Separation of motions and vibrational separation of fractions for biocide brass

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ABSTRACT

The mathematical method of separation of motions represents the effect of fast high-frequency oscillations by an effective averaged force or potential. Ultrasound acoustic vibrations are an example of such rapid oscillations leading to cavitation in water due to the gas phase formation (bubbles). Ultrasound cavitation is used to treat the surface of brass microparticles submerged in water. The formation of bubbles and their collapse triggers the modification of surface roughness and chemical composition. Consequently, the suspension separates into various fractions related to demonstrating biocide properties. While the exact mechanism of this process is complex, it can be explained phenomenologically by using the Onsager reciprocal relations for coupling the copper ion diffusion with the gas phase separation in water as a result of the action of the effective average vibrational force.

1. Introduction

The mathematical method of separation of motions involves substituting small-amplitude fast oscillations by an effective potential or force. The method was developed in the 1950 s, and its most common illustration is the vibrational stabilization of the inverted pendulum attached to a vibrating foundation[1,2]. Such a pendulum is often called the Kapitza pendulum (Fig. 1a). The inverted upside-down position of a pendulum constitutes an unstable equilibrium. However, when the foundation of the pendulum oscillates with high frequency and small (say, microscale) amplitude, the inverted position stabilizes. The effect is often perceived at the macroscale if an effective stabilizing spring force is applied to the inverted pendulum[3,4].

The equation of motion of the inverted pendulum of length L on a foundation harmonically vibrating with amplitude A and frequency Ω is given by

\[ L\ddot{\psi} = g \sin \psi - A\Omega^2 \sin \psi \cos \Omega t \]  

(1)

Where \( \psi \) is the angular coordinate[4]. For small angle \( \sin 2\psi \approx 2\psi \), and the following approximation can be used

\[ L\ddot{\psi} = g\psi = -k\psi \]  

(2)

where \( k = \frac{mgL^2}{2} \) is the effective spring constant, providing the stabilizing effect in the case of \( k > g \) or \( A^2\Omega^2 > 2gL \).

The effect of the vibration-induced stabilization can be extended to the case of multiple degrees of freedom, namely, for an inverted double and multiple pendula and a flexible stiff rope representing a pendulum with an infinite number of degrees of freedom[3,4]. In the latter case (sometimes called the “Indian wire trick”), vibration induces “effective hardening” of the flexible rope, which still possesses some stiffness akin to a stiff beam, and thus effective properties of the rope material change as an effect of vibration [5,6]. Moreover, the vibration-induced “effective hardening” of fibers in the composite material can lead to a novel class of “dynamic materials” whose effective properties are controlled by an externally applied electric field[7].

Among other notable effects of small, fast vibrations is a shear thickening of non-Newtonian fluids, which is perceived as an effective force acting upon the liquid, often demonstrated with cornstarch (sometimes called the “cornstarch monster” trick). The figurines of the liquid rise somewhat similarly to the flexible rope when the bath with the liquid vibrates[4]. There are also many other systems involving the fluid flow and propulsion activated by vibration, including such phenomena as effective “freezing” of water in a vibrating vessel (so that water does not flow or droplets do not coalesce [4]). These are non-
linear (hysteretic) systems, ranging from the beams stabilized for buckling by vibration to the transport and separation of granular material, soft matter, bubbles, and droplets, to the self-synchronization of rotating machinery.

The common among these systems is that the small, fast vibrational motion can be excluded from the consideration and substituted by effective slow forces acting on the system, causing the change of the equilibrium type (e.g., from unstable to stable) or of the state. Many of these systems demonstrate the transformation of effective properties, which are similar to phase transitions, including effective “freezing” of liquid in a vibrating tank or droplets suspended over it so that water does not flow through a hole and droplets do not coalesce effectively levitating over a liquid bath (vibro-levitation) [4]. In other experiments, granular material behaves as a liquid under the effect of vibration, for example, demonstrating surface tension [8]. The vibration-induced transition of soft to stiff properties [4-6] as well as from hydrophilic to hydrophobic has been demonstrated (superhydrophobicity is induced by vibration) [9,10]. The effective characteristics of oscillating fields, such as the effective spring constant in a pendulum on a vibrating foundation, are determined using the averaging by the mathematical method called “the method of separation of fast and slow motions” [3,4,9].

