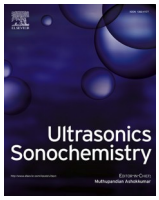
Ultrasonics Sonochemistry 114 (2025) 107263



Contents lists available at ScienceDirect

Ultrasonics Sonochemistry

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





Comparison of sonochemical and sonophysical activity under various geometric conditions in 28 kHz Double-Bath sonoreactors

Mireu Song [a,b,1], Dukyoung Lee [a,1], Younggyu Son [a,b,*]

[a] Department of Environmental Engineering, Kumoh National Institute of Technology, Gumi 39177, Republic of Korea
[b] Department of Energy Engineering Convergence, Kumoh National Institute of Technology, Gumi 39177, Republic of Korea

ARTICLE INFO

Keywords:
Geometric optimization
Double-bath-type sonoreactors
Sonochemical activity
Sonophysical activity
Lightweight expanded clay aggregates (LECAs)

ABSTRACT

Sonochemical and sonophysical activities were investigated under various geometric conditions using 28 kHz double-bath-type sonoreactors. Sonochemical activity was quantified using KI dosimetry (triiodide ion concentration), while sonophysical activity was measured via lightweight expanded clay aggregate (LECA) desorption tests (turbidity). Thirty-five different geometric conditions were tested, comprising seven distances between the sonoreactor bottom and vessel bottom (L_2) and five water levels (L_3). The optimal conditions for sonochemical activity [(L_2/L_3, unit: mm): 70/76, 90/116, 70/116, 110/146, and 70/96] and sonophysical activity [(L_2/L_3, unit: mm): 30/78, 70/88, 150/168, 30/68, and 30/38] did not match, and no conditions showing high values in both activities were found. The presence of a thin-walled vessel did not affect ultrasound transmission. However, the presence of LECAs caused a large attenuation of ultrasound and the formation of different cavitational active zones in the vessel. This was identified as the main reason for the mismatch in optimal geometric conditions for sonochemical and sonophysical activities. The sonochemical activity could be enhanced by the presence of LECAs under conditions; however, the enhanced sonochemical activity was much lower than the five highest sonochemical activities. In addition, the movement of LECAs induced by ultrasound irradiation significantly enhanced the sonophysical activity.

1. Introduction

Acoustic cavitation has been studied for decades to enhance sonochemical and sonophysical activities in various chemical and environmental engineering processes [1,2]. Sonochemical effects, such as pyrolysis and radical reactions, can be used for novel material synthesis and the removal of recalcitrant pollutants in homogeneous and heterogeneous systems [3–6]. Sonophysical effects, including shock waves, microstreaming, and microjets, are useful for processes such as mixing, washing, cleaning, and extraction in heterogeneous systems [7–10]. Studies have shown that cavitational activity derived from sonochemical or sonophysical effects can be significantly enhanced by optimizing applied frequency and input power conditions [1,11,12]. Recent studies have reported that the optimization of geometric conditions significantly enhances the cavitational activity under the same frequency or input power conditions [7,13–22]. These studies mainly focused on enhancing sonochemical activity by altering liquid heights, transducer/probe positions, and reactor shapes/sizes. They found that even small changes in geometric conditions can result in significant changes in sonochemical activity.

Double-bath-type sonoreactors offer advantages such as safe handling of toxic, hazardous, and corrosive materials and easy temperature control by protecting ultrasonic transducers from severe physicochemical damage [23]. They have been employed in applications such as washing, chemical degradation, and polymerization [8–10,24–29]. However, only a few studies have examined the role of geometric factors in sonoreactors in enhancing sonochemical and sonophysical activities in the liquid phase. For instance, Kobayashi et al. investigated the effects of reactor position on polymerization and chemical degradation in double-bath sonoreactors [24,25]. Yasuda et al. investigated the effects of vessel position, diameter, and liquid height on the generation of oxidizing radicals in double-bath sonoreactors [26]. They also reported significant changes in transducer impedance under various geometric conditions.

Most researchers have used arbitrarily determined single geometric conditions for applications, especially in processes involving solid

* Corresponding author.
E-mail address: yson@kumoh.ac.kr (Y. Son).
[1] The authors equally contributed to this study as first authors.

https://doi.org/10.1016/j.ultsonch.2025.107263
Received 29 November 2024; Received in revised form 20 January 2025; Accepted 7 February 2025
Available online 9 February 2025
1350-4177/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

materials such as soil particles, and rarely conducted experiments on optimizing geometric factors [8–10,27,30]. Previous studies on the enhancement of sonochemical activity by optimizing geometric conditions [13–22], suggest that the sonophysical activity of solid materials in heterogeneous systems can also be enhanced under geometrically optimized conditions in double-bath systems. Developing design strategies for double-bath sonoreactors that can significantly enhance both sonochemical and sonophysical activities can greatly expand the applications of ultrasound technology in various engineering fields.

This study investigates the effects of two geometric factors—1) the distance between the bottom of the submerged vessel and the transducer module plate of the sonoreactor and 2) the liquid height in the sonoreactor—on sonochemical and sonophysical activities in a 28 kHz double-bath-type system under 35 different geometric conditions. Sonochemical activity was quantified using KI dosimetry, while sonophysical activity was quantitatively analyzed by performing desorption tests on lightweight expanded clay aggregates (LECAs). In addition, the sonochemical activity was measured for the cases in which the highest sonophysical activity was obtained to understand the ultrasonic desorption mechanism in the presence of LECAs.

2. Materials and methods

2.1. Chemicals

Potassium iodide (KI) and sodium hydroxide (NaOH) were obtained from Junsei Chemical Co., Ltd. (Tokyo, Japan). Luminol (3-aminophthalhydrazide) was purchased from Sigma–Aldrich (St. Louis, MO). All chemicals were used as received.

