Ostapenko, Zhanna

Article

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Zhanna Ostapenko

DETERMINATION OF THE INFLUENCE OF THE SOUND CAPILLARY EFFECT ON THE PROCESS OF SOAKING VEGETABLE RAW MATERIALS IN THE ACOUSTIC EXTRACTOR

The object of research is the process of liquid movement in capillaries during the extraction of biologically active substances (BAS) from plant raw materials under the action of the sound capillary effect. A characteristic feature of vegetable raw materials is a large number of pores of the capillary type. Penetration of the extractant into the raw material occurs through capillaries and leads to the filling of cells and voids in it. The process of filling the capillaries and cell voids with the extractant can be quite long and significantly increase the extraction time as a whole.

It was established that the penetration of the extractant into the capillaries of plant raw materials is affected by ultrasonic vibrations that cause cavitation. Under the action of cavitation, which occurs in the ultrasonic field, the penetration of the extractant into narrow cavities and crevices is accelerated and deepened. This phenomenon is called the sound capillary effect. The analysis of literary sources showed that there are no data on the study of the conditions for the occurrence of the sound capillary effect and the effect on the speed of movement of liquid in the capillaries of ultrasonic pressure during the BAS extraction from plant raw materials. Numerical modeling was used to study the movement of liquid (extractant) in capillaries during the BAS extraction from plant raw materials under the conditions of ultrasound.

As a result of the conducted research, the conditions for the occurrence of ultrasonic cavitation in the process of BAS extraction from plant raw materials with the most common extractants, such as water and ethanol solutions, were found. The values of the amplitude of the sound pressure of the extractant, which occurs under the conditions of the sound capillary effect directly at the entrance to the capillary, were also found. The dependences of the sound capillary pressure on the diameter of the capillary for the most common extractants have been established. The influence of the sound-capillary effect on the speed of movement of the most common extractants in capillaries of different sizes is determined.

The obtained research results allow to quantitatively evaluate the influence of the sound-capillary effect on the movement of extractants in the capillaries of plant raw materials, on the rate of wetting of plant raw materials and the speed of mass exchange processes during extraction. These results can be used when choosing operating modes of existing and designing new equipment for the BAS extraction from plant raw materials under ultrasound conditions.

Keywords: *extraction of biologically active substances, plant raw materials, ultrasound, extractant, sound capillary effect, capillary, cavitation.*

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1. Introduction

The application of the effect of ultrasonic radiation on the process of extracting biologically active substances (BAS) from plant raw materials is a proven means of intensifying mass exchange in a liquid medium [1, 2]. In the process of ultrasonic extraction, the phenomenon of acoustic cavitation occurs, which is caused by the propagation of ultrasonic pressure waves. Due to acoustic cavitation, a sharp destruction of cell walls and cell membranes of plant material occurs, which can significantly increase the extraction rate [3, 4]. At the same time, as a result of acoustic cavitation, liquid circulation flows and turbulence are formed, which facilitate the penetration of solvents into cellular materials, lead to a significant increase in the rate of mass exchange, and contribute to an increase in the yield of BAS [5, 6].

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Most of the work involving ultrasound extraction has been done using a low-frequency ultrasound emitter and an ultrasound bath. Ultrasonic baths are more widely used because direct sonication can affect the quality of the extracted ingredients and can be harmful for thermolabile materials because they cause intense cavitation [5].

The conducted studies confirmed that ultrasound can be used to increase the efficiency of extraction and reduce the BAS extraction time [7].

In addition to the beneficial effect of ultrasound on the yield and kinetics of extraction, it allows changing the experimental conditions, for example, lowering the temperature and pressure [8].

Extraction of phytopreparations is carried out mainly from crushed and dried plant material. Changes occur in plant materials during drying. The cell juice turns into a dry residue, the inside of the cell is filled with air. Cell walls and membranes of cell organoids turn into porous membranes after drying. In the process of preliminary soaking, the penetration of the extractant into the raw material occurs due to capillary forces. Wetting is related to the rate of air displacement from the cells. If the capillary ends in the cell, then the air is kept in it until it dissolves in the extractant. Ultrasound helps dissolve air.

The rate of penetration of the extractant into the raw material depends on the size of the capillaries and pores formed as a result of the destruction of cells during the grinding of the raw material, but mainly on the size of the capillaries and pores that are in the intact cells and intercellular space.

Cell membranes have a wide range of thickness and depend on the type of plants and their organs. The shells consist of micro- and macro-fibrils, between which there are micropores and capillaries. Micro-fibrils have a width of about 25 nm, and the width of macro-fibrils ranges from 200–400 nm [9].