Small-amplitude fast oscillations often lead to an effective change of equilibrium, phase state, or phase separation. It is particularly interesting to consider vibration-induced phase separation in systems subject to the sonochemical treatment [11-16]. In such systems, ultrasound is often used as a source of acoustic treatment. The ultrasound in liquid, such as water, often results in cavitation, i.e., the generation of gas microbubbles containing dissolved oxygen or vapor, which collapse, resulting in local high temperatures and pressures. A solid surface immersed in the water results in surface treatment, affecting its roughness and chemical composition. The acoustic force resulting from averaging acoustic oscillations is well known in fluid mechanics [17], however, it is rarely viewed as a source of phase transformation. The acoustic force acting on the bubble (the Bjerknes force) is equal to the volume of the bubble times the gradient of pressure, \(-V\nabla P\). This force is different from zero throughout the wave because the bubble is compressed, and thus the phenomenon is similar to other systems described above, which demonstrate non-linear behavior with hysteresis. In this work, we will apply the method of separation of motions to the acoustic (sonochemical) treatment of the brass (Cu-Zn alloy) particles used for antibacterial purposes (Fig. 1b).

Ultrasound-driven phase segregation is observed in many multi-component systems [13,16,18]. Thus, the ultrasound treatment of
metals leads to new phases through oxidation or in situ reductions. High-intensity ultrasound is used as a one-step method of synthesis of composite materials, facilitating interpenetration of metal-polymer hybrids, core–shell particles, two-layered composites, multi-metal composites, and others[16,19-22]. Skorb and Andreeva proposed an ultrasound-driven method for modifying zinc particles by top-down “sononanostructuring” [12]. Cu-Zn alloys are effective catalysts [16,22-25] with a strong biocidic function due to free radicals on the alloy’s surface dramatically affecting cell function [26]. The surface roughness effect [27] possibly enhances the biocidic function. The surface morphology of the Zn particles changes while damage of the cell membrane correlates with Zn ion release [28]. The sonochemical treatment combined with bacterial metabolism contributes to the protection of biocompatible surfaces [11].

One particularly promising area of application of the separation of motions is acoustic phase separation in alloys. A Cu-Zn alloy can be subject to the sonochemical treatment, which modifies its properties. In this paper, we will investigate the vibrational separation of components or fractions in the Cu-Zn alloy (Fig. 1c).

2. Experimental

2.1. Preparation of Cu-Zn fractions

5 g of Cu-Zn alloy were dispersed in 100 mL of 0.5 M NaOH. The solution was sonicated using ultrasonic system UP100Hd (Hielsher Ultrasonics, Germany) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1). The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A. The apparatus was equipped with the sonotrode BS2d40 (head 2.1) for 30 min and different amplitudes 30%, 70%, 90% A.

2.2. Characterization of morphology

The sample morphology was studied by field-emission scanning electron microscope Tescan Vega3 (TESCAN ORSAY HOLDING, Czech Republic) at the operating voltage of 5 kV. The Cu-Zn alloy particles were fixed in the holder with a double-sided conductive tape.

2.3. Differential pulse anodic stripping voltammetry

The release of cations was investigated by the differential pulse anodic stripping voltammetry (DPASV) technique for zinc and copper ions detection in samples. For this purpose, the three-electrode system based on a Screen-printed electrode was used in a 1 mL volume cell. The electrolyte was prepared by mixing 100 μM Hg(NO₃)₂, 1 mM HNO₃, 0.5 M HCl. All electroanalytical measurements were repeated three times for the statistical evaluation of the results. The 0.051 g of each fraction was dispersed in DI water. After 24 h, metal-containing solutions were tested by voltammetric analyzer using electrochemical measurements.

2.4. Biocide activity

The biocide activity of modified particles was studied using Escherichia coli (ATCC 25922) bacteria culture. A 5 μL droplet of the particle solution was incubated for 24 h at 37 °C in the grown lawn, and inhibition zone diameter was measured. The difference of inhibition zones correlated with various containing of copper ions [29]. All experiments were done in triplicate.