2.2. Experimental setup

A schematic of the double-bath-type ultrasonic system used in this study is shown in Fig. 1. The system consisted of a rectangular acrylic sonoreactor (dimensions: 320 mm × 320 mm × 215 mm) equipped with a 28 kHz ultrasonic transducer module (Mirae Ultrasonic Tech., KOR) at the bottom and a 1.25 L cylindrical glass vessel (D: 90 mm, H: 215 mm), which was partially submerged in the sonoreactor. The transducer module included 12 transducers with a working power of 315 W (maximum power: 600 W), as measured using a power meter (HPM-300A, ADpower, KOR). The submerged height of the vessel was controlled using an acrylic lid and rings at the top of the sonoreactor. The volume of the liquid in the vessel was fixed at 150 mL (L_1: 26 mm), and seven distances were tested between the sonoreactor bottom and the vessel bottom (L_2: 30, 50, 70, 90, 110, 130, and 150 mm). Five water height conditions in the sonoreactor (L_3) were determined by changing the water level as follows: $L_1 + L_2$ (reference water height), $L_1 + L_2 - 20$ mm, $L_1 + L_2 - 10$ mm, $L_1 + L_2 + 10$ mm, and $L_1 + L_2 + 20$ mm for each L_2 condition. Consequently, a total of 35 unique combinations of L_2 and L_3 were used in this study. The sonoreactor was filled with 2.7–17.3 L of tap water (L_3: 36–196 mm). Fresh tap water was used in each experiment. The temperature in the vessel was maintained at 20 ± 3 ℃.

2.3. Quantification and visualization of sonochemical oxidation activity

The cavitation-induced radical oxidation reaction was quantified using a KI solution (1.0 g/L KI) and visualized using a luminol solution (0.1 g/L luminol and 1 g/L NaOH). When KI solution is irradiated by ultrasound, iodine (I_2) is generated due to the reaction between iodide ions (I^-) and highly reactive radical species, such as hydroxyl radicals (OH•), and hydrogen peroxide (H_2O_2) formed by acoustic cavitation. Subsequently, the iodine spontaneously reacts with excess iodide ions to form triiodide ions (I_3^-). The concentration of triiodide ions (I_3^-) was measured using a UV–vis spectrophotometer (Carry 60, Agilent, USA). The duration of ultrasound irradiation was 10 min. The generation of I_3^- in KI dosimetry followed a pseudo-zero-order reaction. All tests and measurements were repeated three to five times, and the average values were reported.

Under ultrasound irradiation, luminol molecules react with cavitation-induced oxidizing radicals such as OH•, transform into excited-state fluorescing 3-aminophthalate (3-APA), and then stabilize as 3-APA by emitting visible light via sonochemiluminescence (SCL). SCL images were captured using an exposure-controlled digital camera (α58, Sony Corp., JPN) in a completely dark room. The exposure time was set to 10 s.

2.4. Quantification of sonophysical activity

Lightweight expanded clay aggregates (LECAs), also known as expanded clay pellets or Hydroton, are commonly used in hydroponics and have a mean diameter of 0.5–2.0 mm. In this study, LECAs were purchased from Retech Korea Co., Ltd. (Anseong, Korea) and used to quantify sonophysical activity through ultrasonic washing/desorption tests. LECAs are small ball-shaped materials with a highly porous structure, and their surfaces can be damaged or broken by relatively weak physical actions. There was no interaction between the LECAs and water and between the LECAs and KI solution. In this study, LECAs were considered as hypothetical soil particles. Preliminary tests revealed that low-frequency ultrasound damaged LECAs in water and desorbed fine particles from the LECAs induced quantifiable turbidity. Solid-to-liquid (S:L) ratios ranging from 1:2.5 to 1:10 are commonly used in ultrasonic soil washing processes [8–10,27,30,31]. In this study, an S:L ratio of 1:5

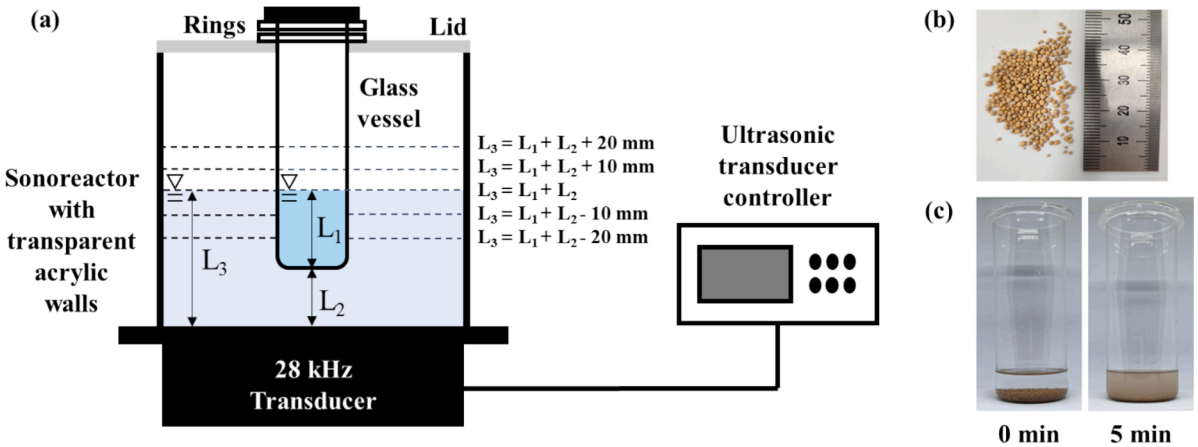


Fig. 1. (a) Schematic of the experimental setup (L_1: the liquid height in the vessel (26 mm); L_2: the distance between the sonoreactor bottom and vessel bottom; L_3: the water height in the sonoreactor); (b) Lightweight expanded clay aggregates (LECAs); (c) Turbidity change after ultrasound irradiation.

was tested, using 30 g of LECAs. The duration of the ultrasound irradiation was 5 min. Turbidity was measured using a UV–vis spectrophotometer under 35 different L_2 and L_3 conditions as mentioned above. In the presence of LECAs (5 g), the liquid height in the vessel (L_1) increased by 2 mm compared to that in the absence of LECAs. In this study, the variations in turbidity followed a pseudo-zero-order reaction.

Ultrasonic aluminum foil erosion tests were conducted as described in previous studies [7,8,27]. An aluminum foil with a thickness of 16 μm was placed at the center of the vessel, perpendicular to the bottom of the vessel, and exposed to ultrasound irradiation for 30 s. The damaged foil was dried, scanned, and visually analyzed.

2.5. Sound pressure levels measurement

The acoustic emission spectra in the vessel were recorded using a hydrophone (TC4034-1, Teledyne Marine) and a spectrum analyzer (N9320B, Agilent, USA) in the absence and presence of LECAs. The hydrophone was placed at the center, 15 mm above the bottom of the vessel. The measured frequency ranged from 1 Hz to 450 kHz, corresponding to the operational range of the hydrophone.

