Investigating the impact of ultrasonic exposure frequency and reduced pressure on the liquid evaporation process

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Abstract. Theoretical and experimental investigations of the ultrasonic exposure (USE) frequency impact on the liquid evaporation process are carried out. Investigations were carried out under reduced pressure in a vacuum chamber. A refined physico-mathematical model of the USE thermodynamic process is developed. The dependences of the change in mass and temperature of various liquids (distilled water, alcohol mixture, kerosene TS-1) on the USE frequency and external pressure are obtained. The effect of a sudden liquid "explosion" at certain USE frequency and external pressure values is discovered. The results of physical and mathematical modeling are obtained as the dependence of the change in liquid temperature on the USE frequency and external pressure. The results of physical and mathematical modeling and experimental research are analyzed and compared. The obtained results can be used for drying various materials and cleaning surfaces.

1. Introduction

USE is a promising way to accelerate the heat and mass transfer during evaporation of liquids [1]. Currently, there is a limited amount of investigation into the effects of USE on the heat and mass transfer processes under reduced pressure. Existing investigations show that the heat transfer coefficient during USE and atmospheric pressure increases by about 15–20% due to acoustic cavitation [2, 3].

The literature review on the USE effect on liquid has shown that currently there are few works considering the dynamics and evaporation of a liquid under USE and reduced pressure simultaneously. In work [4], the study was made of vertically and horizontally superimposed ultrasound vibrations with a frequency of 40 kHz affecting the dynamics and evaporation of various liquids droplets (dimethylformamide, isopropyl alcohol, water) located on teflon or glass substrates. The influence of horizontally and vertically applied ultrasound vibrations leads to a significant reduction in the droplets lifetime and affects their behavior (sticking, sliding).

In work [5], the results of theoretical and experimental investigations of the liquid evaporation process under reduced pressure are presented. The investigations were carried out at different rates of decompression, all the liquid remaining in a superheated metastable state and returning to a stable state due to evaporation and heat exchange with the environment. However, investigations were conducted without additional USE.

Earlier investigations of the liquids evaporation process under USE and thermal effects [6] under reduced pressure [7] showed that the influence of these factors increases the liquid evaporation intensity.
Since the existing investigations were carried out with a constant ultrasonic vibrations frequency of 25 kHz, it is of particular interest to investigate the influence of other ultrasound frequencies and reduced pressure on the liquids evaporation process.

2. Problem statement

It is proposed to carry out theoretical and experimental investigations of the USE frequency impact on the liquids evaporation process at a constant USE amplitude and reduced pressure in a closed volume.

To solve this problem, it is necessary:
– to develop a refined physico-mathematical model of the USE thermodynamic process based on the initial physico-mathematical model of the thermodynamic process described in work [7];
– to conduct numerical experiments to assess the effect of the USE frequency and reduced pressure on the liquids evaporation process, using the refined physico-mathematical model;
– to develop the scheme of the experimental stand, the program and methods of conducting experiments, to modernize the existing experimental stand [8];
– to conduct experiments and a comparative analysis of the theoretical and experimental investigations results.

Initial data for investigations are as follows:
– model liquid: distilled water, alcohol mixture and kerosene TS-1 (table 1);
– boundary liquid position in a cylindrical container (diameter 35 mm, height 8 mm): free liquid surface film, with an area of 962 mm$^2$;
– initial mass of the liquid: 7 g;
– initial temperature of the liquid: 18...21 °C;
– pressure in a closed volume (vacuum chamber): from 101 kPa to 0.2 kPa;
– USE frequency: 22 kHz, 30 kHz, 36 kHz;
– mass of the ultrasonic radiator 22kHz – 1482 g, 30 kHz – 945 g, 36 kHz – 770 g;
– material container of the ultrasonic radiator: titanium;
– oscillations amplitude for the container bottom surface: 2 μm.

Termination conditions of the experiment are:
– formation of the ice crust on the surface of the liquid;
– complete evaporation of the liquid;
– 10 minutes after the beginning of a experiment.