3. Results and discussion

The sonochemical treatment due to the ultrasound cavitation facilitated the oxidation reaction leading to different phases formation. These phases can release different amounts of copper and zinc ions. The oxidation facilitated the formation of the two fractions due to cavitation. For the kinetics of this reaction, one can write a linearized equation for the flow of copper ions

\[ \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \]

where \( D \) is the coefficient of diffusion and \( \rho \) is the density. The next step is to relate the flow of the copper ions to the rate of formation of the cavitation bubbles, as calculated from Eq. (3). Given the Onsager reciprocal relations, one can write now

\[ J_x = -D \frac{\partial \rho}{\partial x} + C_\rho \rho \frac{\partial \rho}{\partial \Omega} \]

where \( C_\rho \) is a phenomenological reciprocal coefficient. Thus, the flow of the copper ions formation is expected to be dependent on \( \langle \Omega \rangle^2 \). The output in terms of fraction separation shows a non-linear dependency on the amplitude of acoustic vibrations.

3.1. Mathematical separation of slow and fast motions

Russian physicist Kapitza first suggested the method of separation of motions in 1951 [2]. It was generalized for the case of an arbitrary motion in a rapidly oscillating field, as discussed in the classical theoretical physics textbook by Landau and Lifshits [12].

The equation of motion of a particle of mass \( m \) in a potential field \( \Pi(x) \) is given by \( m \ddot{x} = -\frac{d\Pi}{dx} \). Let us assume that besides the potential \( \Pi(x) \), a harmonic oscillating force \( f \cos \Omega t \) acts upon the mass. The oscillating force possesses a small amplitude \( f \) and high frequency \( \Omega \gg > > \)

\[ \sqrt{\frac{d^2\Pi}{dx^2}}/m \] . The equation of motion with the account to the small, fast oscillating force is

\[ m \ddot{x} = -\frac{d\Pi}{dx} + f \cos \Omega t \]

The method of separation of motions is to present the action of the particle as a sum of slow-motion \( X(t) \) caused by force \(-\frac{d\Pi}{dx}\) and of small fast oscillations \( \ddot{\xi}(t) \) caused by the force \( f \cos \Omega t \). The total motion is then given by the fast motion imposed over a slow one \( \dot{X}(t) = X(t) + \ddot{\xi}(t) \). The mean value of the slow-motion, \( \bar{X}(t) = \bar{X}(t) + \bar{\ddot{\xi}(t)} \), while the mean of the fast oscillation \( \ddot{\xi}(t) = \frac{\partial}{\partial t} \bar{\ddot{\xi}(t)} \), \( \dddot{\xi}(t)dt = 0 \), over that period is zero. Consequently, the averaged position of the particle is \( \bar{X}(t) = \bar{X}(t) + \bar{\ddot{\xi}(t)} \). Further substituting into the equation of motion and using the first term of the Taylor series expansion yields

\[ \frac{dX}{dx} + \frac{d\mu}{dx} = -\frac{d\Pi}{dx} + f \cos \Omega t + \frac{\partial}{\partial t} \frac{d(f \cos \Omega t)}{dx} \]

Equating the slow and fast terms separately, neglecting the terms on the right-hand side of Eq. (7) containing the small \( \dddot{\xi} \), one finds fast terms and integrates \( \mu = f \cos \Omega t \) with respect to time \( t \) yielding

\[ \dddot{\xi} = -\frac{f \cos \Omega t}{m \ddot{\xi}} \]

Further averaging concerning time and using \( \frac{\partial}{\partial t} \int_{0}^{\infty} f \cos \Omega t dt = 0 \) gives,
where $\Pi_{\text{eff}}$ is effective potential energy given by

$$
\Pi_{\text{eff}} = \Pi + \frac{1}{2m\omega^2} \oint_0^\infty f(\cos \omega t)^3 \, dt = \Pi + \frac{f^2}{4m\omega^2} = \Pi + \frac{m\nu^2}{2} \quad (10)
$$

The effect of fast vibrations $\xi$ when averaged over the period time $2\omega/\Omega$ is equivalent to the additional term $m\nu^2/2$ in the potential energy. Therefore, small, fast vibrations can be substituted by an additional term in the potential energy [12].

For the stability analysis and the phase transition analysis, it is essential to know that the effective term given by Eq. (10) can affect the state of the equilibrium of a system. Thus, vibrations can bring a system to a state of equilibrium. Thus, vibrations can affect the equilibrium and manifest as an effective stabilizing force.

