

Influence of Vessel Material on the Effectiveness of Ultrasonic Treatment of Metalworking Fluids

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Abstract. This article reviews the influence of process vessel material on the effectiveness of ultrasonic treatment of liquid media. The physical processes occurring when ultrasonic waves interact with the liquid–vessel wall interface are considered, including the reflection, transmission, absorption, and scattering of acoustic energy. The effects of specific acoustic impedance, density, stiffness, wall thickness, and the vibration-damping capacity of the material on acoustic pressure distribution, cavitation field formation, acoustic streaming intensity, and heating of the treated medium are analysed. Vessels made of glass, polymers, and metals used in ultrasonic cleaning, dispersion, emulsification, extraction, and regeneration of metalworking fluids are compared. It is shown that the influence of vessel material should be considered in relation to vessel geometry and dimensions, wall thickness, the method of ultrasonic energy transmission, transducer position, and the volume of the treated liquid. The theoretical considerations are compared with previously obtained experimental results on the ultrasonic treatment of a metalworking fluid in glass and polypropylene vessels. The observed differences in the physical processes and changes in the monitored parameters confirm that the properties of the vessel walls must be considered when selecting ultrasonic treatment parameters. The main requirements for vessel material selection are established, and directions for further research into the transducer–liquid–process vessel system are proposed.

Keywords: ultrasonic treatment, vessel material, acoustic impedance, cavitation, glass, polypropylene, stainless steel, liquid media, metalworking fluid.

Introduction

Ultrasonic treatment is considered a promising method for intensifying physical and chemical processes in liquid media. Ultrasound is used for liquid purification and disinfection, solid-particle dispersion, homogenisation, emulsification, extraction of biologically active compounds, material synthesis, and treatment of process fluids. This wide range of applications is attributed to the combined effects of acoustic cavitation, acoustic microstreaming, shock waves, local pressure and temperature gradients, and high-velocity microjets generated during the collapse of cavitation bubbles [1, 2].

In a liquid medium, an ultrasonic wave produces alternating compression and rarefaction cycles. When the negative pressure amplitude reaches a certain threshold, cavitation bubbles are formed, grow, and subsequently collapse. This process is accompanied by localised energy release, which contributes to the disruption of particle agglomerates, reduction in particle and droplet sizes, enhancement of mass transfer, changes in the interfacial area, and initiation or acceleration of various chemical reactions. Cavitation phenomena therefore account for a substantial proportion of the technological effects produced by ultrasonic treatment [1, 3].

The effectiveness of ultrasonic treatment is traditionally associated primarily with treatment frequency, power, and duration. Temperature, viscosity, surface tension, dissolved-gas content, and the volume of the treated liquid are also important. However, recent studies indicate that the intensity and spatial distribution of cavitation depend not only on the specified operating parameters but also on the design of the entire processing system. The main design factors include the type and position of the ultrasonic transducer, its immersion depth, the geometry and dimensions of the process vessel, liquid-column height, wall thickness, and the conditions under which ultrasonic waves are reflected from the boundaries of the working system [2, 3].

The ultrasonic field within a process vessel is generally non-uniform. Regions with different acoustic pressure levels and cavitation intensities may form throughout the liquid volume. An experimental investigation of the acoustic field in a cylindrical cavitation cell demonstrated that the relationship between acoustic pressure and applied power may be nonlinear and that the spatial distribution of cavitation is governed by the configuration of the working system [4]. When scaling up an ultrasonic system, changes in the process vessel parameters also redistribute acoustic energy and shift the regions of intense cavitation [5]. Consequently, results obtained using systems of different volumes and geometries cannot always be directly compared solely on the basis of identical frequency and power values.

The influence of system design has also been confirmed in studies of ultrasonic systems equipped with immersion transducers. Changes in the transducer position relative to the vessel bottom and walls have been shown to significantly affect the intensity of ultrasound-induced oxidation processes and the size of the active cavitation region. This effect is attributed to the reflection of ultrasonic waves from the system components and the resulting differences in the spatial structure of the acoustic field [6]. Therefore, the process vessel should not be regarded as a

passive enclosure containing the liquid but as an integral component of the transducer–liquid–vessel wall oscillatory system.

The vessel wall material is of particular importance in such a system. When an acoustic wave reaches the liquid–solid interface, it is partially reflected and partially transmitted into the wall material, while some of its energy is lost through absorption, scattering, and the damping of mechanical vibrations. The proportions of these components depend on the specific acoustic impedance of the liquid and wall material, their densities, the speed of sound in each medium, material stiffness, and internal energy losses. Ultrasonic energy transmission is also affected by wall thickness, vessel geometry, mounting conditions, and the presence of additional interfaces between the transducer and the treated medium.

Glass, metal alloys, and polymers differ considerably in their mechanical and acoustic properties. Glass is characterised by relatively high stiffness and limited deformation under acoustic excitation. Metal vessels have high mechanical strength and are widely used in industrial ultrasonic equipment. Polymeric materials exhibit lower stiffness and a greater capacity to absorb energy and damp mechanical vibrations. However, the actual transmission of ultrasonic energy is determined not only by the material properties but also by the design of the entire working system.