In addition, there are micropores of 0.1–0.2 μm in the cell membranes that connect cells, forming intercellular passages along which the slow movement of the extractant from cell to cell can occur [10, 11].

In general, macro-pores and capillaries have a width ranging from tens to hundreds of nanometers.

An important factor in the occurrence of the sound capillary effect is the formation of a stationary flow of liquid through the capillary. That is, the liquid penetrates the capillaries at a certain speed. The sound-capillary effect is observed under ultrasonic action and cavitation occurs near the capillary sections. The reason for the stationary flow of the extractant is the constant pressure near the capillary section [12].

The aim of research is to determine the speed of movement of the extractant in the capillaries of plant raw materials under the conditions of the sound capillary effect. Also, in the research process, it is necessary to establish:

1. Conditions for the occurrence of ultrasonic cavitation in the process of BAR extraction from plant raw materials by the most common extractants.
2. Dependencies of the sound pressure amplitude on the properties of the extractant.
3. Dependence of the sound capillary pressure on the properties of the extractant and the size of the capillaries.
4. Dependencies of the speed of movement of the extractant in the capillaries under the action of sound-capillary pressure on the dimensions of the capillaries and the properties of the extractant.

The obtained results will help to evaluate the influence of the sound-capillary effect on the speed of liquid movement in the capillaries of plant raw materials, which affects the speed of wetting of plant raw materials and the speed of mass exchange processes during extraction. In addition, the obtained results can be used in the design of extraction equipment.

2. Materials and Methods

The subject of research is the effect of sound-capillary pressure on the movement of the most common extractants in the capillaries of plant raw materials.

The object of research is the process of liquid movement in capillaries during the extraction of biologically active substances (BAS) from plant raw materials under the action of the sound capillary effect.

The conditions for the occurrence of ultrasonic cavitation were determined using mathematical dependencies obtained on the basis of solving the equations describing the deformation of a gas bubble in an infinite ideal incompressible liquid [13, 14]. The equation for calculating the sound capillary pressure is derived from the assumption that the force acting on the cavitation cloud under the capillary section is determined by the potential energy gradient. And the potential energy of the cavitation medium of a certain volume is proportional to the energy density of the ultrasound-induced field [12, 15].

For ultrasonic cavitation to occur there must be steam-gas bubbles in the extractant, the size of which exceeds R_{cr}, m [15, 16]:

$$R_{cr} = \sqrt{3} \cdot R_o \cdot \left[\frac{R_o}{2\sigma} \cdot \left(P_{st} + \frac{2\sigma}{R_o} \right) \right]^{1/2}, \tag{1}$$

where P_{st} – the hydrostatic pressure, Pa; σ – coefficient of surface tension of the extractant, N/m; R_o – the initial radius of the bubble, m.

The minimum amplitude of the sound pressure $P_{m0\min}$, Pa necessary for the occurrence of cavitation, in the presence of steam-gas nuclei with a radius R_0 in the extractant, can be determined by the equation [16]:

$$P_{m0\min} = P_{st} + \frac{2 \cdot \pi \cdot \sigma}{3\sqrt{3} \cdot R_o}. \tag{2}$$

The bubble collapse time is determined by the equation, s [16]:

$$t_c = \frac{0.36}{f} \left(1 - \frac{P_{st}}{P_{m0\min}} \right) \times$$
$$\times \left[2.9 \cdot \frac{P_{st}}{P_{m0\min}} - 3.4 \left(\frac{P_{st}}{P_{m0\min}} \right)^2 + 0.6 \right]^{-1/2}. \tag{3}$$

The bubble expansion time is determined by the formula [16]:

$$t_e = \frac{0.4}{f} \cdot \left(1.9 - \frac{P_{st}}{P_{m0\min}} \right). \tag{4}$$

The average sound pressure amplitude P_{m0}, Pa is determined by the formula [16]:

$$P_{m0} = \frac{1}{\Delta t} \cdot \int_{t_{max}}^{t_{min}} P_{m0\min} \cdot (\sin \omega t) dt, \quad (5)$$

where $\Delta t = t_{max} - t_{min}$ – the duration of the existence of the cavitation bubble, s; t – time, s; ω – the circular frequency of ultrasonic oscillations.

Dependence of the speed of movement of the extractant in the capillaries on their size and properties of the extractant.

To determine the sound capillary pressure, it is necessary to establish the ratio of the density of acoustic energy W_{us}, J/m^3 and the energy concentrated in a unit volume of the moving extractant W_m, J/m^3.