The slow stabilizing force for the system V is given by

$$
V = -\frac{\partial}{\partial x} \left( \frac{1}{2m\omega^2} \oint_0^\infty f(\cos \omega t)^3 \, dt \right) = -\frac{\partial}{\partial x} \left( \frac{f^2}{4m\omega^2} \right) \quad (11)
$$

For an inverted pendulum on a harmonically vibrating (Acos$\Omega t$) foundation, the torsional spring constant $k = \frac{4m\omega^2}{\Omega^2}$. Thus, small fast vibrations can affect the equilibrium and manifest as an effective stabilizing force.

### 3.2. Phenomenological relationships for ultrasonic cavitation

One particularly interesting effect is the ultrasonic cavitation in liquid caused by acoustic (sound) waves of the ultrasonic frequency range (typically between 20 kHz and 10 MHz). Such ultrasonic waves can be seen as propagating fast low-amplitude oscillations of pressure and density in the liquid medium. The typical values of the pressure amplitude are in the range of $10^5$–$10^6$ Pa (1–100 atm), leading to negative (tensile) pressures in the liquid. Note that although low (and negative) pressures at ambient temperatures would correspond to the stable gas (vapor) phase on the water phase diagram, pure (homogeneous) water can withstand quite a significant negative (tensile) pressures on the order of $10^6$ Pa. This is because of the metastable state of superheated water, which can remain liquid above the boiling point due to the lack of new phase nucleation sites. The tensile strength (maximum absolute value of the tensile stress or negative hydrostatic pressure) of water corresponds to the so-called “spinalodal limit” on the water phase diagram, at which boiling occurs due to the homogenous nucleation of the vapor phase [30]. In practice, however, water is rarely homogeneous since it contains contamination particles, which become nucleation seeds of the new phase. Heterogeneities at the solid–liquid interface, such as asperities or cavities of the surface roughness, also contribute to the heterogeneous nucleation, which occurs at absolute values of tensile pressure much smaller than the spinalodal limit.

Consequently, ultrasound oscillations in water with the pressure amplitude of $10^7$ Pa cause bubble nucleation, particularly near a rough solid surface. The bubbles of water vapor and dissolved gases, whose typical diameter is 1–100 $\mu$m, oscillate under the action of the ultrasound. They grow at the pressure oscillation’s negative (tensile) phase and decrease during the positive (compressive) phase. Large bubbles can become unstable and tend to collapse, resulting in the bubble’s energy being released, causing high local temperatures (on the order of thousands K) and pressures at the center of collapse. The liquid–gas interface accelerates during the collapse, and its speed often exceeds the speed of sound in the liquid, causing shock waves. Such high temperatures and pressures and the shock waves modify the solid surface and material, facilitating various chemical reactions and mechanical treatment. This serves as the basis of the sonochemical treatment approach.

The Rayleigh–Plesset equation describes the dynamics of the spherical bubble with the radius $R$

$$
R \frac{d^2 R}{dt^2} + \frac{3}{2} \frac{dR}{dt} \frac{d^2 R}{dt^2} \Delta P \Delta R^2 + \frac{2\gamma}{\rho} R \frac{dR}{dt} = 0 \quad (12)
$$

Where $\rho$, $\nu$ , and $\gamma$ are the density, kinematic viscosity, and surface tension of water, and $\Delta P$ is the pressure difference inside and outside the bubble. In the static situation, there is an equilibrium radius of the bubble supplied by the Laplace equation, $R_0 = \frac{2\gamma}{\Delta P}$. And a critical radius above which the bubble can spontaneously grow corresponding to $\Delta P$ equal to the difference of the saturated vapor pressure and the actual liquid pressure [30,31]. However, when a harmonically oscillating ultrasound is applied, $\Delta P = \Delta P_0 - \Delta \cos \Omega t$ , the equilibrium size of the bubble oscillates triggering the nucleation and collapse of the bubbles.