Table 1. Parameters of model liquids.

| Parameters of the liquid | Distilled water | Alcohol mixture | Kerosene TS-1 |
|--------------------------|----------------|----------------|--------------|
| 1. Density, kg/m$^3$     | 997            | 940            | 814          |
| 2. Speed of sound liquid, m/s | 1485          | 1300           | 1315         |
| 3. Specific heat of vaporization, J/kg | 2.3*10$^6$ | 0.9*10$^6$ | 0.2*10$^6$ |
| 4. Specific heat capacity, J/(kg*K) | 4220          | 3480           | 2000         |

3. Mathematical model

Theoretical investigations of the USE frequency and reduced pressure effect on the process of various liquids evaporation were carried out using the developed physical and mathematical model [7].

The proposed physico-mathematical model allows us to determine the change in liquid temperature at USE and changes in external pressure in a closed volume in the form of dependence:

$$\Delta T = \left[ \frac{K_p S \rho_m C_m 2 \pi^2 f^2 A_m}{\left( \frac{\rho_0 (t)}{\rho_1} \right)^{\frac{3}{2}}} \left( 2 \pi f A_m + \frac{4 \sqrt{\rho_0 (t)}}{\rho_1} \right) \right] t - q c \int_0^t \frac{p_n (1 - \varphi)}{p_0 (t)} dt - \frac{C_{l} m l c_{l} + m c_{r}}{1}$$

(1)
where $K_p$ is the pressure ratio; $S$ is the radiator surface area; $\rho_m$ is the average density of the vapor-air mixture; $C_m$ is the average sound velocity in the vapor-air mixture; $f$ is the frequency of US; $A_m$ is the amplitude of the oscillations; $c_r$ is the coefficient depending on the body shape and is a function of the Reynolds number; $S_l$ is the surface area of the liquid; $\rho_l$ is the liquid density; $p_0$ is external barometric pressure; $\gamma$ is the adiabatic index of air; $q$ is the specific heat of vaporization; $c$ is the proportionality coefficient; $S_e$ is the surface area of evaporation; $p_h$ is the saturated vapor pressure of the liquid; $\varphi$ is the relative humidity; $m_l$ is the liquid mass; $c_l$ is the specific heat of the liquid; $m_r$ is the mass of the radiator; $c_r$ is the specific heat capacity of the material from which the radiator is made.

The coefficients $K_p$ and $K$, obtained empirically, are added to formula (1). The dimensionless pressure coefficient $K_p$ regards the change in the relative load of the radiator from the USE amplitude at the external pressure change:

$$K_p = \frac{P_p}{P_0},$$  \hspace{1cm} (2)

where $P_p$ is the external pressure; $P_0$ is the atmospheric pressure.

Change in external pressure $P_p$:

$$P_p = P_0 + \rho_l g h,$$  \hspace{1cm} (3)

where $P_0$ is atmosphere pressure; $\rho_l$ is liquid density; $g$ is gravitational acceleration; $h$ is the depth of the radiator working end immersion into the liquid, or the liquid level height above the radiator working end.

The coefficient $K$ determines the ratio for the densities of the resulting vapor-air mixture elements when cavitation forms [9]:

$$\frac{\rho_g}{\rho_l} = \frac{C_g}{C_l} = K,$$  \hspace{1cm} (4)

where $\rho_g$ is gas or vapor-air density; $\rho_l$ is liquid density; $C_g$ is acoustic velocity in gas; $C_l$ is acoustic velocity in the liquid.

Average value for the product of the density $\rho_m$ by the acoustic velocity $C_m$ in the resulting gas-liquid mixture [10]:

$$\rho_mC_m = \left[ \rho_g \left( \frac{K}{K+1} \right) + \rho_l \left( \frac{1}{K+1} \right) \right] \left[ C_g \left( \frac{K}{K+1} \right) + C_l \left( \frac{1}{K+1} \right) \right].$$  \hspace{1cm} (5)

4. Experimental stand

The scheme of the experimental stand is shown in figure 1.

![Figure 1. Scheme of the experimental stand](image-url)

The experimental stand includes:

- vacuum chamber with a viewing window;
- vacuum pump;
– ultrasonic piezoceramic radiators with a frequency of 22, 30 and 36 kHz (figure 2);
– pneumatic valve installed between the vacuum chamber and the vacuum pump;
– chromel-alumel thermocouple, for measuring the temperature of the liquid;
– thermometer;
– laboratory scales;
– pressure sensor (convection vacuum gauge);
– personal computer;
– video camera.