3. Results and Discussion

The effects of geometric conditions, including the distance from the sonoreactor bottom to the vessel bottom (L_2) and the water height (L_3) in

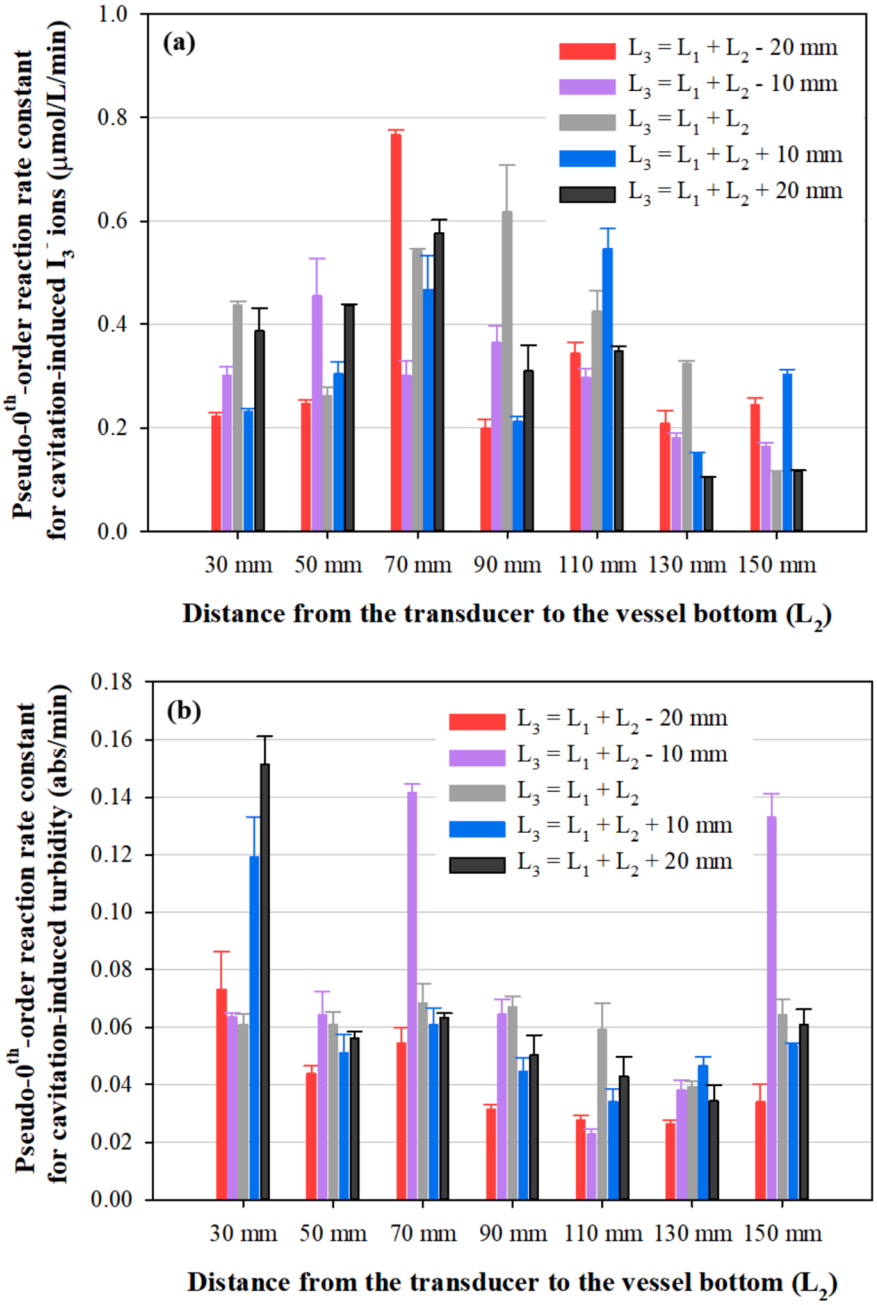


Fig. 2. The pseudo-zero-order reaction rate constants for the (a) sonochemical oxidation activity and (b) sonophysical activity under various geometric conditions.

the sonoreactor, on sonochemical and sonophysical activities were investigated using a 28 kHz double-bath-type ultrasonic system. Sonochemical activity was quantified through KI dosimetry in a homogeneous system. Sonophysical activity was analyzed using ultrasonic washing/desorption tests of LECAs in a heterogeneous system. LECAs were considered model soil particles in this study. The pseudo-zero-order reaction rate constants for the sonochemical generation of I_3^- ions and the sonophysical generation of turbidity were obtained, as shown in Fig. 2(a) and 2(b), respectively. In addition, the rate constants and their coefficient of determination (R^2) values for the sonochemical and sonophysical activities are presented in Table S1 and S2, respectively. The SCL images for the L_2 conditions of 3, 7, 11, and 15 cm in the sonoreactor and vessel are shown in Fig. 3.

Considerable differences in sonochemical and sonophysical activities were observed for the 35 geometric conditions tested. Sonochemical activity ranged from 0.105 to 0.767 μmol/L/min, and the five highest activities were obtained under the following conditions (L_2/L_3, unit: mm) in order: 70/76, 90/116, 70/116, 110/146, and 70/96. The highest activity on average was obtained under the L_2 = 70 mm conditions, while the lowest activity on average occurred at L_2 = 130 or 150 mm.

Under the assumption that ultrasound attenuates exponentially in confined reactors as it travels in water [23,32–34], the strongest ultrasound can be introduced into the vessel at the lowest L_2 value of 30 mm, corresponding to the shortest irradiation distance from the transducer module. Moreover, in bath-type sonoreactors, previous studies have demonstrated that relatively high sonochemical oxidation activity, quantified by the amount of H_2O_2 and I_3^- ions generated, is obtained at liquid heights of several times the ultrasound wavelength compared to those at liquid heights of 1–2 times the wavelength because of the formation and expansion of a stable sonochemical active zone, including a standing wave field adjacent to the liquid surface [6,18–20,22,35]. Note that power densities (input power / liquid volume) decreased significantly as the liquid height increased in sonoreactors. Thus, higher sonochemical activity was expected under L_2 conditions of 30/50 mm (0.7–1.8 λ) or 130/150 mm (2.5–3.7 λ). However, the highest activity on average was observed at L_2 = 70 mm (1.4–2.2 λ), and it could be attributed to the following factors: 1) The presence of the vessel might have changed the ultrasound energy distribution and the formation of the sonochemical active zone. However, in this study, no significant changes were found in the formation of the sonochemically active zone owing to the presence of the vessel, as shown in Fig. 3(b) and 3(c). The sound pressure level did not change significantly due to the presence of the vessel, as discussed later. Using the following equation, the theoretical transmission ratio of ultrasound amplitude before passing through the glass layer to that after passing through the glass layer in the three-layer system (water/glass/water) [36] was calculated as 0.93, indicating that no significant ultrasound absorption occurred by the thin glass layer.