For bubbles oscillating in the acoustic field created by ultrasound, the energy should be averaged over the period of oscillations

$$
\Pi_{\text{eff}} = \oint_0^\infty \left[ \frac{3}{4\pi R^3} \frac{dR}{dt} + \frac{4}{3} \pi R^2 (\Delta P_0 + \Delta \cos \Omega t) \right] dt \quad (13)
$$

where the dependency $R(t)$ should be obtained by integrating Eq.12. Note that the effective pressure acting on the bubble can be obtained by differentiating the energy

$$
\rho_{\text{eff}} = \frac{1}{4\pi R^2} \frac{d\Pi_{\text{eff}}}{dR} \quad (14)
$$

### 3.3. Separation of motions and kinetics of phase separation

The sonochemical reactions involve many processes acting simultaneously, including mechanical, thermal, electrical, photoluminescent, and chemical. The process is also not at a thermodynamical equilibrium. It is difficult to account for the exact contribution of all these effects. However, as in many systems where many processes act simultaneously, phenomenological relations of non-equilibrium thermodynamics can be written. Such relations would usually involve thermodynamic flow variables $J_\nu$, which in many cases can be linearly related to the so-called “thermodynamic forces,” $F_\nu$ [20]. Integrating Eq. (9) usually provides a term proportional to $(\Delta \Omega)^2$.

For the sonochemical reaction, one can assume that the intensity of the gas phase formation is dependent upon the energy density of the acoustic vibrations, $J_\nu = f(E_{ac}) \approx C_\nu F_{ac}$

$$
(15)
$$

where flow variable $J_\nu$ represents the volume of the gas phase (new bubbles) generated per second per unit volume and the force variable $E_{ac} = \rho_{ac} (\Delta \Omega)^2$ is the energy density of the acoustic vibrations per unit volume. The phenomenological constant $C_\nu$ reflects the assumption of the linear relation between the flow and force. This assumption is justified when the system is close to its local equilibrium.
Fig. 2. The SEM images of Cu-Zn alloy after ultrasonic treatment: a), d) control Cu-Zn alloy; b), e) Fraction 2A (70% amplitude); c), f) Fraction 2B (70% amplitude). The scale bars are 10 μm (a–c) and 2 μm (d–f).

Fig. 3. Anodic stripping voltammetry (parameters: amplitude is 10 mV, frequency is 10 Hz) of for (a) Zn$^{2+}$ and for (b) Cu$^{2+}$ of Cu-Zn alloy after ultrasonic treatment for samples 1–3 and its Fractions A and B.
At present research, three different amplitudes were tested: 30% (1), 70% (2), 90% (3). During experimental work, several amplitudes were tested, for amplitude less than 70%, fraction's separation was not observed. Two different fractions (fraction A and fraction B) were fabricated after sonication at 70% and 90% (named 2A and 2B, 3A and 3B, respectively). The Cu-Zn alloy formed micro size particles ca. 100 µm diameter, as seen in the scanning electron microscopy (SEM) images (Fig. 2). The morphology of particles has been changed by sonochemical treatment in 0.5 M NaOH, the particle concentration was 0.05 g/mL. Significant changes were observed visually. Differences in the morphology of particles could provide different surface properties as well. The main idea was to correlate the morphology changes with the antibacterial mechanism. Thus, we study the release of copper and zinc ions by the DPASV technique (Fig. 3). The results have demonstrated non-linear release behavior. Surprisingly, release of both ions faded at the maximal amplitude (90%), and it reaches maximum concentrations for both fractions (3A: Cu\(^{2+}\) – 0.0196 µmol/L, Zn\(^{2+}\) – 0.393 µmol/L, 3B: Cu\(^{2+}\) – 0.371 µmol/L, Zn\(^{2+}\) – 0.041 µmol/L) after treatment at 70%. It could be explained by forming a copper hydroxide and zinc hydroxide simultaneously, which affects each other and decreases the release of both.