The acoustic energy density is determined by the formula [15]:

$$W_{us} = \frac{P_{mo}}{2 \cdot \rho \cdot c^2}, \quad (6)$$

where P_{mo} – the amplitude of the sound wave pressure at the level of the capillary section, Pa; ρ – density of the extractant, kg/m^3; c – the speed of sound in the extractant, m/s.

When cavitation occurs under the section of the capillary in its channel, there is a steady movement of the extractant with a speed of v, m/s.

The energy concentrated in a unit volume of the moving extractant is determined from the equation [15]:

$$W_m = \frac{\rho \cdot v^2}{2}, \text{ J/m}^3. \quad (7)$$

Then let's determine the coefficient α, which characterizes the ratio of the energy concentrated in a unit volume of the moving extractant to the acoustic energy density [15]:

$$\alpha = \frac{W_m}{W_{us}}. \quad (8)$$

To determine the attenuation coefficient β, which characterizes the decrease in amplitude in the sound wave in the capillary channel, let's use the equation [15]:

$$\beta = \frac{2\pi}{d_{cap}}, \quad (9)$$

where d_{cap} – the capillary diameter, m.

Sound capillary pressure is determined by the formula, Pa [15]:

$$P_{sc} = \frac{4}{\pi \cdot d_{cap}^2} \cdot \alpha \cdot \beta \cdot \frac{P_{mo}^2}{\rho \cdot \ ^2} \cdot V, \quad (10)$$

where V – the volume of a particle of cavitationally excited liquid (extractant) placed near the capillary section [15]:

$$V = \frac{1}{4} \cdot \pi \cdot d_{cap} h_{ch}, \quad (11)$$

where h_{ch} – the immersion depth of cavitation cavities in the capillary channel, m.

The speed of movement of the extractant in the capillaries depending on the sound capillary pressure and the geometric dimensions of the capillary and the properties of the extractant is determined from the equation [11]:

$$\upsilon = \frac{(P_{sc} - P_{st}) \cdot R_{cap}^2}{8\mu \cdot l_{cap}}, \quad (12)$$

where R_{cap} – the capillary radius, m; μ – the coefficient of dynamic viscosity of the extractant, Pa·s; l_{cap} – the capillary length.

3. Results and Discussion

The process of BAS extraction from plant raw materials is associated with the penetration of the extractant into the raw materials under the influence of capillary forces. A characteristic feature of vegetable raw materials is a large number of pores of the capillary type. Penetration of the extractant into the raw material occurs through capillaries and leads to the filling of cells and voids in it. The process of filling the capillaries and cell voids with the extractant can be quite long and significantly increase the extraction time as a whole. Ultrasonic radiation is used to accelerate this process. Under the action of cavitation, which occurs in the ultrasonic field, the penetration of the extractant into narrow cavities and crevices is accelerated and deepened due to the sound capillary effect.

The influence of the sound-capillary effect on the speed of liquid movement in capillaries is used in various technological processes, in particular, for the impregnation of fibrous materials. The literature provides data on the sound capillary pressure and the speed of water movement in capillaries with a diameter of 0.34 mm to 0.7 mm. In vegetable raw materials, the diameters of the capillaries lie in the range of 0.025 mm to 0.4 mm. In addition to water, ethanol solutions are used as extractants, for example. There are no data on the study of the conditions for the occurrence of the sound-capillary effect and the effect on the speed of liquid movement in capillaries, ultrasonic pressure during the extraction of BAR from plant raw materials under ultrasound conditions.

The study of the process of liquid movement in capillaries during the extraction of biologically active substances (BAS) from plant materials under the action of the sound capillary effect was carried out on the basis of mathematical modeling of the process using mathematical ratios to determine the conditions for the occurrence of ultrasonic cavitation, the amplitude of sound pressure, sound capillary pressure, the speed of movement of the extractant in the capillaries. The mathematical model of the process is represented by equations (1)–(12). A numerical experiment was carried out based on a mathematical model for the quantitative assessment of the conditions for the occurrence of the sound capillary effect and the influence on the speed of liquid movement in capillaries, ultrasonic pressure during the BAS extraction from plant raw materials under ultrasound conditions. The results of the numerical experiment are presented in the Table 1 and Fig. 1–6.

A numerical experiment was carried out for the extraction processes of biologically active substances from plant raw materials with the most common extractants, such as

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water, 40 % ethanol solution in water and 70 % ethanol solution in water. Conditions for extraction:

1. Process temperature: $t=20$ °C; $t=30$ °C; $t=40$ °C.
2. Static pressure $P_{st}=0.4\cdot10^5$ Pa.
3. Frequency of ultrasonic vibrations $f=50$ kHz.
4. The initial radius of the bubble $R_0=1\cdot10^{-6}$ m.

