Liquid streaming by high-frequency ultrasonic waves," *Jpn. J. Appl. Phys.,* vol. 35, pp. 3248-3250, 1996.

[10] D. P. Chandler *et al.*, "Continous spore disruption using radially focused, high-frequency ultrasound," *Anal. Chem.,* vol. 73, pp. 3784-3789, 2001.

[11] J. Zhu *et al.*, "Localized cell lysis by self focused acoustic transducers," presented at the Transducers, Denver, CO, 2009.

[12] D. W. Branch, G. T. Smith, E. C. Vreeland, R. Blakemore, and D. Alland, "Nucleic Acid Extraction using a Rapid, Chemical Free, Ultrasonic Technique for Point-of-Care Diagnostics," presented at the IEEE International Ultrasonics Symposium, Chicago, 2014.

[13] L. T. Wang, Y. J. Li, A. Lin, Y. Choe, M. E. Gross, and E. S. Kim, "A Self-Focusing Acoustic Transducer That Exploits Cytoskeletal Differences for Selective Cytolysis of Cancer Cells," (in English), *J Microelectromech S,* vol. 22, no. 3, pp. 542-552, Jun 2013, doi: Doi 10.1109/Jmems.2012.2229696.

[14] T. J. Mason, Paniwnyk, L., and Lorimer, J. P., "The Use of Ultrasound in Food Technology," *Ultrason. Sonochem.,* vol. 3, pp. 253–260, 1996.

[15] Y. Deng, H. Bi, J. Yu, J. Dong, M. Yang, and Y. Ma, "Influence of ultrasound assisted thermal processing on the physicochemical and sensorial properties of beer," vol. 40, pp. 166-173, 2018.

[16] F. V. M. Silva, Milani, E. A., and Carr, K., "Beer Pasteurized by Pulsed Electric Fields, High Pressure Processing, and Power Ultrasound: Taste Assessments," presented at the 12th International Congress of Engineering and Food (ICEF). Quebec: Canada, 2015.

[17] V. M. Borsato, Jorge, L. M., Mathias, A. L., Jorge, R. M., "Ultrasound Assisted Hydration Improves the Quality of the Malt Barley," *J. Food Process Eng.,* vol. 42, no. 6, p. e13208, 2019.