

# Impact of ultrasonic exposure and external pressure in a closed volume on the temperature of the evaporated liquid

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**Abstract.** The influence of ultrasonic exposure (UE) and external pressure on the process of heat and mass transfer during liquid evaporation is studied, which is an urgent task, since UE is widely used in various technological processes, and the parameters of UE and external pressure determine their effectiveness. Experimental studies of the effect of UE and pressure in a vacuum chamber on the temperature of the evaporated liquid at a constant ultrasonic frequency of 25 kHz and an amplitude of ultrasonic vibrations of 2  $\mu\text{m}$  were carried out. The dependences of the change in the relative load on the amplitude of the oscillations of the bottom of the bath with a change in pressure in a closed volume are obtained, and coefficients are determined that refine the thermal physico-mathematical model of the wave processes in a liquid with ultrasound and a change in external pressure in a closed volume. The liquid temperature from the initial moment of time sharply increases from 27.7 °C to 32.8 °C, and then, when the pressure in the vacuum chamber reaches 45 kPa, it gradually decreases until an ice crust forms on the liquid surface. A comparative analysis of the results of mathematical modeling, taking into account the use of refinement coefficients and the results of experimental studies showing that the discrepancy between the temperature of the evaporated liquid, from the initial moment of time to the moment of formation of cavitation bubbles on the surface of the liquid, is 8%. The discrepancy between the temperature of the evaporated liquid from the moment of formation of cavitation bubbles to the freezing point of the liquid is up to 50%, which is explained by the error in measuring the temperature of the liquid with thermocouples during the formation of cavitation bubbles.

## 1. Introduction

The parameters of UE (amplitude, frequency) and external pressure for most technological processes determine their efficiency, for example, the quality of cleaning or the rate of chemical reactions, etc., which are considered in works [1–3].

External pressure and oscillations amplitude for the “radiator-environment” system are interrelated due to the present masses of liquid, bath and radiator, while the intensity of cavitation processes in the liquid depends on the optimal ratio of these parameters [4–6]. It should be noted that in works [7, 8] the consideration is made of the processes at external pressures from atmospheric one and above, with the impact level estimated by calculating the processes of cavitation bubbles formation, their development and influence on the UE energy efficiency.

Various publications consider the possibility to use reduced external pressure efficiently for some types of ultrasonic technologies, for example, in the chemical [9, 10] and rocket-space industries [11].

In publication [12] the influence of reduced external pressure and temperature on the liquid viscosity in vacuum boilers for boiling and non-boiling liquids in the absence of acoustic effects is



considered. Moreover, with an increase in the heat flow, the heat transfer coefficient is shown to rise together with viscosity during bubble boiling of the liquid.

Thus, the aim of this theoretical and experimental investigation can be formulated as determining the influence of the UE amplitude and reduced external pressure in a closed volume on the change in liquid temperature.

## 2. Theory

Earlier investigations of the heat and mass transfer processes during the evaporation of liquid with a free surface under a joint UE and reduced pressure showed [11] that the proposed physical-mathematical model for these processes behavior describes them rather similar to the real ones at small values of the UE amplitudes, as long as the linearity of processes in the liquid is retained [13].

The existing physical-mathematical model [11] makes it possible to determine the change in the temperature of the liquid under UE and changing external pressure in a closed volume in the form of the relation:

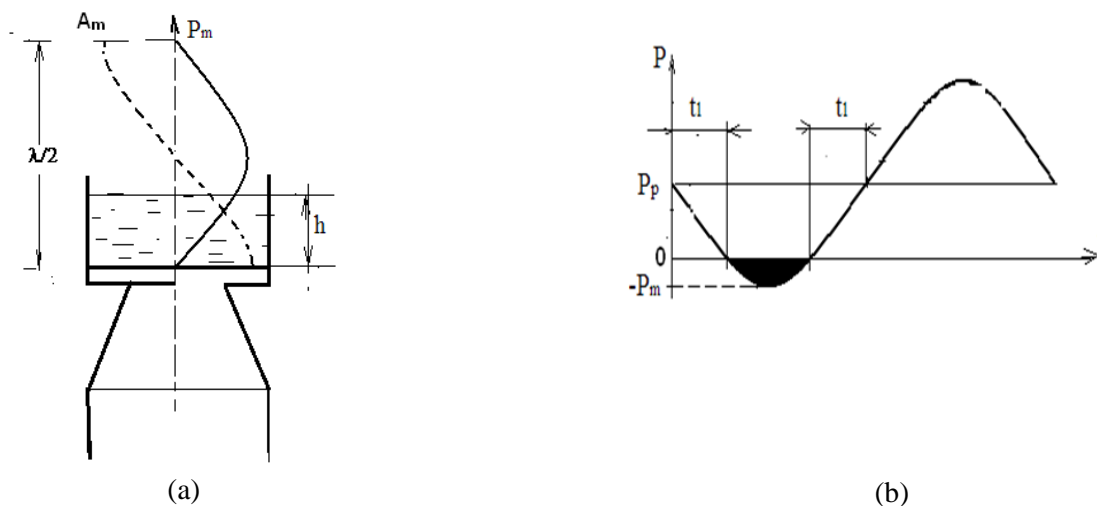
$$\Delta T = \frac{\left[ S_a \rho_l C_l 2\pi^2 f^2 A_m^2 - c_R S \frac{\rho_l}{2} \left( 2\pi f A_m + \frac{4}{9\pi^2} \sqrt{\frac{3p_0(t)\gamma}{\rho_l}} \right)^3 \right] t - q c S_s \int_0^t \frac{p_n(1-\varphi)}{p_0(t)} dt}{m_l c_l + m_r c_r}, \quad (1)$$