The results of the numerical experiment are given in Table 1.

Table 1

Calculation results

Extract agent	Water			40 % ethanol solution			70 % ethanol solution		
Temperature	20 °C	30 °C	40 °C	20 °C	30 °C	40 °C	20 °C	30 °C	40 °C
$R_{cr}\cdot10^6$, m	1.847	1.85	1.852	2.000	2.009	2.018	2.038	2.049	2.062
$P_{m0\min}\cdot10^{-4}$, Pa	10.8	10.61	10.42	5.628	5.507	5.386	5.144	5.023	4.902
$P_{m0}\cdot10^{-4}$, Pa	0.6107	0.6834	0.7553	2.153	2.174	2.194	2.231	2.247	2.262

Analyzing the results of a numerical experiment, it can be established that the minimum radius of a bubble capable of growth, when using water as an extractant, depends little on temperature and is $1.85\cdot10^{-6}$ m on average. In the case of using solutions of ethanol in water of different concentrations, the minimum radius of a bubble capable of growth on average is is $2\cdot10^{-6}$ m.

The minimum sound pressure amplitude for water and ethanol solutions in water of different concentrations differs significantly. This is explained by a significant difference in the values of the surface tension of water and ethanol solutions in water. The same tendency can be observed for the average sound pressure amplitude values. A comparison of the obtained results with those given in [13, 14] allows to establish that the specified conditions for the extraction process from plant raw materials ensure the occurrence of ultrasonic cavitation and the sound capillary effect.

Taking into account that the sizes of capillaries in plant raw materials range from tens to hundreds of nanometers, it is necessary to perform a quantitative assessment of the influence of capillary sizes and properties of the extractant on the value of sound capillary pressure. To determine the level of sound-capillary pressure and the speed of movement of the extractant, the dimensions of the capillaries were chosen, which are the most characteristic for plant raw materials [9]:

$d_{cap}=25\cdot10^{-9}$ m;

$d_{cap}=100\cdot10^{-9}$ m;

$d_{cap}=200\cdot10^{-9}$ m;

$d_{cap}=400\cdot10^{-9}$ m;

Fig. 1–3 show the graphs of the dependence of the sound capillary pressure R_{sc}, Pa on the capillary diameter d_{cap}, mm.

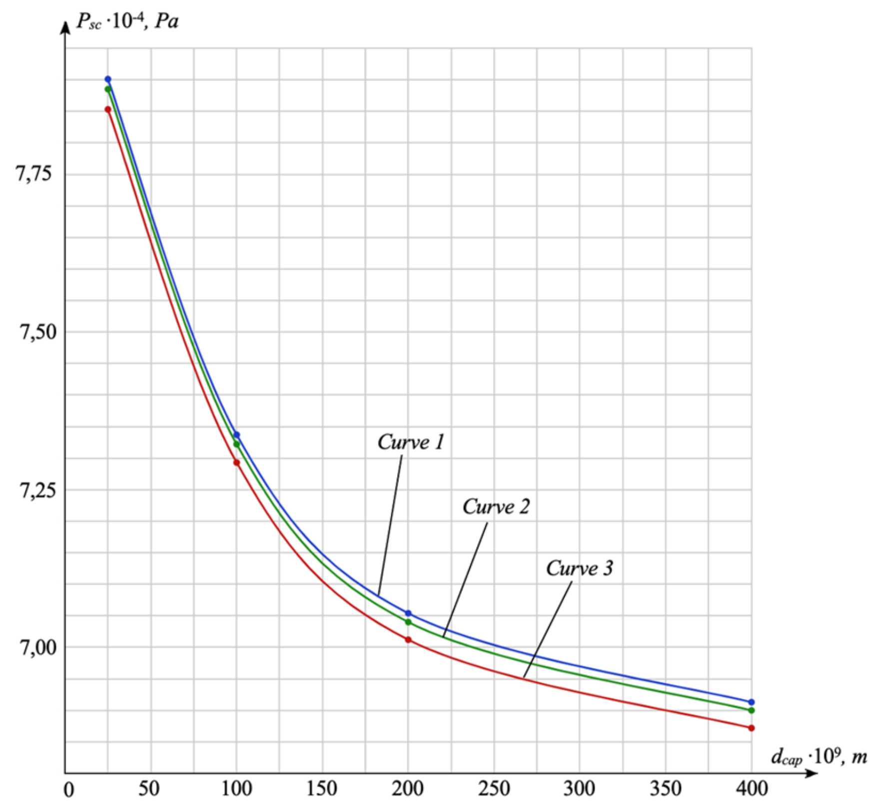

Fig. 1. Dependence of sound capillary pressure P_{sc}, Pa on capillary diameter d_{cap}, m for water as an extractant: Curve 1 – at a temperature of 20 °C; Curve 2 – at a temperature of 30 °C; Curve 3 – at a temperature of 40 °C