$$T = \frac{2}{2\cos k' L + j\left(\frac{\rho_0' c_0'}{\rho_0 c_0} + \frac{\rho_0 c_0}{\rho_0' c_0'}\right)\sin k' L} \quad (1)$$

where T is the transmission ratio, k' is the wavenumber, ρ_0 is the density of water, c_0 is the sound speed in water, ρ_0' is the density of glass, c_0' is the sound speed in glass, and L is the thickness of the glass layer. 2) Higher sonochemical activity is generally observed at higher liquid height conditions (several times the ultrasound wavelength), as mentioned above [6,18–20,22,35]. A much brighter light was emitted from a larger area of the sonoreactor at higher liquid height conditions under the same electrical input power conditions, as shown in Fig. 3(b) and 3(c). However, the sonochemical oxidation activity shown in Fig. 2(a) was obtained only from the liquid volume in the vessel, and the activity in the vessel might not increase in proportion to the overall activity of the sonoreactor, as shown in the cases of "SCL in the vessel (w/vessel)" in Fig. 3(d). 3) When multiple ultrasonic transducers are used in a single-plate-type module, each transducer can interfere with other transducers, leading to different ultrasound irradiation patterns compared to those obtained in a single-transducer-module sonoreactor [37]. In bath-type sonoreactors equipped with a transducer at the bottom, the sonochemically active zone mainly forms in the top region close to the liquid surface because of the formation of a standing wave fields induced by the superposition of incident and reflected sound waves [6,15,18]. However, in this study, the formation of a standing wave field as reported in previous studies [6,18,20,22,38], was not clearly observed, as shown in Fig. 3(b) and 3(c). Few studies have investigated the variation and optimization of ultrasound irradiation patterns and the corresponding cavitational activity induced by the installation of multiple transducers on a single plate.

Consequently, the aforementioned geometric factors appear to be complicated and intertwined, making it difficult to determine the optimal geometric conditions for sonochemical activity. Kobayashi et al. investigated the sonochemical activity, quantified using the KI dosimetry and phenol degradation in a 28 kHz double-bath sonoreactor under

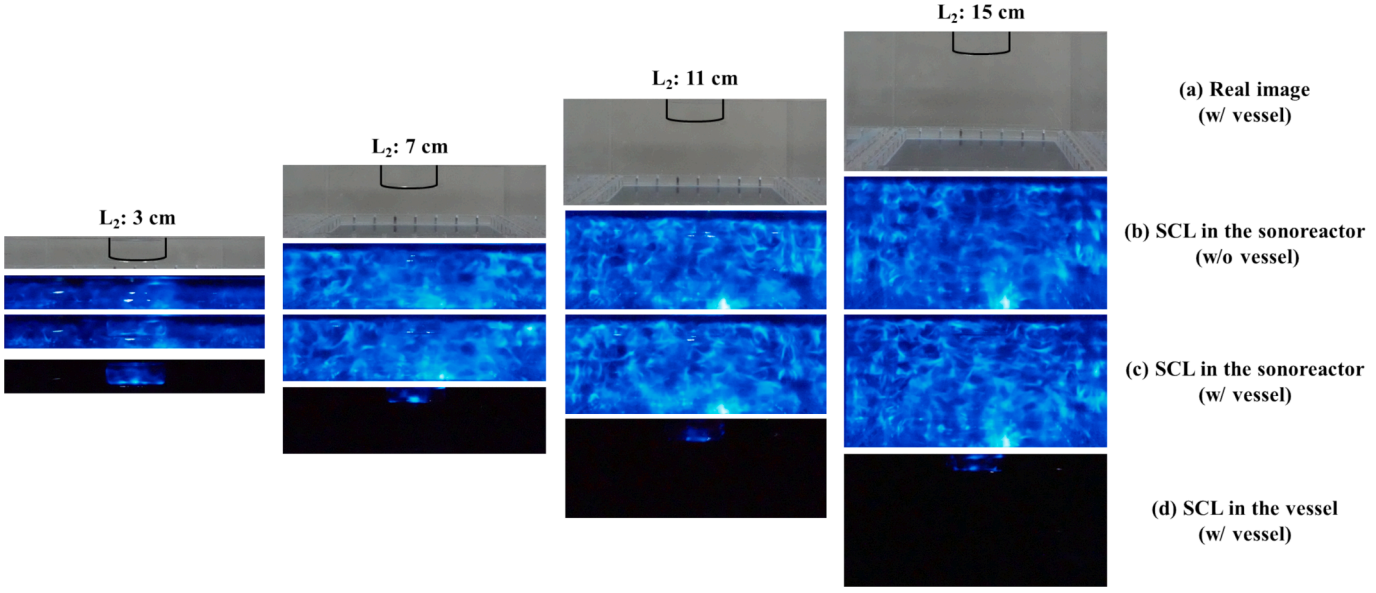


Fig. 3. SCL images at the conditions of L_2 = 3, 7, 11, and 15 cm in the absence of LECAs under various vessel conditions.

various geometric conditions including the distance between the sonoreactor bottom and the vessel bottom (10–60 mm) [24,25]. They reported the peak sonochemical activities at the distances of 40–50 mm. They suggested the relationship between the peak-value positions and the wavelength of ultrasound. Yasuda et al. reported the highest sonochemical activities, quantified using KI dosimetry, occurred repeatedly when the vessel was vertically moved in 0.1 mm increments in a 500 kHz double-bath sonoreactor [26]. They also mentioned the importance of the wavelength of ultrasound in determining the optimal geometric conditions.

In addition, it is noteworthy that the sonochemical activity changed significantly depending on whether the liquid levels inside and outside the vessel matched or varied, as shown for each L_2 condition (Fig. 2). This observation highlights the need for further research to establish a rule of thumb for determining the optimal L_2 and L_3 conditions under fixed L_1 conditions to enhance sonochemical activity in double-bath sonoreactors.