where  $S_a$  is radiator surface area;  $\rho_l$  is liquid density;  $C_l$  is sound velocity in liquid;  $f$  is UE frequency;  $A_m$  is oscillation amplitude of the radiator bath bottom;  $C_R$  is coefficient depending on the body shape and is a function of the Reynolds number;  $S$  is liquid surface area;  $p_0$  is external barometric pressure;  $\gamma$  is air adiabatic index;  $q$  is specific heat of vaporization;  $c$  is coefficient of proportionality;  $S_s$  is evaporation surface area;  $p_n$  is liquid vapor pressure;  $\varphi$  is relative humidity;  $m_l$  is liquid mass;  $c_l$  is specific heat of the liquid;  $m_r$  is radiator mass;  $c_r$  is specific heat of the radiator material.

To improve the physical-mathematical model [11], it is necessary to conduct additional theoretical and experimental investigations to obtain results in the form of refinement coefficients considering the influence of the UE amplitude and the reduced pressure.

It is obvious that the physical nature of the acoustic environment changes during the exposure since the cavitation process is that of vapor-gas formations creation in a liquid environment [14].

At the acoustic wave emission by the radiator end surface, the first assumption is that the main wave propagation occurs in the region of spatial volume confined by the radiating surface area as shown in figure 1(a).



**Figure 1.** Scheme of wave processes near the working end of the radiator. (a) Spatial wave processes:  $\lambda$  is acoustic wave length,  $h$  is the liquid level height;  $P_m$  is maximum acoustic pressure in the liquid;  $A_m$  is oscillation amplitude of the radiator bath bottom. (b) Temporary wave processes:  $P_p$  is external pressure;  $P_m$  is maximum acoustic pressure in the liquid;  $2t_1$  is temporal region of linear elastic deformations in the liquid

Temporal wave processes occurring in a virtual volume (volume occupied by the liquid and supplemented up to the half of the UE wavelength) [shown in figure 1(a)] can be viewed in accordance with figure 1(b), where the non-blackened area is the elastic deformations area for the considered virtual volume.

Obviously, there is a limiting value for the negative pressure of the acoustic field in the liquid  $P_m = P_p$ , which still maintains the continuity of the liquid stretching processes in a virtual volume.

The change of the pressure  $P_p$  that must be overcome for the wave process to go beyond the linear region (figure 1(b) interval  $t_1$ ) is:

$$P_p = P_0 + \rho gh, \quad (2)$$

where  $P_0$  is atmosphere pressure;  $\rho$  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.

As shown in figure 1(b), the continuity of wave processes in a liquid environment is maintained only within  $2t_1 + T/2$  for the period  $T$  of the output frequency. As for the shaded zone, during the remaining time of the output frequency period equal to  $T/2 - 2t_1$ , a gap forms in the virtual liquid rod. The ratio of these times is denoted by the coefficient  $K$ :

$$K = \frac{\frac{T}{2} - 2t_1}{\frac{T}{2} + 2t_1} = \frac{1 - 4ft_1}{1 + 4ft_1}. \quad (3)$$