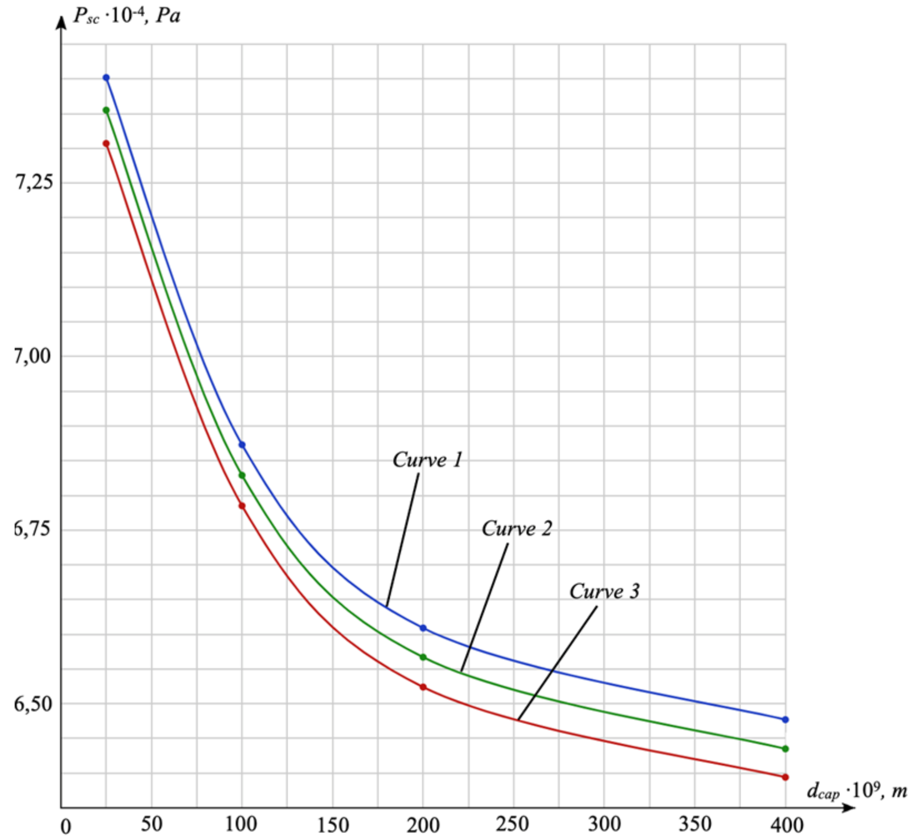

Fig. 2. Dependence of sound capillary pressure P_{sc}, Pa on capillary diameter d_{cap}, m for 40 % ethanol solution as an extractant: Curve 1 – at a temperature of 20 °C; Curve 2 – at a temperature of 30 °C; Curve 3 – at a temperature of 40 °C