A direct comparison of ultrasonic wave transmission through vessel walls made of glass, stainless steel, polyethylene, perfluoroalkoxy alkane, and polytetrafluoroethylene confirmed differences in the intensity of the transmitted ultrasonic effects. The authors evaluated extraction efficiency and cavitation-induced erosion under different operating modes of an ultrasonic bath. The results showed that the vessel material affects the degree of ultrasonic wave attenuation; however, the magnitude of this effect depends on the frequency, excitation mode, and properties of the treated medium [7]. Therefore, claims regarding the universal superiority of a particular material, without considering the system design and treatment conditions, are insufficiently substantiated.

The practical significance of this factor is supported by the results of ultrasonic regeneration of metalworking fluids. Differences in the characteristics of cavitation processes, the degree of heating, and changes in the monitored physicochemical parameters were observed when a metalworking fluid was treated in glass and polypropylene vessels [8]. These findings indicate that the vessel wall material must be considered when selecting treatment conditions and comparing the effectiveness of ultrasonic treatment in different systems. Nevertheless, the relationships established for a specific experimental system require further theoretical substantiation and validation using other liquids, vessel materials, and vessel designs.

Despite the substantial number of publications devoted to ultrasonic systems, most studies focus on power, frequency, transducer arrangement, process vessel geometry, and equipment scale-up from laboratory to industrial conditions [2–6]. Vessel material is more commonly regarded as an accompanying design characteristic than as an independent process parameter. Only a limited number of comparative studies have examined different wall materials under identical geometric, energy, and temperature conditions. Furthermore, no unified approach has been developed to assess the combined effects of vessel material, wall thickness, vessel shape, and the method of ultrasonic energy transmission.

Therefore, the available scientific evidence must be systematised, and the mechanisms through which the physical, mechanical, and acoustic properties of vessel walls affect ultrasonic field distribution and liquid-treatment effectiveness must be identified. Such an analysis will improve the comparability of experimental results, provide a basis for selecting materials for laboratory and industrial systems, and facilitate the development of design requirements for ultrasonic processing equipment.

The aim of this study is to systematise and comparatively analyse the available data on the influence of the physical, mechanical, and acoustic properties of process vessel materials on ultrasonic wave propagation, cavitation field formation, and the effectiveness of liquid treatment.

1. Physical Principles of Ultrasonic Treatment of Liquids

1.1 Propagation of Ultrasonic Waves and Formation of the Acoustic Field

Ultrasonic treatment of liquids is based on the transfer of mechanical energy from the transducer to the treated medium through elastic vibrations. In liquids, ultrasonic waves propagate predominantly as longitudinal waves. The particles of the medium oscillate along the direction of wave propagation, resulting in alternating compression and rarefaction regions [9].

The ultrasonic wavelength is determined by the following expression:

$$\lambda = c/f \quad (1)$$

where λ is the wavelength, m;

c - is the speed of sound in the liquid, m/s;

f - is the ultrasonic frequency, Hz.

As the frequency increases, the wavelength decreases, affecting the spatial distribution of acoustic pressure. Assuming that the speed of sound in water is approximately 1,500 m/s, the wavelengths at frequencies of 25, 28, and 40 kHz are approximately 60.0, 53.6, and 37.5 mm, respectively. These values are comparable to the dimensions of

laboratory-scale vessels; therefore, changes in vessel shape and dimensions, liquid-column height, and transducer position can substantially alter the ultrasonic field.

The time-averaged intensity of a plane progressive wave is determined as follows:

$$I = p_a^2 / (2\rho c), \quad (2)$$

where I - is the ultrasonic intensity, W/m^2 ;

p_a - is the acoustic pressure amplitude, Pa ;

ρ - is the liquid density, kg/m^3 ;

c - is the speed of sound in the liquid, m/s .

Equation (2) is applicable to a plane progressive wave propagating through a homogeneous medium. In an actual process vessel, the acoustic field becomes more complex because of wave reflection, superposition, and absorption, as well as the presence of bubbles and solid particles.

Within a confined volume, incident and reflected waves may form standing waves. This results in the formation of nodes, where the acoustic pressure amplitude is at its minimum, and antinodes, where it reaches its maximum. Consequently, the ultrasonic field within the vessel becomes non-uniform: cavitation and mixing are intense in some regions, whereas the ultrasonic effect is weaker in others [4].

The positions of nodes and antinodes depend on the wavelength, vessel dimensions, liquid-column height, and transducer position. Therefore, systems operating at identical frequency and power levels may produce different acoustic pressure distributions if their design characteristics differ [5, 6].

1.2. Cavitation, Acoustic Streaming, and Liquid Heating

Acoustic cavitation is the principal physical phenomenon governing the effects of high-intensity ultrasound on liquids. It involves the formation, growth, oscillation, and collapse of gas- or vapour-filled bubbles under an alternating acoustic pressure field [9, 11].

Cavitation bubbles generally form at gas inclusions, suspended particles, surface irregularities, and phase boundaries present in the liquid. During the rarefaction phase, the bubbles expand, whereas during the compression phase, they contract or collapse. Their behaviour depends on the frequency and acoustic pressure amplitude, dissolved-gas content, viscosity, surface tension, and liquid temperature.