Let us make the second assumption that the ratio of linearity processes times in the environment and liquid rupture time is proportional to that of the phase states times for the liquid in contact with the radiator working surface – liquid and vapor-air mixture (since a vapor-air mixture is formed when cavitation occurs). The ratio of the elements density in the resulting mixture is determined by the coefficient  $K$  [15]:

$$\frac{\rho_g}{\rho_l} = \frac{C_g}{C_l} = K, \quad (4)$$

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

Average value for the product of the density  $\rho_m$  by the sound speed  $C_m$  in the resulting gas-liquid mixture [16]:

$$\rho_m C_m = \left[ \rho_g \left( \frac{K}{K+1} \right) + \rho_l \left( \frac{1}{K+1} \right) \right] \left[ C_g \left( \frac{K}{K+1} \right) + C_l \left( \frac{1}{K+1} \right) \right]. \quad (5)$$

To determine the duration  $t_1$  the following equation is used:

$$\sin \omega t_1 = \frac{P_p}{P_m}, \quad (6)$$

$$\omega t_1 = 2\pi f t_1 = \arcsin \frac{P_p}{P_m} = \arcsin \frac{(P_0 + \rho gh)}{\rho_l C_l \omega A_m}, \quad (7)$$

where  $\omega$  is circular resonant frequency of a piezoceramic ultrasonic radiator;  $f$  is UE frequency.

Equations (6) and (7) make sense when  $P_m \geq P_p$  (blackened area in figure 1(b)). When  $P_m < P_p$  (not blackened area in figure 1(b)), one moves to a linear area, where  $t_1 = T/4$ .

From figure 1(a) it follows that it is necessary to consider the spatial changes of the main process parameters, in particular, the changes of acoustic pressure in the liquid at its various liquid levels in the bath.

At the liquid level  $h$ , the value of the current pressure developed in the liquid is:

$$P_h = P_m \sin 2\pi h / \lambda, \quad (8)$$

where  $\lambda = c/f$  is ultrasound wavelength for the given liquid;  $c$  is speed of ultrasound propagation;  $f$  is UE frequency.

From equations (3), (7) and (8) the coefficient  $K$  is found:

$$K = \frac{\pi - 2 \arcsin \mu}{\pi + 2 \arcsin \mu}, \quad (9)$$

where  $\mu = \frac{(P_0 + \rho gh)}{\rho_l C_l \omega A_m \sin 2\pi h / \lambda}$ .

When cavitation bubbles appear, the expression for the equivalent mechanical load in the gas-liquid mixture is correct:

$$r_e = \rho_m c_m S, \quad (10)$$

where  $S$  is liquid surface area.

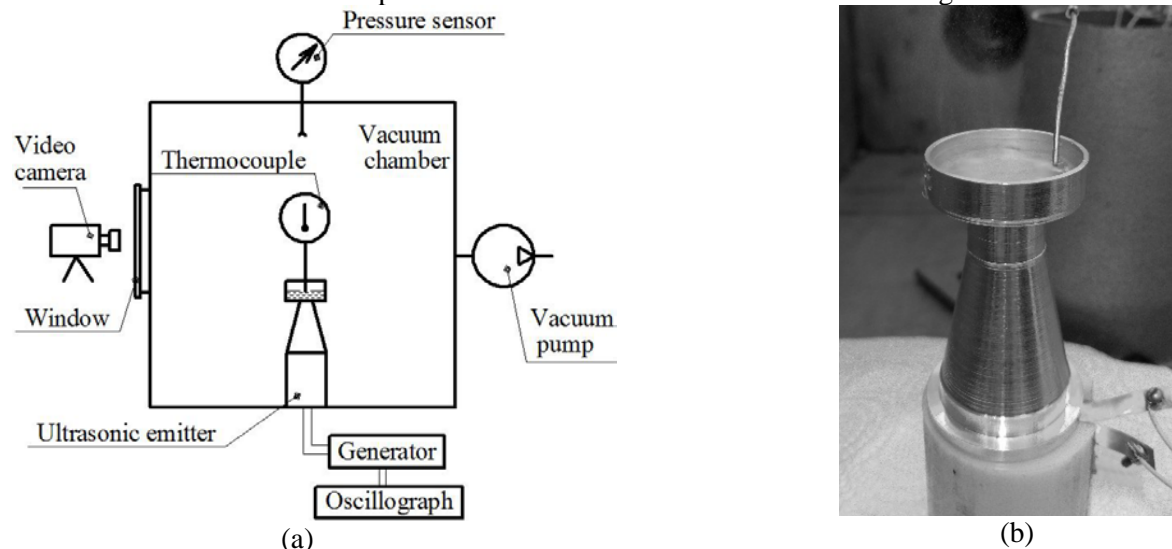
Relative load is:

$$\frac{r_e}{r_l} = \frac{\rho_m c_m S}{\rho_l c_l S} = \frac{[\rho_g (\frac{K}{K+1}) + \rho_l (\frac{1}{K+1})][c_g (\frac{K}{K+1}) + c_l (\frac{1}{K+1})]}{\rho_l c_l}, \quad (11)$$

where  $r_l$  is equivalent mechanical load in the liquid.