Sonophysical activity varied from 0.023 to 0.151 abs/min, and the five highest activities were obtained under the following conditions of L_2/L_3 (unit: mm) in order: 30/78, 70/88, 150/168, 30/68, and 30/38. The highest activity on average was obtained under $L_2 = 30$ mm, while the lowest activity on average was obtained at $L_2 = 110$ or 130 mm. These optimal conditions for sonophysical activity were not consistent with those for sonochemical activity discussed above. This can be attributed to the presence of LECAs in the vessel, which acted as porous media. As ultrasound waves travel through water-saturated granular media, significant attenuation can occur at particle boundaries owing to the difference in impedance between the two phases. The extent of attenuation can be determined by the solid fraction and the product of the wavenumber and mean particle size [33,39]. Consequently, the sound pressure distribution and corresponding cavitational active zones are significantly changed depending on the presence of LECAs in the vessel [40].

Sound pressure levels from 1 Hz to 450 kHz were measured under L_2 conditions of 3, 7, 11, and 15 cm (Fig. S1) [23,41]. No significant decrease in sound pressure levels was observed when the vessel was placed in the sonoreactor compared to the case of no vessel. In contrast, the presence of LECAs in the vessel resulted in a significant decrease in sound pressure levels. In particular, no significant sound pressure level was observed in frequencies below 100 kHz, which includes the fundamental frequency range. Thus, it is confirmed that significant ultrasound attenuation occurs in the LECAs layer, which explains the mismatch between the optimal geometric conditions for sonochemical and sonophysical activity.

As shown in Fig. 4(a), the presence of LECAs significantly influenced the sonophysical activity in the region above the LECAs layer. Cavitation-induced damage to the surface of the aluminum foil was tested, and much less damage was observed in the region above the LECAs for all applied L_2 conditions. Note that the sonophysical activity observed above the LECAs might not be related to that in the LECAs layers. In addition, the SCL light was observed only in the region immediately above the LECAs under all applied conditions, as shown in Fig. 4(b). This was attributed to active cavitation events occurring adjacent to the surface of the LECAs. Nucleation phenomena for

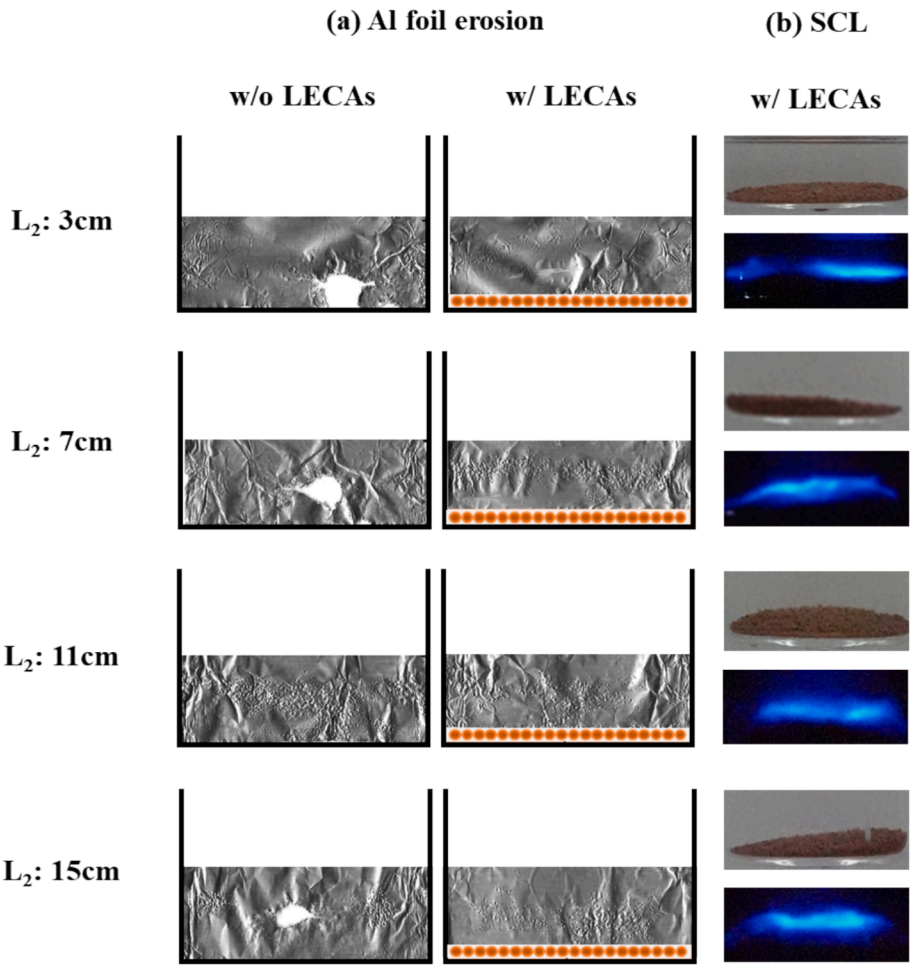


Fig. 4. Erosion of aluminum foil and SCL images in the presence and absence of lightweight expanded clay aggregates (LECAs) in the vessel under L_2 conditions of 3, 7, 11, and 15 cm.

cavitation events can occur more vigorously on the surfaces of solid materials than in the bulk phase [40,42]. Although cavitation events actively occurred in the LECAs layer, SCL light emitted from the LECAs layer was not detected in this study because the light was blocked by the LECAs themselves.

Furthermore, the LECAs moved violently under ultrasound irradiation, and the debris, which was the main cause of turbidity, was generated by the erosion of the LECAs, as shown in Movie S1(a). The extent of LECA movement and debris generation varied significantly with L_2 and L_3 conditions, as shown in Fig. 2(b). Thus, ultrasound attenuation may also vary significantly depending on the amount of debris generated and the applied geometric conditions.

Fig. 5 shows the relationship between normalized sonochemical and sonophysical activities based on the results shown in Fig. 2. Both activities were normalized to their respective maximum values. Higher sonochemical and sonophysical activities were obtained with the geometric conditions for the 2nd and 3rd quadrants and the 1st and 2nd quadrants, respectively. In this study, we expected to suggest optimal geometric conditions included in the 2nd quadrant for both sonochemical and sonophysical activities. Once a double-bath-type sonoreactor is designed for both activities, it can be used for a wide range of sonophysical and sonochemical processes. However, none of the 35 geometric conditions tested yielded conditions suitable for enhancing both activities. No meaningful general explanation could be provided for determining geometrically optimal conditions and for the correlation between the two activity levels at this stage. The results suggest that optimal geometrical conditions could only be obtained by experimenting with the conditions selected by the researchers, as shown in this study.