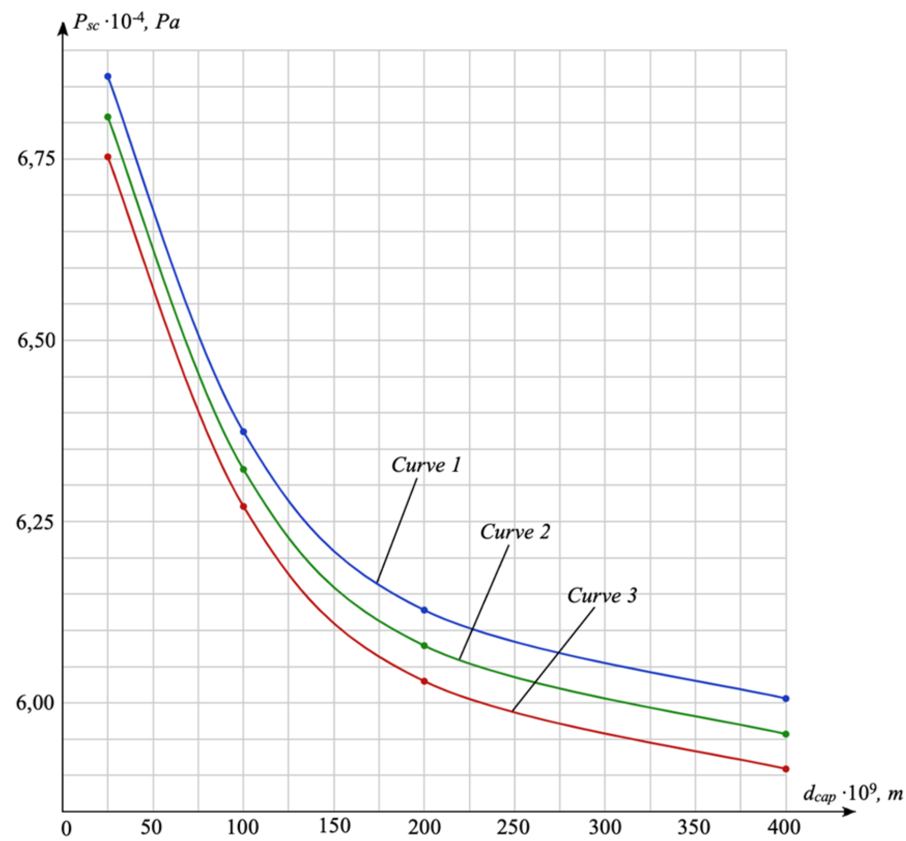

Fig. 3. Dependence of sound capillary pressure P_{sc}, Pa on capillary diameter d_{cap}, m for 70 % ethanol solution as an extractant: Curve 1 – at a temperature of 20 °C; Curve 2 – at a temperature of 30 °C; Curve 3 – at a temperature of 40 °C

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Analysis of graphs in Figs. 1–3 shows that for the given conditions, the acoustic capillary pressure is the largest for capillaries with a diameter $d_{cap} = 25\cdot 10^{-9}$ m for all extractants. The smallest pressure is observed at the diameter of the capillaries $d_{cap} = 400\cdot 10^{-9}$ m. When the temperature of the extractant increases, the acoustic capillary pressure decreases, which is explained by the decrease in the values of the coefficients of dynamic viscosity and surface tension of the extractants. A comparison of the nature of the dependence of sound-capillary pressure on the size of the capillaries of plant raw materials and the values of sound-capillary pressure shows slight deviations from the experimental data given in [15].

Fig. 4–6 show the dependence of the penetration rate of the extractant into the capillaries of plant raw materials on the size of the capillaries.

Analysis of graphs in Figs. 4–6 shows that for all used extractants, the rate of penetration of the extractant into the capillaries increases with the increase in the temperature of the extractant, which is explained by the decrease in the values of the coefficient of dynamic viscosity, and therefore, the decrease in the motor resistance.

Analyzing the rate of penetration of the extractant into the capillaries of plant raw materials of different diameters and the size of solid particles of plant raw materials in general, it is possible to conclude that the extractant penetrates quite intensively and the wetting of solid particles of plant raw materials due to sound capillary pressure.

The practical significance of the obtained research results is that these results make it possible to quantitatively assess the influence of the sound-capillary effect on the movement of extractants in the capillaries of plant raw materials, on the rate of wetting of plant raw materials and the rate of flow of mass exchange processes during extraction. The obtained results can be used when choosing the operating modes of existing equipment and designing new equipment for extraction under the conditions of ultrasound action.

The obtained results of studies of the influence of the sound-capillary effect on the movement of the extractant in the capillaries of plant raw materials, taking into account the peculiarities of its structure, namely, the presence of capillaries whose sizes vary in a wide range from 25 microns to 400 microns.

The results of the research can be used to evaluate the movement of a liquid (extractant), such as water or ethanol solutions of different concentrations, in capillaries, the sizes of which lie in the range from 25 microns to 400 microns.