At a low acoustic pressure amplitude, bubbles undergo stable oscillations over many acoustic cycles. Under more intense excitation, they expand rapidly and collapse violently. Bubble collapse generates shock waves, high-velocity microjets, and local pressure gradients. These phenomena contribute to the disruption of contaminant agglomerates, surface cleaning, dispersion, and enhanced mass transfer [9, 11].

An excessive increase in the number of bubbles does not necessarily improve treatment effectiveness. Dense bubble clouds near the transducer may scatter and absorb ultrasonic waves, thereby preventing their propagation into more distant regions of the liquid. As a result, the non-uniformity of the acoustic field increases [2, 3].

Alongside cavitation, acoustic streaming occurs in the liquid. Acoustic streaming is the directional motion of a fluid caused by momentum transfer from an attenuating ultrasonic wave. It promotes mixing, equalises temperature and component concentrations, facilitates particle transport, and enhances mass transfer. The direction and velocity of acoustic streaming depend on vessel geometry, transducer position, and the manner in which waves are reflected from the vessel walls [10].

A proportion of the supplied energy is converted into heat through ultrasonic wave absorption, viscous friction, fluid motion, and cavitation bubble activity. In the absence of significant heat losses, the power actually absorbed by the liquid can be approximately determined from its heating rate:

$$P_{abs} = m \cdot c_p \cdot \Delta T / \Delta t, \quad (3)$$

where P_{abs} - is the absorbed power, W ;

m - is the liquid mass, kg ;

c_p - is the specific heat capacity, $J/(kg \cdot K)$;

ΔT - is the temperature change, K ;

Δt - is the measurement duration, s .

Under actual operating conditions, some of the heat is transferred to the vessel walls, the transducer, and the surrounding environment. Therefore, liquid heating characterises the overall energy absorption but cannot be used to determine acoustic pressure or cavitation intensity directly.

Temperature also affects cavitation. As the temperature increases, liquid viscosity and surface tension generally decrease, whereas the saturated vapour pressure increases. These changes facilitate bubble formation; however, a

higher vapour content within the bubbles may reduce the intensity of their collapse. Therefore, the relationship between cavitation activity and temperature is complex and often non-monotonic [11, 12].

1.3. Influence of Operating and Design Parameters

Frequency determines the wavelength, the duration of the compression and rarefaction cycles, and the dynamics of cavitation bubble growth. At relatively low frequencies, the bubbles have sufficient time to grow to larger sizes and generate a more pronounced mechanical effect upon collapse. As the frequency increases, the duration of each cycle decreases, while the number of excitation cycles per unit time increases [2, 9, 11].

An increase in power is generally accompanied by an increase in vibration amplitude, acoustic pressure, and the number of cavitation bubbles. However, the nominal electrical power of the generator is not equal to the power actually transferred to the liquid because some of the energy is lost in the converter, transducer, vessel walls, and connecting components [2].

The total amount of energy supplied to the system at constant power is determined as follows:

$$E = P \cdot t \quad (4)$$

where E is the supplied energy, J;

P - is the power, W;

t - is the treatment duration, s.

Increasing the treatment duration increases the total energy supplied to the system; however, the technological outcome does not always change proportionally. Prolonged treatment may cause excessive heating, changes in the dissolved-gas content, and renewed fragmentation of previously agglomerated particles.

Frequency, power, treatment duration, and temperature are interrelated. The treatment outcome is also affected by the liquid volume, vessel geometry and dimensions, wall thickness, and transducer position. Therefore, the process vessel should be regarded as an integral component of the transducer–liquid–vessel wall system rather than as a neutral enclosure [2–6].

2. Interaction of an Ultrasonic Wave with the Process Vessel Wall

2.1 Reflection, Transmission, and Absorption of Ultrasonic Waves

When an incident ultrasonic wave reaches the liquid–wall interface, it is divided into a reflected wave returning to the liquid and a transmitted wave propagating through the wall material. Some of the energy is dissipated as a result of internal friction, absorption, and scattering by material inhomogeneities [13, 14].

The relationship between the energy components can be expressed as follows:

$$I_{inc} = I_{ref} + I_{tr} + I_{loss} \quad (5)$$

where I_{inc} - is the intensity of the incident wave, W/m²;

I_{ref} - is the intensity of the reflected wave, W/m²;

I_{tr} - is the intensity of the transmitted wave, W/m²;

I_{loss} - represents intensity losses due to absorption and scattering, W/m².

An actual vessel wall has a finite thickness and two interfaces: an inner and an outer interface. Therefore, the wave transmitted into the material undergoes multiple reflections within the wall. Some of the energy returns to the liquid, some is transmitted to the external medium, and some is converted into heat. The resulting energy distribution is affected by the wall material and thickness, ultrasonic frequency, angle of incidence, and the medium surrounding the outer surface of the vessel.

The reflected waves are superimposed on the waves propagating through the liquid and contribute to the formation of standing waves. Depending on their phase relationship, they may either increase or decrease the acoustic pressure. Therefore, strong reflection does not necessarily result in more uniform or effective ultrasonic treatment.