The sonochemical activity in the presence of LECAs was quantitatively analyzed under the conditions associated with the five highest sonophysical activities (L_2/L_3: 30/+20, 70/-10, 150/-10, 30/+10, and 30/-20). The pseudo-zero-order reaction rate constants for the sonochemical generation of I_3^- ions were 0.227 ± 0.000, 0.213 ± 0.006, 0.281 ± 0.009, 0.281 ± 0.012, and 0.122 ± 0.007 μmol/L/min for (L_2/L_3): 30/+20, 70/-10, 150/-10, 30/+10, and 30/-20, respectively. For the cases of (L_2/L_3): 150/-10 and 30/+10, sonochemical activity enhanced by 172.2 % and 121.5 %, respectively. In contrast, reductions in sonochemical activity by 54.9 % to 70.8 % were observed in the other three cases. This may be due to the combination of significant ultrasound attenuation and cavitation enhancement in the presence of particles in the LECAs layer, as mentioned above. Thus, appropriate geometric conditions can enhance both sonophysical and sonochemical activities. However, all sonochemical activities in the presence of LECAs significantly decreased compared to those in the absence of LECAs under the same geometric conditions. The pseudo-zero-order reaction rate constants in the absence of LECAs ranged from 0.542 to 0.767 μmol/L/min, while those in the presence of LECAs ranged from 0.122 to 0.281 μmol/L/min.

Consequently, achieving high sonochemical activity under conditions favoring high sonophysical activity is unlikely in heterogeneous systems. Nevertheless, it is possible to suggest optimal conditions for high sonophysical activity (vigorous ultrasonic washing/desorption/extraction) and moderate sonochemical activity (not high but some degree of sonochemical reactions for desorbed chemicals). For example, in ultrasonic soil-washing processes, sorbed pollutants can be readily removed from soil particles, while desorbed pollutants in the washing liquid phase can be partially degraded under optimal conditions.

The ultrasonic desorption mechanism was investigated under two scenarios: 1) LECAs attached to a wire mesh (attached LECAs) and 2) LECAs not attached (free LECAs). The ultrasonic desorption of particles can occur via microjets induced by cavitation. Violent collisions and scrubbing of particles due to particle movement induced by ultrasound irradiation can also lead to ultrasonic desorption [7–9]. For the free LECAs case, vigorous sonophysical desorption occurred under ultrasound irradiation, leading to a significant increase in turbidity, as shown in Fig. 6 and Movie S1. Conversely, in the attached LECAs case, no desorption occurred and no detectable turbidity was observed. The desorption of the LECAs was further tested using an overhead stirrer equipped with a Teflon blade (at 100 and 200 rpm) without ultrasound irradiation, and no turbidity was generated despite severe movement of the LECAs. These results align with our previous research using a 20 kHz probe system, where no significant ultrasonic desorption occurred when painted beads with diameters of 0.2, 1, and 4 mm were attached [7]. Thus, effective ultrasonic desorption is achievable only when sufficient spacing exists between particles. Further research is required for the

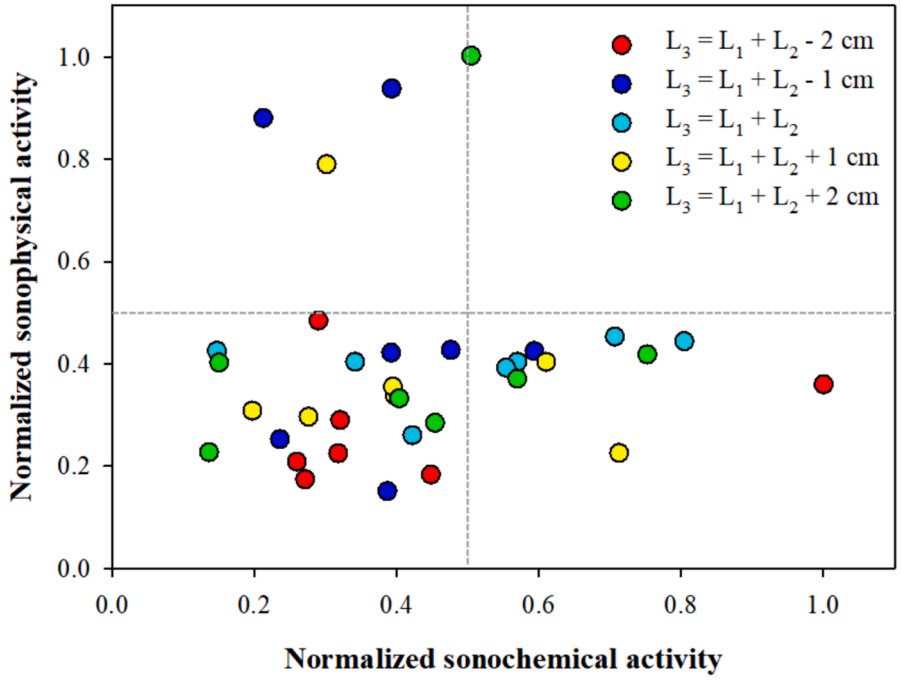


Fig. 5. Relationship between normalized sonochemical and sonophysical activities for 35 geometric conditions, based on the results shown in Fig. 2.