The hypothesis was to study the biocide activity for samples that release copper and zinc ions simultaneously. Sample 2 in both fractions was chosen for the microbiology experiment. In our previous research, it has been shown that sonicated Zn particles demonstrate a string biocide activity[14]. Also, copper nanoparticles demonstrated an antibacterial mechanism[32-34] based on the toxic effect of the ability to exchange oxidation state between Cu\(^{+}\) and Cu\(^{2+}\). It is provided copper generates reactive oxygen species on the surface, which potentially damages a vital cell. Simultaneous release of copper and zinc ions should represent the synergistic biocide effect. Moreover, a very promising way to bacterial growth control is the usage of materials with gradient functions. Our scientific group previously suggested several model systems to programable material to control biological systems [14,35-37]. The critical factor is to find a material with dynamic properties that can be easily managed in situ to new-way materials[38]. Thus, depending on the mode of ultrasonic exposure, we can obtain fractions capable of releasing different amounts of copper or zinc ions. Particularly, fraction A predominantly releases copper ions (Fig. 4 a), while fraction B releases zinc ions. A well-known bacterial strain, E. coli, was chosen to test the Cu-Zn alloy fraction (Fig. 4).

As seen in Fig. 4, the biocidal activity of fraction B is much higher than that of fraction A. This effect could be due to the different phase composition of the obtained samples and, consequently, to the release of

![Bacterial cell](image)

**Fig. 4.** a) Putative mechanisms involved in bacteria-killing: direct destruction of the membrane by Cu\(^{2+}\)/Cu\(^{+}\) (black pathway); interactions between copper ions and glutathione under anaerobic conditions (blue path) and displacement of iron from iron-sulfur clusters (dark blue path), reactive oxygen species generation via hydrogen peroxide formation in the presence of Cu\(^{2+}\)/Cu\(^{+}\), inactivation of key proteins/enzymes, among which are those involved in the respiratory system as well as RNA and DNA damages. b) The biocidal activity of nanostructured Cu-Zn alloy (sample 2) was estimated using E. coli. c) The diameter of the inhibition zone of prepared Cu-Zn particles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
various ions. Particularly, it is found that fraction A predominantly releases copper ions. In contrast, fraction B predominantly releases zinc ions, and the concentration of copper ions is approximately two times lower than the concentration of copper ions released from fraction A. The copper particles were used as another control sample. Surprisingly, the inhibition zone of fraction A, which predominantly releases copper ions, is about four times smaller than the inhibition zone of pure copper alloy. However, even more, surprising is the biocidal activity of fraction B predominantly releases zinc ions. Particularly, it is found that fraction A predominantly releases copper ions from iron-sulfur clusters (dark blue path). The copper ions are also known to produce reactive oxygen species. Therefore, one of the ways for H₂O₂ production in reactions leading to the depletion of sulphydryl groups (R-SH) through a cycle between Cu²⁺ and Cu⁺ ions (Fig. 4 a). All these effects lead to the inactivation of key proteins/enzymes, which are those involved in the respiratory system, and oxidative stress and DNA/RNA damage result in bacterial cell death[39,42]. The antibacterial mechanism of zinc ions may be associated with the interaction between zinc ions and protein molecules that make up zinc fingers. Spontaneous binding of these proteins can disrupt bacterial metabolism and DNA synthesis[43,44].

Thus, in the present research, we have demonstrated the concept of fabrication the materials with gradient biocidal activity. The Cu-Zn alloy’s antibacterial mechanism can be easily varied by sonochemical treatment with fraction formation.

4. Conclusion

Fraction separation in an alloy due to the sonochemical treatment by ultrasonic cavitation is a complex process that involves many mechanisms. A phenomenological model of such a process can be predicted in line with models of vibrational phase separation, which can rely on the concept of separation of motions. The approach has been successful in various areas of non-linear mechanics and materials science. One particular application area is phase separation, which includes such diverse situations as filtering, vibrational multi-phase flow separation, and sorting of granular material.

Fast small-amplitude acoustic oscillations are substituted by an effective force, which is typically proportional to (ΔΩ)². An experimental study showed that the output of a new phase or fraction increases with increasing ΔΩ. Potential biomedical application of the newly formed phase due to its biocidal activity is discussed.

A representative of the bacterial species studied in the experiment, E. coli, is the causative agent of various diseases and nosocomial infections. Sometimes E. coli is the cause of complications after various surgical operations. In such cases, the use of the described materials in prosthesis or intravascular manipulations is very promising.

In addition, recently strains of E. coli bacteria have been characterized by resistance to antibiotics. The described technology for obtaining materials with a bactericidal effect can be used in the treatment of wounds and burns in the form of applications, as well as solutions for irrigation of mucous membranes. Therefore, the presented development is very relevant for both medicine and biotechnology.

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.

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