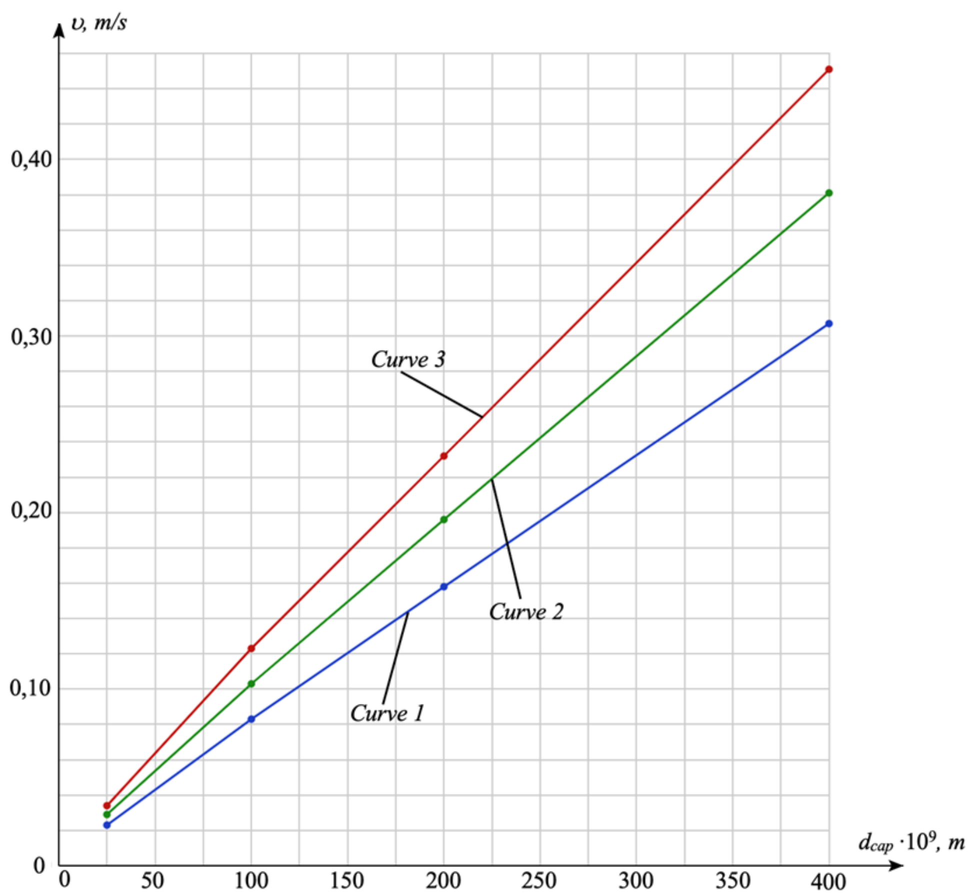

Fig. 4. Dependence of the penetration rate v, m/s of the extractant into the capillaries on the diameter of the capillaries d_{cap}, m for water:
Curve 1 – at a temperature of 20 °C;
Curve 2 – at a temperature of 30 °C;
Curve 3 – at a temperature of 40 °C

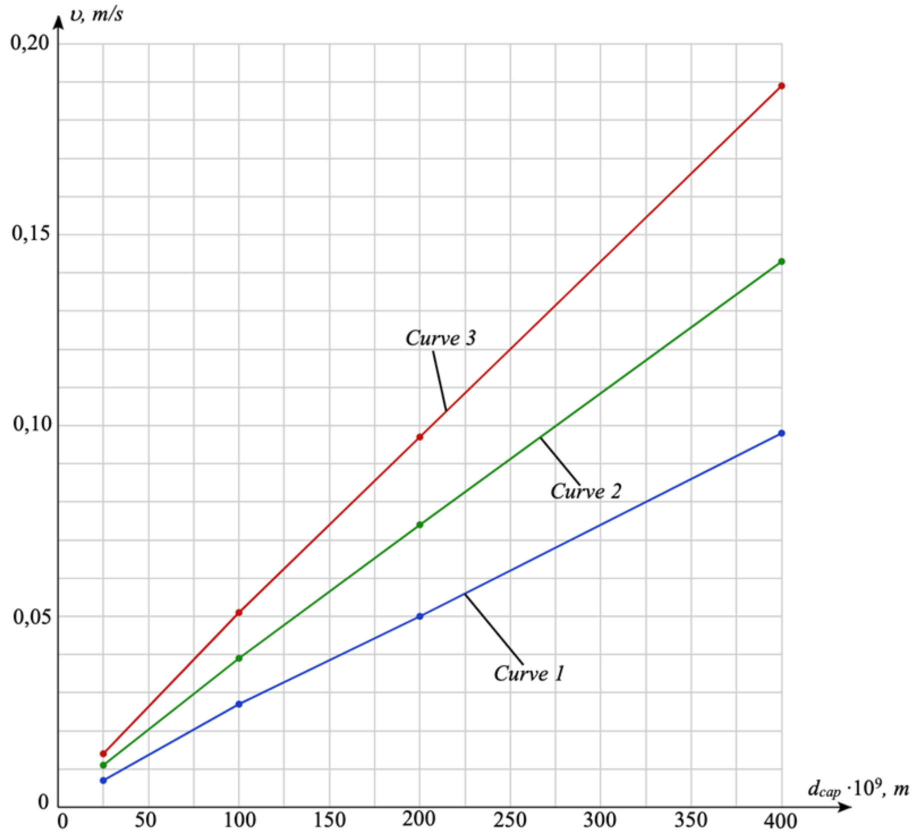

Fig. 5. Dependence of the penetration rate *v*, m/s of the extractant into the capillaries on the diameter of the capillaries d_{cap}, m for 40 % ethanol solution: Curve 1 – at a temperature of 20 °C; Curve 2 – at a temperature of 30 °C; Curve 3 – at a temperature of 40 °C