![Figure 2. Piezoceramic ultrasonic radiator with a frequency of 22 kHz located at the laboratory scale in a vacuum chamber](image)

Before starting the experiments, an ultrasonic radiator with a specific frequency of 22, 30 or 36 kHz is selected and installed on a laboratory scale located in a vacuum chamber. A model liquid is poured into the ultrasonic radiator tank (distilled water, alcohol mixture or kerosene TS-1). The mass of the model liquid is determined by laboratory scales installed in a vacuum chamber. The thermocouple is lowered into the liquid, then the temperature of the liquid is determined by a temperature meter connected to a personal computer during the whole experiment. The door of the vacuum chamber is closed, the pneumatic valve is opened, the vacuum pump and the ultrasonic radiator are simultaneously activated. The generator is used to set the power value, corresponding to the required oscillations amplitude for the tank bottom of 2 μm. The pressure in the vacuum chamber is monitored using a pressure sensor installed in the line between the vacuum pump and the vacuum chamber. Through the viewing window in the vacuum chamber, the behavior of the liquid is recorded using a video camera (vaporization, boiling, formation of a crust of ice, etc.) during the whole experiment.

When conducting experiments, the measurement error is:
- ± 1.0 °C temperature of the liquid, which is determined using a chromel-alumel thermocouple;
- ± 2.0 % pressure in the vacuum chamber, which is determined using a convection vacuum gauge;
- ± 0.05 g mass of liquid, which is determined using laboratory scales.

5. Experimental results
The results of the theoretical and experimental investigations are shown in figures 3 – 5.

Theoretical investigations were carried out using the engineering mathematical software PTC Mathcad 15.0.
Figure 3. Change of distilled water temperature under conditions of decreasing pressure in the vacuum chamber with a constant oscillations amplitude at the bath bottom of 2 μm and frequency of: 1 – 22 kHz (experiment); 2 – 30 kHz (experiment); 3 – 36 kHz (experiment); 4 – 22 kHz (equation (1)); 5 – 30 kHz (equation (1)); 6 – 36 kHz (equation (1)); 7 – pressure in the vacuum chamber

The mass of evaporated distilled water at a frequency of 22 kHz is 3.75 g; 30 kHz – 4.55 g; 36 kHz – 4.95 g.

Figure 4. Change of alcohol mixture temperature under conditions of decreasing pressure in the vacuum chamber with a constant oscillations amplitude at the bath bottom of 2 μm and frequency of: 1 – 22 kHz (experiment); 2 – 30 kHz (experiment); 3 – 36 kHz (experiment); 4 – 22 kHz (equation (1)); 5 – 30 kHz (equation (1)); 6 – 36 kHz (equation (1)); 7 – pressure in the vacuum chamber

The mass of the evaporated alcohol mixture at a frequency of 22 kHz is 4.5 g; 30 kHz – 4.9 g; 36 kHz – 5.3 g.
Figure 5. Change of kerosene TS-1 temperature under conditions of decreasing pressure in the vacuum chamber with a constant oscillations amplitude at the bath bottom of 2 μm and frequency of: 1 – 22 kHz (experiment); 2 – 30 kHz (experiment); 3 – 36 kHz (experiment); 4 – 22 kHz (equation (1)); 5 – 30 kHz (equation (1)); 6 – 36 kHz (equation (1)); 7 – pressure in the vacuum chamber

The mass of evaporated kerosene TS-1 at a frequency of 22 kHz is 6.25 g; 30 kHz – 6.3 g; 36 kHz – 6.32 g.

6. Results and discussion

In mathematical and physical modeling, the liquids temperatures have the same pattern of changes (figures 3 – 5).

In figure 3, it can be seen that with an increase in the USE frequency from 22 kHz to 36 kHz, the temperature of distilled water increases on average by 14 % from the initial time moment to the time moment of 1 … 1.5 minutes. From 1.5 minutes until the end of the experiment, the temperature of the liquid decreases until an ice crust forms on the surface of the liquid, followed by its sudden destruction. In this case, the higher the frequency of the USE, the faster the ice crust forms on the surface of the liquid. The moment of crust destruction is shown in figure 6.

The decrease in the liquid temperature after the first minute of the experiment is explained by the loss of thermal energy from the liquid at the reduced pressure value of 30 kPa and below in the vacuum chamber. At the same time, there is periodic dusting, boiling and a sudden surge of liquid.