2.2. Specific Acoustic Impedance and Energy Transmission

The resistance of a medium to acoustic wave propagation is characterised by its specific acoustic impedance:

$$Z = \rho c \quad (6)$$

where Z - is the specific acoustic impedance, Pa·s/m;

ρ - is the density of the medium, kg/m³;

c - is the speed of sound in the medium, m/s.

The greater the difference between the specific acoustic impedances of two media, the larger the proportion of energy reflected from their interface. For a plane wave normally incident on the boundary between two homogeneous, lossless media, the intensity reflection coefficient is determined as follows:

$$R = [(Z_2 - Z_1)/(Z_2 + Z_1)]^2, \quad (7)$$

where R - is the fraction of reflected intensity;

Z_1 and Z_2 - are the specific acoustic impedances of the first and second media, respectively.

The intensity transmission coefficient is determined as follows:

$$T = 4Z_1Z_2/(Z_1 + Z_2)^2, \quad (8)$$

where T - is the fraction of intensity transmitted into the second medium.

For an ideal lossless interface, the following condition applies: $R+T=1$. These expressions describe a single plane interface and do not account for the finite wall thickness, wall curvature, internal energy losses, or interaction with the external medium [13]. They therefore describe the fundamental relationships but cannot fully determine ultrasonic transmission through an actual process vessel.

Within the wall material, the acoustic pressure amplitude decreases as the wave propagates:

$$p(x) = p_0 e^{(-\alpha x)}, \quad (9)$$

where $p(x)$ - is the acoustic pressure amplitude after the wave has travelled a distance x , Pa;

p_0 - is the initial acoustic pressure amplitude, Pa;

α - is the attenuation coefficient, m^{-1} ;

x - is the distance travelled by the wave through the material, m.

Attenuation is caused by absorption and scattering. During absorption, mechanical energy is predominantly converted into heat, whereas scattering redistributes the energy in other directions. In polymers, internal friction and the time lag between deformation and the applied load are additional important factors.

2.3. Influence of Wall Thickness, Geometry, and Mounting Conditions

Wall thickness affects both energy absorption and the phase relationships between waves undergoing multiple reflections from the wall surfaces. Therefore, the dependence of ultrasonic transmission on wall thickness is not always monotonic. A thicker wall does not necessarily transmit less energy under all conditions, because reflected waves may constructively interfere at certain ratios of wall thickness to wavelength.

A numerical and experimental investigation of cylindrical glass vessels with wall thicknesses of 1.2, 1.8, and 3.2 mm showed that variations in thickness altered not only the acoustic pressure level but also its spatial distribution. The numerical results were validated using the observed son chemiluminescence pattern of a luminol solution [15].

Vessel geometry determines the angles of incidence and directions of wave reflection. In a cylindrical vessel, the angle of incidence varies around the circumference; therefore, different regions of the wall reflect and transmit ultrasound differently. A curved surface may cause wave scattering, local focusing, and divergence. The vessel bottom, side walls, and free liquid surface jointly determine the positions of nodes, antinodes, and regions of developed cavitation [3, 5, 15].

Under alternating acoustic pressure, the wall undergoes forced mechanical vibrations and becomes a secondary source of ultrasonic waves. The amplitude of these vibrations depends on material elasticity, wall thickness, excitation frequency, and mounting conditions. Supporting elements may dissipate some of the energy and alter the natural frequencies of the structure. Therefore, comparisons between vessels should specify not only the wall material and thickness but also the installation and mounting conditions [2, 3].

2.4. Characteristics of Glass, Polymer, and Metal Vessels

Glass is characterised by high stiffness, chemical resistance, and transparency, allowing the observation of cavitation, mixing, and liquid phase separation. The considerable difference between the specific acoustic impedances of glass and the liquid promotes pronounced wave reflection. Relatively low internal mechanical energy losses allow the wall to contribute to the formation of a stable acoustic field. However, glass is brittle, and its interaction with ultrasound is strongly dependent on vessel wall thickness and geometry [7, 15].

Polypropylene has lower stiffness and is more readily deformed. Its internal friction contributes to the damping of mechanical vibrations and the conversion of some energy into heat. However, the similarity between the specific acoustic impedances of the liquid and polymer may facilitate wave transmission across the inner interface. Therefore,

it cannot be unequivocally stated that polypropylene transmits ultrasound less effectively under all conditions. The resulting transmission is determined by the combined effects of reflection, absorption, wall thickness, and mounting conditions [7].

Stainless steel is characterised by high strength and stiffness and is widely used in industrial ultrasonic equipment. Its high specific acoustic impedance causes pronounced reflection at the liquid–metal interface. At the same time, a metal wall can transmit mechanical vibrations when an ultrasonic transducer is directly attached to it. Therefore, the behaviour of a metal vessel must be evaluated with consideration of the ultrasonic energy transmission method: through an immersion transducer, through the liquid in an ultrasonic bath, or through a transducer attached directly to the vessel wall [2, 3, 7].