### 3. Experimental model

To determine the dependence of the relative load on the oscillations amplitude for the radiator bath bottom at various pressure values in a closed volume and to confirm the mathematical modeling results, the evaporation of the liquid in a vacuum chamber at UE is investigated experimentally. The scheme of the test bench and a piezoceramic ultrasonic radiator are shown in figure 2.



**Figure 2.** Test bench. (a) The scheme of the test bench to investigate the effect of UE and pressure in the vacuum chamber on the temperature of the evaporated liquid. (b) Piezoceramic ultrasonic radiator with a frequency of 25 kHz

When conducting experimental investigations, the following initial data have been used: liquid used is distilled water; liquid mass of 0,005 kg; ultrasonic frequency of 25 kHz; ultrasonic amplitude of 2  $\mu\text{m}$ ; pressure in the vacuum chamber from 101 kPa to 0.5 kPa; initial liquid temperature of 27.7  $^{\circ}\text{C}$ ; surface area of the ultrasonic radiator is  $9,8 \times 10^{-4} \text{ m}^2$ .

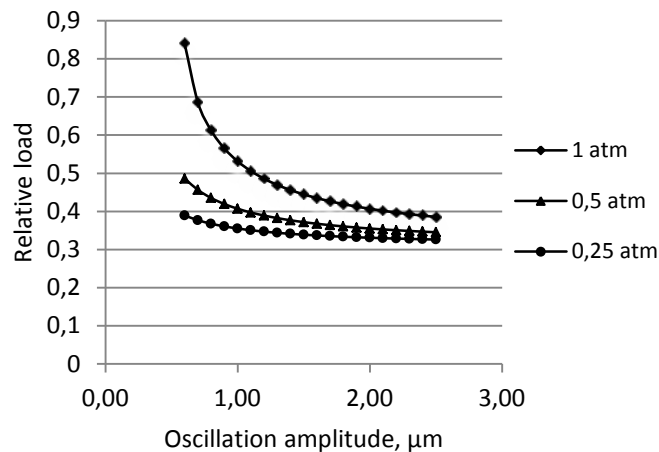
The experiment procedure is as follows. Before starting the experiments, distilled water is poured into the bath of the piezoceramic ultrasonic radiator. A thermocouple is lowered into distilled water to determine the temperature of the liquid during the experiments. The ultrasonic radiator with distilled water is placed in a vacuum chamber, then a vacuum pump is turned on and the pressure decreases from 101 kPa to 0.5 kPa. Simultaneously, the generator and the oscilloscope are turned on, providing the oscillations amplitude for the bath bottom equal to 2  $\mu\text{m}$ . Through the inspection window in the vacuum chamber, the liquid evaporation process is visualized using a video camera. This allows observing characteristic changes in the liquid behavior (dusting, ice crust formation, active boiling, etc.).

The pressure in the vacuum chamber is determined by a pressure sensor installed in the pipeline between the vacuum pump and the vacuum chamber.

The experiment is terminated in 10 minutes after the start or when an ice crust forms on the liquid surface.

#### 4. Results and discussions

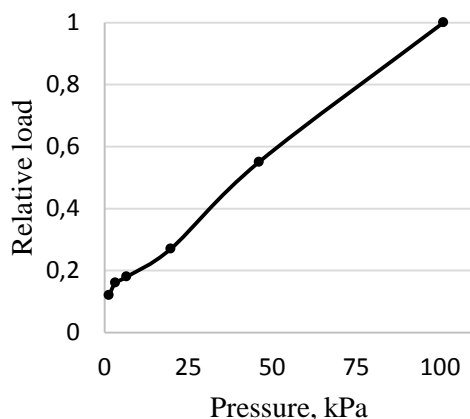
Using equation (11), the dependences of the relative load change on the oscillations amplitude of the radiator bath bottom have been obtained for the case when the pressure in a closed volume changes (shown in figure 3).