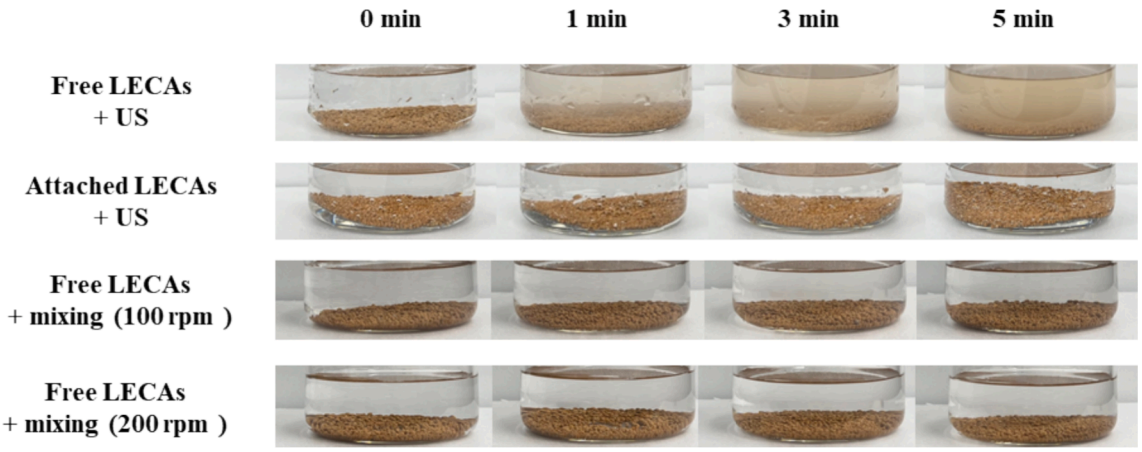


Fig. 6. Variations in turbidity under different conditions: "Free LECAs + US", "Attached LECAs + US", and "Free LECAs + mixing".

physicochemical properties of the desorbed debris to fully understand the sonophysical activity. In previous studies on ultrasonic soil washing processes, additional mechanical mixing resulted in higher pollutant removal from soil particles [10,27,30].

4. Conclusions

In this study, cavitational activity was investigated in 28 kHz double-bath-type sonoreactors to determine the geometrically optimal conditions for sonochemical and sonophysical processes. Sonochemical activity was quantified using KI dosimetry in the absence of LECAs, while the sonophysical activity was quantified using the LECAs desorption test in the presence of LECAs. Thirty-five geometric conditions were tested, and five optimal conditions were determined for each activity. However, the optimal conditions for sonochemical and sonophysical activities did not match. This discrepancy was attributed to the presence of LECAs, which significantly attenuated the ultrasound and resulted in the formation of different cavitational active zones. In addition, no general rule could be suggested to obtain geometrically optimal conditions for each activity, based on the results of 35 cases in this study, because of the complicated and intertwined characteristics of the geometric factors of double-bath-type sonoreactors. Therefore, it was suggested that geometrically optimal conditions could only be obtained by experimenting with the conditions selected by the researchers, as shown in this study. Further research is required to accumulate relevant results and better understand the effects of geometric factors on cavitational activity.

CRediT authorship contribution statement

Mireu Song: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Dukyoung Lee:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Younggyu Son:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National Research Foundation of Korea [RS-2024-00350023] and the Korea Ministry of Environment (MOE) as part of the "Subsurface Environment Management (SEM)" Program [RS-2021-KE001466]. Dr. Y.G. Ahn (Korea Basic Science Institute, Western Seoul Center) is gratefully acknowledged for the help with data analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ultsonch.2025.107263. Movie 1. (a) Free LECAs + US, (b) Attached LECAs + US, (c) Free LECAs + mixing (100 rpm), (d) Free LECAs + mixing (200 rpm). All video clips are played at 15x speed.

References

[1] R.J. Wood, J. Lee, M.J. Bussemaker, A parametric review of sonochemistry: Control and augmentation of sonochemical activity in aqueous solutions, Ultrason. Sonochem. 38 (2017) 351–370.
[2] D. Meroni, R. Djellabi, M. Ashokkumar, C.L. Bianchi, D.C. Boffito, Sonoprocessing: From Concepts to Large-Scale Reactors, Chem. Rev. 122 (2022) 3219–3258.
[3] P. Liu, Z. Wu, A.V. Abramova, G. Cravotto, Sonochemical processes for the degradation of antibiotics in aqueous solutions: A review, Ultrason. Sonochem. 74 (2021) 105566.
[4] Y. Son, J. Choi, Effects of gas saturation and sparging on sonochemical oxidation activity in open and closed systems, part II: NO2−/NO3− generation and a brief critical review, Ultrason. Sonochem. 92 (2023) 106250.
[5] J. Choi, S. Yoon, Y. Son, Effects of alcohols and dissolved gases on sonochemical generation of hydrogen in a 300 kHz sonoreactor, Ultrason. Sonochem. 101 (2023) 106660.
[6] Y. Son, J. Seo, Effects of gas saturation and sparging on sonochemical oxidation activity in open and closed systems, Part I: H2O2 generation, Ultrason. Sonochem. 90 (2022) 106214.
[7] J. Choi, Y. Son, Quantification of sonochemical and sonophysical effects in a 20 kHz probe-type sonoreactor: Enhancing sonophysical effects in heterogeneous systems with milli-sized particles, Ultrason. Sonochem. 82 (2022) 105888.
[8] D. Lee, Y. Son, Ultrasound-assisted soil washing processes using organic solvents for the remediation of PCBs-contaminated soils, Ultrason. Sonochem. 105825 (2021).
[9] J. Choi, D. Lee, Y. Son, Ultrasound-assisted soil washing processes for the remediation of heavy metals contaminated soils: The mechanism of the ultrasonic desorption, Ultrason. Sonochem. 74 (2021) 105574.
[10] B. Park, Y. Son, Ultrasonic and mechanical soil washing processes for the removal of heavy metals from soils, Ultrason. Sonochem. 35, Part B (2017) 640-645.
[11] Y.G. Adewuyi, Sonochemistry: Environmental Science and Engineering Applications, Ind. Eng. Chem. Res. 40 (2001) 4681–4715.
[12] L.H. Thompson, L.K. Doraiswamy, Sonochemistry: Science and Engineering, Ind. Eng. Chem. Res. 38 (1999) 1215–1249.
[13] I. Na, Y. Son, Sonochemical oxidation activity in 20-kHz probe-type sonicator systems: The effects of probe positions and vessel sizes, Ultrason. Sonochem. 108 (2024) 106959.
[14] S. Lee, Y. Son, Effects of gas saturation and sparging on sonochemical oxidation activity under different liquid level and volume conditions in 300-kHz sonoreactors: Zeroth- and first-order reaction comparison using KI dosimetry and BPA degradation, Ultrason. Sonochem. 98 (2023) 106521.
[15] D. Lee, I. Na, Y. Son, Effect of liquid recirculation flow on sonochemical oxidation activity in a 28 kHz sonoreactor, Chemosphere 286 (2022) 131780.