At the third minute of the experiment, when the pressure in the vacuum chamber is 4 … 6 kPa, a short-term “explosion” of the liquid is observed at frequency of ultrasonic 22 kHz and 30 kHz (figure 7). At a frequency of 36 kHz, this effect is not observed.

The mass of evaporated distilled water with an increase in the USE frequency from 22 kHz to 36 kHz increases by about 30%. With an initial mass of distilled water being 7 g, 4.95 g evaporated in no time at the USE frequency of 36 kHz.
Figure 6. The destruction of the ice crust on the surface of distilled water

Figure 7. Short-term “explosion” of the liquid during the experiments

Figure 4 shows that the alcohol mixture evaporated at the 7th minute of the experiment, the liquid temperature drops below 0 °C, and at the end of the experiment it is at most -14.9 °C. Comparative analysis with the results of distilled water evaporation showed that the temperature of distilled water also drops below 0°C after 7 minutes of the experiment, with an ice crust forming and destructing on the surface of the liquid and subsequent experiment stopping. With an increase in the USE frequency, the temperature of the liquid decreases faster, i.e. an increase in the USE frequency results in greater heat release. For example, with an increase in the USE frequency from 22 kHz to 30 kHz and 36 kHz, the temperature of the alcohol mixture at the end of the experiment is -7.20 °C, -11.7 °C and -14.9 °C, respectively.

At the fourth minute of the experiment, when the pressure in the vacuum chamber is 3 … 4 kPa, a similar short-term “explosion” of the liquid is observed at the USE frequency values of 30 kHz. At a frequency of 22 kHz and 36 kHz, this effect is not observed.

The mass of the evaporated alcohol mixture at the USE frequency of 36 kHz is 5.3 g., which is greater than the mass of evaporated distilled water at the same frequency. However, an increase in the USE frequency from 22 kHz to 36 kHz increases the mass of the evaporated alcohol mixture by only 17%, and distilled water by 30%.

When the frozen surface of distilled water is destroyed, some ice fragments fly out of the bath, therefore the mass of distilled water at the end of the experiment is not accurate.

As seen in figure 5, when kerosene TS-1 evaporates, an increase in the USE frequency from 22 kHz to 36 kHz does not affect the temperature significantly. Experimental curves 4, 5 and 6 in figure 5 are almost the same. The temperature of kerosene at the fifth minute of the experiment drops below 0 °C and at the end of the experiment it is -2 °C at most. At the same time, kerosene almost completely evaporates in about 6.5 minutes. On the bath walls there remain 0.68 … 0.75 grams of kerosene. The effect of sudden “explosion” for the kerosene surface is not observed.

In further investigations, it is planned to consider the dynamics of the internal liquid pressure, which in some cases leads to the “explosion” of the liquid.

7. Conclusions
A refined physico-mathematical model of the USE thermodynamic process has been developed, allowing us to consider the change in the relative load of the radiator from the USE amplitude as the external pressure changes.

Theoretical and experimental investigations of the USE frequency and external pressure effect on the liquid evaporation process showed that the obtained dependences of the change in liquid temperature have the same pattern.
The USE frequency and low pressure affect the temperature of the evaporated liquid. The degree of influence depends on the type of evaporated liquid, namely on its physico-chemical properties. For example, increasing the USE frequency from 22 kHz to 36 kHz, the temperature of distilled water increases by 14%, alcohol mixture by 11% and kerosene TS-1 by 3%.

The effect of a sudden short-term "explosion" of the liquid surface (distilled water, alcohol mixture) was detected at certain values of USE frequency and pressure in the vacuum chamber, for example, for distilled water, this effect is observed at the USE frequency of 22 kHz and 30 kHz and a pressure in the vacuum chamber of 4…6 kPa; for the alcohol mixture - 30 kHz and a pressure of 3…4 kPa. When evaporating kerosene TS-1, this effect is not observed. In further investigations, it is planned to consider the dynamics of the internal liquid pressure, which in some cases leads to the liquid “explosion”.

The USE frequency and reduced pressure affect the liquid evaporation rate, which was estimated by the mass values of the liquid before and after the experiments. For example, when the USE frequency rises from 22 kHz to 36 kHz, the mass of evaporated distilled water increases by 30%, and alcohol mixture by 17%. Kerosene TS-1 evaporates almost completely in 6.5 minutes.

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