An experimental comparison of ultrasonic transmission through glass, stainless steel, polyethylene, perfluoroalkoxy alkane, and polytetrafluoroethylene confirmed that vessel material affects the transmitted ultrasonic energy. However, the results also depended on frequency, the operating mode of the system, liquid properties, and the selected assessment method. Therefore, no single material can be regarded as universally optimal [7].

2.5. Influence of the Vessel Wall on the Acoustic and Cavitation Fields

The vessel wall material and design affect the proportions of reflected, transmitted, and absorbed energy; the formation of standing waves; the spatial distribution of acoustic pressure; the acoustic streaming pattern; and the location of regions of developed cavitation. Wall vibrations and surface roughness, which may promote cavitation bubble nucleation, are also important.

Cavitation develops primarily in regions where the negative acoustic pressure reaches the cavitation threshold. Therefore, changes in the positions of nodes and antinodes cause the cavitation regions to shift. The resulting bubbles, in turn, scatter and absorb ultrasonic waves, thereby modifying the initial acoustic pressure distribution [2, 4, 9].

When comparing glass and polypropylene vessels, the influence of the material must be distinguished from that of the vessel design. If the vessels differ in wall thickness, geometry, or internal dimensions, it is more appropriate to describe the study as a comparison of the vessels as complete systems. To evaluate the influence of material independently, vessels of identical geometry and comparable wall thickness should be used, or the design differences should be accounted for numerically.

Changes in liquid temperature should not be regarded as an independent indicator of cavitation intensity. Direct measurements of acoustic pressure and cavitation intensity would provide additional quantitative evidence for the observed differences between the vessels. Such measurements could be performed using a hydrophone or sonochemical indicators, including sonoluminescence, in future experimental studies. More pronounced heating indicates a greater proportion of ultrasonic energy being converted into heat, but does not necessarily correspond to higher acoustic pressure or more intense bubble collapse. Temperature measurements should therefore be considered together with acoustic pressure distributions, optical or chemical indicators of cavitation activity, and changes in the properties of the treated liquid.

Thus, the process vessel wall is an active component of the ultrasonic system. Wall material, thickness, geometry, and mounting conditions jointly determine wave reflection, transmission, absorption, and scattering. Vessel material should therefore be regarded as an independent process parameter whose influence must be evaluated in relation to the design of the entire system.

3. Comparison of the Theoretical Considerations with the Results of Ultrasonic Treatment of Metalworking Fluids

3.1 Experimental Conditions

To evaluate the influence of process vessel material, the results of previous studies on the ultrasonic treatment of a metalworking fluid in glass and polypropylene vessels were analysed [8]. The experiments were conducted under identical treatment conditions, allowing the physical processes and changes in the monitored fluid parameters to be compared.

Vessels with capacities of 1, 3, and 5 L were used in the experiments. Ultrasonic treatment was performed at frequencies of 25, 28, and 40 kHz and a power of 100 W. The treatment duration was 5 min. The principal comparison between the glass and polypropylene vessels was conducted at 28 kHz, which had previously been identified as the most effective treatment frequency.

Metalworking fluid samples with different service durations were examined: fresh fluid, moderately contaminated fluid used for 2–3 weeks, and heavily contaminated fluid used for more than one month. Each experiment was performed in triplicate. The results were statistically processed and expressed as the mean $\pm$ standard deviation. Differences were considered statistically significant at $p < 0.05$ [8].

Samples were collected before ultrasonic treatment, immediately after treatment, and after the fluid had been allowed to stand for 24 h. The treatment results were evaluated by measuring temperature, density, the Brix value, and the electrical properties of the fluid. Cavitation, mixing, contaminant particle agglomeration, and subsequent phase separation were additionally assessed by visual and microscopic observations.

This experimental design made it possible to evaluate not only the immediate effects of ultrasound but also the changes occurring after treatment had been discontinued. The 24-h settling period was particularly important because contaminant agglomeration and migration and the formation of a separable upper layer continued after the transducer had been switched off. No visible re-emulsification of the separated contaminants was observed during the 24-h settling period; however, possible chemical degradation of the base emulsion was not assessed and requires further chemical analysis.

3.2 Influence of Vessel Material on Physical Processes

During ultrasonic treatment, liquid heating, cavitation bubble formation, intensive mixing, contaminant particle agglomeration, and subsequent phase separation were observed in the metalworking fluid. The characteristics and intensity of these processes depended on the process vessel material.

Bubble formation and fluid motion were more intense in the glass vessels than in the polypropylene vessels. Small, dark agglomerates containing metal particles, dust, tramp oil, and other contaminants formed within the fluid. Bubbles that entrained solid and oily contaminants formed near the vessel walls. These agglomerates moved upwards, gradually forming a contaminated upper layer.

The observed separation can be explained by the combined effects of cavitation, acoustic streaming, and contaminant particle agglomeration. Ultrasonic treatment disrupted the bonds between the contaminant particles and the dispersion medium. Simultaneously, the bubbles and upward fluid flows promoted contaminant transport towards the upper part of the vessel. After treatment had been discontinued, the agglomerated contaminants continued to separate from the bulk fluid.