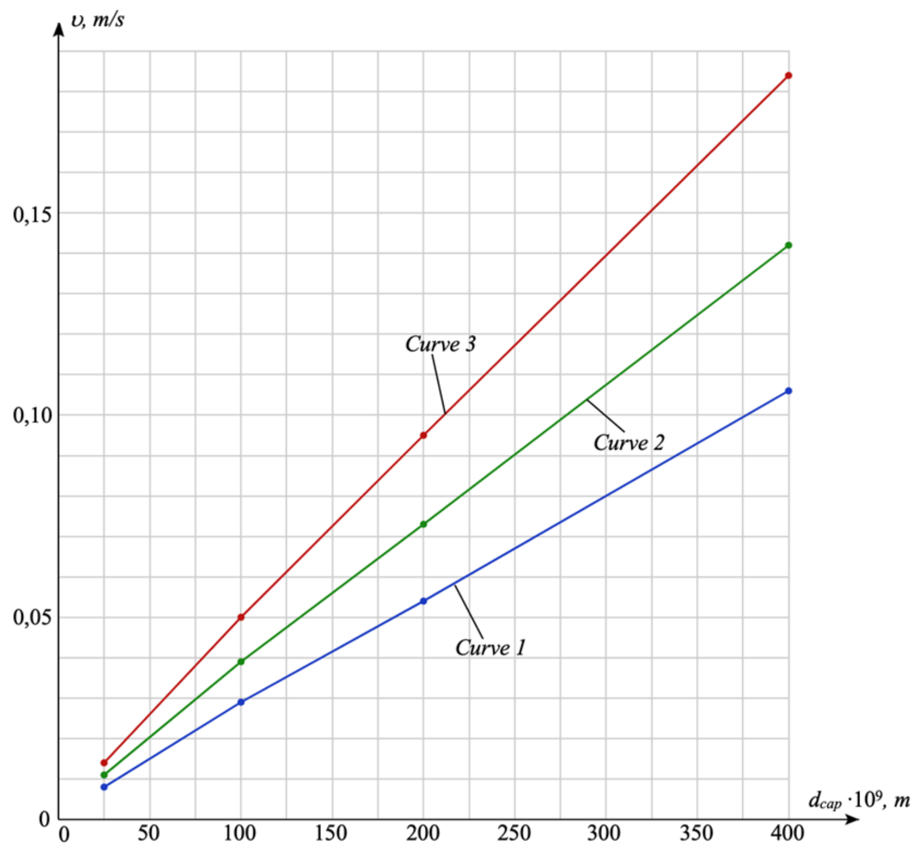

Fig. 6. Dependence of the penetration rate *v*, m/s of the extractant into the capillaries on the diameter of the capillaries d_{cap}, m for 70 % ethanol solution: Curve 1 – at a temperature of 20 °C; Curve 2 – at a temperature of 30 °C; Curve 3 – at a temperature of 40 °C

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4. Conclusions

The conditions for the occurrence of ultrasonic cavitation in the process of extraction with water, 70 % and 40 % solutions of ethanol in water are determined. It was established that the minimum radius of a steam bubble capable of growth is $1.85 \cdot 10^{-6}$, m for water and $2 \cdot 10^{-6}$, m for ethanol solutions. The minimum and average sound pressure amplitudes for water and ethanol solutions are significantly different. At the same time, the values of the minimum and average amplitudes are close to the values given in the works [14, 15], devoted to the study of the movement of liquid in capillaries under the action of the sound capillary effect.

The obtained dependences of the sound capillary pressure on the diameter of the capillary during extraction from plant raw materials with different extractants. The sonic capillary pressure ranges from $6 \cdot 10^4$ Pa to $8 \cdot 10^4$ Pa. The nature of the dependence of the sound capillary pressure and the value of the sound capillary pressure are close to the experimental ones given in [15].

The dependences of the extractant movement speed on the diameter of the capillary were obtained. The speed of movement of the extractant lies in the range from 0.01 m/s to 0.5 m/s. Given that the length of the capillary is commensurate with the diameter, the penetration of the extractant into a separate capillary will take place in a short time, which in general will significantly speed up the soaking of plant material in the extraction process.

Conflict of interest

The author declares that she has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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Zhanna Ostapenko, *Postgraduate Student, Senior Lecturer, Department of Biotechnology and Engineering, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, e-mail: zhanna.ost@gmail.com, ORCID: https://orcid.org/0000-0003-0949-9912*