[16] Y. Son, Y. No, J. Kim, Geometric and operational optimization of 20-kHz probe-type sonoreactor for enhancing sonochemical activity, Ultrason. Sonochem. 65 (2020) 105065.
[17] Y. No, Y. Son, Effects of probe position of 20 kHz sonicator on sonochemical oxidation activity, Jpn. J. Appl. Phys. 58 (2019) SGGD02.
[18] Y. Son, Simple design strategy for bath-type high-frequency sonoreactors, Chem. Eng. J. 328 (2017) 654–664.
[19] M. Lim, M. Ashokkumar, Y. Son, The effects of liquid height/volume, initial concentration of reactant and acoustic power on sonochemical oxidation, Ultrason. Sonochem. 21 (2014) 1988–1993.
[20] Y. Son, M. Lim, M. Ashokkumar, J. Khim, Geometric Optimization of Sonoreactors for the Enhancement of Sonochemical Activity, J. Phys. Chem. C 115 (2011) 4096–4103.
[21] T. Khuyen Viet Bao, A. Yoshiyuki, K. Shinobu, Influence of Liquid Height on Mechanical and Chemical Effects in 20 kHz Sonication, Jpn. J. Appl. Phys. 52 (2013) 07HE07.
[22] Y. Asakura, T. Nishida, T. Matsuoka, S. Koda, Effects of ultrasonic frequency and liquid height on sonochemical efficiency of large-scale sonochemical reactors, Ultrason. Sonochem. 15 (2008) 244–250.
[23] M. Michaud, T. Leong, P. Swiergon, P. Juliano, K. Knoerzer, Design parameters of stainless steel plates for maximizing high frequency ultrasound wave transmission, Ultrason. Sonochem. 26 (2015) 56–63.
[24] D. Kobayashi, K. Sano, Y. Takeuchi, K. Terasaka, Effect of irradiation distance on degradation of phenol using indirect ultrasonic irradiation method, Ultrason. Sonochem. 18 (2011) 1205–1210.
[25] D. Kobayashi, H. Matsumoto, C. Kuroda, Effect of reactor's positions on polymerization and degradation in an ultrasonic field, Ultrason. Sonochem. 15 (2008) 251–256.
[26] K. Yasuda, T. Yamazaki, Y. Asakura, Dependence of reaction on vessel position, diameter, and liquid height in the sonochemical reactor with indirect irradiation, Jpn. J. Appl. Phys. 63 (2024) 04SP12.
[27] Y. Son, J. Cha, M. Lim, M. Ashokkumar, J. Khim, Comparison of Ultrasonic and Conventional Mechanical Soil-Washing Processes for Diesel-Contaminated Sand, Ind. Eng. Chem. Res. 50 (2011) 2400–2407.
[28] C.T. Vu, C. Lin, W. Hung, W.-Y. Huang, A. Kaewlaoyoong, S. Yotapukdee, J.-R. Chen, Y.-H. Shen, Ultrasonic Soil Washing with Fish Oil Extract to Remove Polychlorinated Dibenzo-p-dioxins (PCDDs), Dibenzofurans (PCDFs) from Highly Contaminated Field Soils, Water Air Soil Pollut. 228 (2017) 343.
[29] K. Gotoh, K. Harayama, K. Handa, Combination effect of ultrasound and shake as a mechanical action for textile cleaning, Ultrason. Sonochem. 22 (2015) 412–421.
[30] Y. Son, S. Nam, M. Ashokkumar, J. Khim, Comparison of energy consumptions between ultrasonic, mechanical, and combined soil washing processes, Ultrason. Sonochem. 19 (2012) 395–398.
[31] W. Hung, W.-Y. Huang, C. Lin, C.T. Vu, S. Yotapukdee, A. Kaewlaoyoong, J.-R. Chen, Y.-H. Shen, The use of ultrasound-assisted anaerobic compost tea washing to remove poly-chlorinated dibenzo-p-dioxins (PCDDs), dibenzo-furans (PCDFs) from highly contaminated field soils, Environ. Sci. Pollut. Res. 24 (2017) 18936–18945.
[32] Y. Son, M. Lim, J. Khim, Investigation of acoustic cavitation energy in a large-scale sonoreactor, Ultrason. Sonochem. 16 (2009) 552–556.
[33] Y. Son, M. Lim, J. Khim, M. Ashokkumar, Attenuation of UV Light in Large-Scale Sonophotocatalytic Reactors: The Effects of Ultrasound Irradiation and TiO2 Concentration, Ind. Eng. Chem. Res. 51 (2012) 232–239.
[34] Y. Son, M. Lim, J. Khim, L.-H. Kim, M. Ashokkumar, Comparison of calorimetric energy and cavitation energy for the removal of bisphenol-A: The effects of frequency and liquid height, Chem. Eng. J. 183 (2012) 39–45.
[35] Y. Son, M. Lim, J. Song, J. Khim, Liquid Height Effect on Sonochemical Reactions in a 35 kHz Sonoreactor, Jpn. J. Appl. Phys. 48 (2009) 07GM16.
[36] S. Saito, Chapter 2 - Ultrasound Field and Bubbles, in: F. Grieser, P.-.-K. Choi, N. Enomoto, H. Harada, K. Okitsu, K. Yasui (Eds.), Sonochemistry and the Acoustic Bubble, Elsevier, Amsterdam, 2015, pp. 11–39.
[37] T. Leong, M. Coventry, P. Swiergon, K. Knoerzer, P. Juliano, Ultrasound pressure distributions generated by high frequency transducers in large reactors, Ultrason. Sonochem. 27 (2015) 22–29.
[38] R.J. Wood, J. Lee, M.J. Bussemaker, Disparities between sonoluminescence, sonochemiluminescence and dosimetry with frequency variation under flow, Ultrason. Sonochem. 58 (2019) 104645.
[39] C.M. Atkinson, H.K. Kytömaa, Acoustic wave speed and attenuation in suspensions, Int. J. Multiphas. Flow 18 (1992) 577–592.
[40] Y. Son, D. Lee, W. Lee, J. Park, W. Hyoung Lee, M. Ashokkumar, Cavitational activity in heterogeneous systems containing fine particles, Ultrason. Sonochem. 58 (2019) 104599.
[41] Y. Son, M. Lim, J. Khim, M. Ashokkumar, Acoustic emission spectra and sonochemical activity in a 36 kHz sonoreactor, Ultrason. Sonochem. 19 (2012) 16–21.
[42] K. Su, J. Wu, D. Xia, X. Zhang, Clarification of regimes determining sonochemical reactions in solid particle suspensions, Ultrason. Sonochem. 82 (2022) 105910.