More pronounced heating was also observed in the glass vessels. Under identical treatment conditions of 28 kHz, 100 W, and 5 min, the fluid temperature reached 33–35 °C in the glass vessels, compared with predominantly 30–31 °C in the polypropylene vessels. Given an initial temperature of approximately 23 °C, these results indicate differences in energy transmission and distribution.

The more intense processes observed in the glass vessel are consistent with the theoretical considerations presented in Sections 1 and 2. Glass is characterised by high stiffness and relatively low internal mechanical energy losses. Waves reflected from its walls contribute to the formation of the acoustic field within the liquid. Polypropylene deforms more readily, while some of the energy is dissipated through internal friction and the damping of mechanical vibrations [7, 13]. It should be noted that increased heating does not necessarily indicate that a greater proportion of the supplied acoustic energy contributes to active cavitation. Part of the supplied ultrasonic energy may be dissipated as heat through material damping and losses in the vessel wall, whereas another portion is transmitted into the liquid and contributes to the acoustic field and cavitation activity.

However, the observed differences cannot be attributed solely to the intrinsic properties of the materials. The results are also affected by wall thickness, vessel geometry, internal dimensions, liquid-column height, and transducer position. Studies by other authors have confirmed that changes in wall thickness and geometry alter the acoustic pressure distribution even when the frequency and power remain unchanged [5, 15].

3.3 Changes in the Monitored Parameters

A comparison of the results obtained at a frequency of 28 kHz, a power of 100 W, and a treatment duration of 5 min revealed differences in the monitored parameters between the glass and polypropylene vessels.

Table 1. Effect of Vessel Material and Liquid Volume on the Parameters of Ultrasonically Treated Metalworking Fluid

Liquid volume, L	Vessel material	Brix value, %	Density, g/cm ³	Temperature, °C
1	Polypropylene	1.5	1.0058	30
1	Glass	1.1	1.0040	35
3	Polypropylene	1.6	1.0062	31
3	Glass	0.7	1.0020	34
5	Polypropylene	1.7	1.0066	30
6	Glass	0.7	1.0019	33

*The table presents the results obtained for a moderately contaminated metalworking fluid treated at a frequency of 28 kHz, a power of 100 W, and a treatment duration of 5 min.

The experimental data presented in Table 1 were obtained in our previous study on the ultrasonic regeneration of metalworking fluids [8].

Figures 1–3 show the effect of vessel material and liquid volume on the Brix value, density, and temperature of the metalworking fluid after ultrasonic treatment. For all the investigated volumes, treatment in glass vessels resulted in lower Brix values and lower fluid density than treatment in polypropylene vessels. At the same time, the temperature of the fluid treated in glass vessels was 3–5 °C higher. The most pronounced differences in the Brix value and density were observed at liquid volumes of 3 and 5 L. Taken together, these results indicate more intensive energy transfer and a more pronounced ultrasonic effect in the glass vessels under the experimental conditions employed. However, the observed differences should be attributed to the combined influence of vessel material, wall thickness, geometry, liquid volume, and acoustic field distribution.

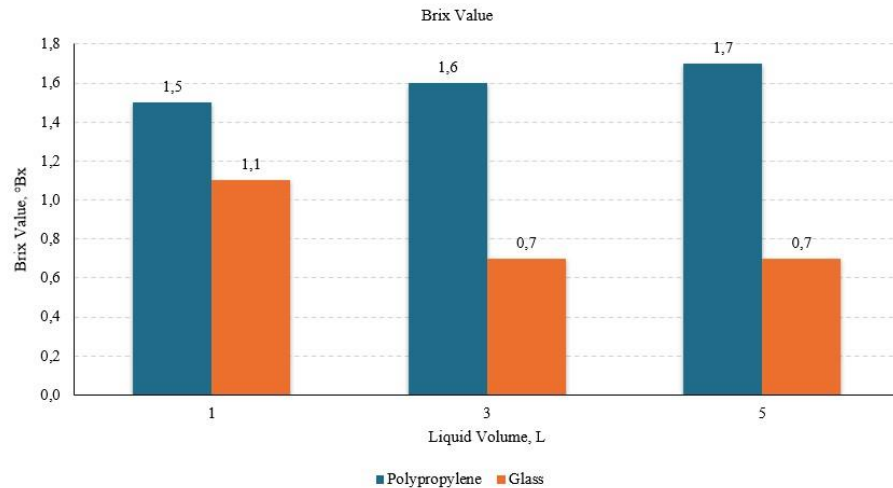


Fig.1. - Effect of vessel material and liquid volume on the Brix value of the metalworking fluid.

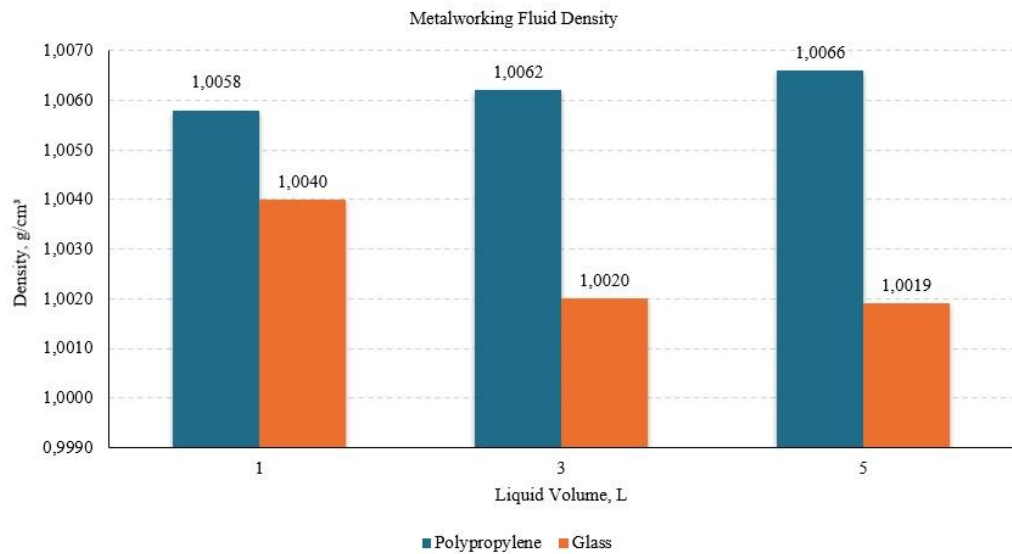


Fig.2. - Effect of vessel material and liquid volume on the density of the metalworking fluid.

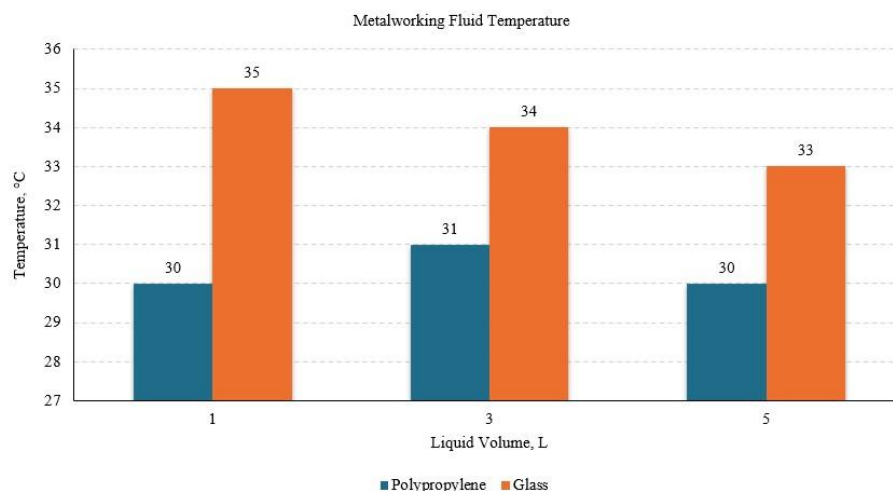


Fig.3. - Effect of vessel material and liquid volume on the temperature of the metalworking fluid

The decrease in the Brix value was associated with a reduction in the concentration of components affecting light refraction in the investigated fluid. Since a metalworking fluid is a complex multicomponent medium, this parameter cannot be directly equated solely with contaminant content. It should be evaluated together with density, electrical properties, turbidity, and microscopic observations.

The decrease in density following ultrasonic treatment confirms the separation of some solid and oily contaminants from the bulk fluid. The most pronounced changes were observed after the settling period, during which the agglomerated contaminants either migrated to the upper layer or settled, depending on their composition and density. Further studies should include chemical composition analysis of the treated fluid to assess whether ultrasonic treatment affects the base emulsion concentration or stability in addition to removing tramp oils and solid contaminants.

Changes in electrical resistance also indicated alterations in the composition of the liquid medium. Previous studies have demonstrated the applicability of electrical resistance as an indirect parameter for monitoring the contamination level of metalworking fluids [16]. However, this parameter depends not only on contaminant content but also on emulsion concentration, temperature, water content, dissolved salts, and ageing products. Therefore, electrical resistance should be used as part of a comprehensive assessment of the condition of the metalworking fluid rather than as the sole indicator of purification efficiency.

3.4. Influence of Frequency, Treatment Duration, and Liquid Volume

A comparison of frequencies of 25, 28, and 40 kHz showed that the most pronounced treatment effect under the investigated conditions was achieved at 28 kHz. At 25 kHz, the ultrasonic effect was less uniform, whereas increasing the frequency to 40 kHz did not further improve the overall set of monitored parameters. Based on the results obtained, the combination of a frequency of 28 kHz, a power of 100 W, and a treatment duration of 5 min was identified as the most effective treatment condition [8].

This finding does not imply that 28 kHz is a universally optimal frequency for all liquids and ultrasonic systems. The most effective operating conditions depend on the composition of the metalworking fluid, liquid volume, vessel material and geometry, transducer position, and acoustic pressure distribution. The established parameters apply to the investigated system and should be refined whenever the treatment conditions are changed.

Increasing the treatment duration beyond 5 min did not result in a proportional improvement in treatment performance. Longer treatment increased fluid heating, whereas further changes in the monitored parameters were insignificant. Furthermore, excessive ultrasonic exposure may disrupt the contaminant agglomerates already formed and redistribute the particles throughout the liquid volume.

The liquid volume also affected the treatment outcome. As the volume increased, the same power was distributed over a larger quantity of the treated medium, thereby reducing the energy input per unit volume. At the same time, the liquid-column height, distance from the reflecting boundaries, and positions of regions of elevated acoustic pressure changed. Therefore, treatment results obtained using different liquid volumes cannot be compared without considering vessel geometry and specific energy input [3, 5].

3.5. Comparison of Experimental Results with the Theoretical Considerations

The results obtained confirm the principal conclusion of this review: process vessel material is one of the factors determining the effectiveness of ultrasonic treatment. Its influence is manifested through wave reflection,

transmission, and absorption; damping of mechanical vibrations; formation of standing waves; and changes in the spatial distribution of acoustic pressure.

Under identical treatment conditions, more intense cavitation and thermal effects were observed in the glass vessels, together with more pronounced changes in density and Brix value. This finding is consistent with the lower internal mechanical energy losses in glass compared with polypropylene.

At the same time, the experimental data do not allow the isolated contribution of the wall material to be quantified because the vessels may have differed not only in material but also in wall thickness, stiffness, dimensions, and mounting conditions. Furthermore, acoustic pressure was not measured directly during the experiments. Therefore, the explanation of the observed differences in terms of wave reflection and absorption should be regarded as a physically substantiated interpretation that requires further quantitative verification. For scientifically rigorous comparison of vessel materials, further experiments should be performed using vessels with identical geometry, dimensions, and comparable wall thicknesses. Maintaining these parameters constant would minimize the influence of vessel design and allow the effect of the wall material on ultrasonic treatment to be assessed more accurately.

To clarify the relationships identified, comparative studies should be conducted using vessels of identical geometry and comparable wall thickness. This approach would distinguish the influence of material from that of vessel geometry and establish requirements for selecting process vessels for laboratory and industrial ultrasonic systems.

Thus, the results of ultrasonic treatment of the metalworking fluid in glass and polypropylene vessels are consistent with the theoretical relationships considered. Under the investigated conditions, the glass vessel provided a more pronounced ultrasonic effect on the fluid. Nevertheless, the material should be selected with consideration of the entire transducer–liquid–process vessel system, and results obtained using a particular experimental system should not be generalised to other treatment conditions without additional verification.

Conclusions

The review demonstrated that process vessel material is a significant parameter in the ultrasonic treatment of metalworking fluids. The vessel walls participate in the reflection, transmission, absorption, and scattering of ultrasonic waves, thereby affecting acoustic pressure distribution, standing-wave formation, cavitation intensity, acoustic streaming patterns, and liquid heating.

The interaction of ultrasonic waves with the vessel walls is governed by the specific acoustic impedance, density, stiffness, and mechanical energy absorption capacity of the material. Wall thickness and geometry, vessel dimensions, liquid volume, transducer position, and the method of ultrasonic energy transmission also exert a substantial influence. Therefore, material properties cannot be considered independently of the design of the entire system.

A comparison of the materials showed that the high stiffness, chemical resistance, and transparency of glass make it suitable for laboratory investigations and the observation of physical processes. Polymeric materials have lower stiffness and a greater capacity to damp mechanical vibrations; therefore, some of the supplied energy may be dissipated within their walls. Stainless steel offers high strength and is suitable for industrial equipment; however, the resulting acoustic field depends on the thickness of the metal walls and the method used to mount the transducers. Thus, no material can be regarded as universally optimal. Material selection should be based on the intended application of the system, the properties of the treated liquid, and the required treatment conditions.

The results of the ultrasonic treatment of the metalworking fluid confirmed the theoretical considerations presented in this review. Under identical treatment conditions, the glass vessels exhibited more intense cavitation and thermal effects and more pronounced changes in density and Brix value than the polypropylene vessels. Under the investigated conditions, the most effective combination comprised a frequency of 28 kHz, a power of 100 W, and a treatment duration of 5 min. These values apply to the experimental system employed and should not be extrapolated to other liquids or equipment designs without additional verification.

Based on the analysis, the following conclusions were drawn:

1. The process vessel is an integral component of the acoustic system and directly contributes to the formation of the ultrasonic field within the treated liquid.
2. The influence of vessel wall material is manifested through wave reflection, transmission, absorption, and scattering; damping of mechanical vibrations; and changes in the spatial distribution of acoustic pressure.
3. The effectiveness of ultrasonic treatment is determined by the combined effects of wall material, thickness, and geometry; liquid volume; transducer position; frequency; power; and treatment duration.
4. Under the investigated operating conditions, glass vessels produced a more pronounced ultrasonic effect on the metalworking fluid than polypropylene vessels.
5. Transparent glass vessels are suitable for laboratory investigations because they allow cavitation and contaminant separation to be observed. For industrial applications, vessel selection should take into account wall thickness and the method of ultrasonic energy transmission.
6. Quantitative confirmation of the influence of vessel material requires comparative studies using vessels of identical geometry and comparable wall thickness, supplemented by measurements of acoustic pressure and the spatial distribution of cavitation activity.

The results confirm that process vessel material must be considered when selecting ultrasonic treatment conditions and designing equipment for the regeneration of process fluids.

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