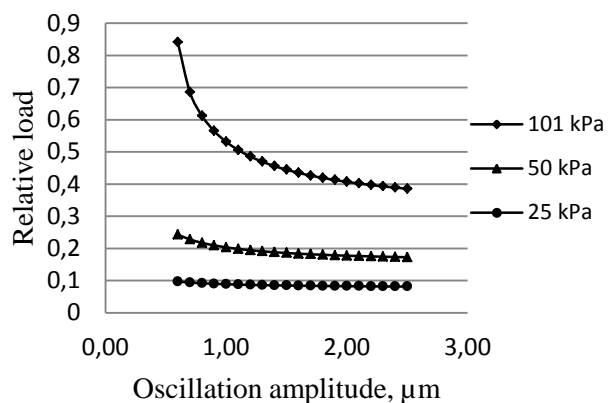
**Figure 3.** The dependence of the relative load on the oscillations amplitude of the radiator bath bottom at various pressure values in a closed volume

From the above given results in figure 3, it can be seen that at amplitudes of 2 – 3  $\mu\text{m}$ , the external pressure does not affect the equivalent load of the radiator significantly. To improve these results on the basis of the existing physical model [11, 17], additional experiments were conducted to assess the influence of external pressure in the vacuum chamber on the relative wave impedance of the liquid.

In figure 4(a) the results of additionally conducted experiments are shown as the dependence of the change in the relative load of the radiator on one in the external pressure in the vacuum chamber at a constant oscillations amplitude of 1  $\mu\text{m}$ .



(a)



(b)

**Figure 4.** Results of experimental (a) and theoretical (b) investigations: (a) experimental dependence of the relative load change on the change in external pressure; (b) refined theoretical dependence of the relative load change on the oscillations amplitude for the radiator bath bottom at different external pressure values in a closed volume

As seen from figure 4(a), the dependence of the relative load for the radiator on the change in external pressure is almost linear, therefore a dimensionless pressure coefficient is additionally

introduced, refining the dependence of the change in relative load on the oscillations amplitude at various pressure values in a closed volume [figure 4(b)]:

$$K_p = \frac{P_p}{P_0}. \quad (12)$$

Then expression (10) takes the following form:

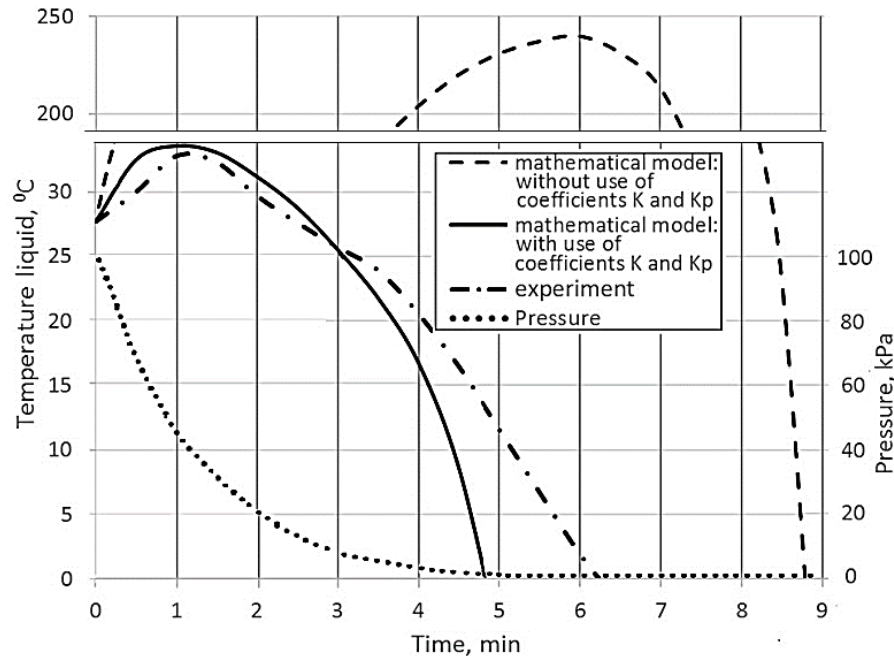
$$r_e = K_p \rho_m C_m S. \quad (13)$$

With the obtained coefficients  $K$  and  $K_p$  refining the physical-mathematical model of the wave processes in the liquid at changing amplitude of the ultrasonic wave and pressure in a closed volume [11], the change in the liquid temperature will look like this:

$$\Delta T = \frac{\left[ K_p S \rho_m C_m 2\pi^2 f^2 A_m^2 - c_r S \frac{\rho_l}{2} \left( 2\pi f A_m + \frac{4}{9\pi^2} \sqrt{\frac{3p_0(t)\gamma}{\rho}} \right)^3 \right] t - qcS_s \int_0^t \frac{p_n(1-\varphi)}{p_0(t)} dt}{m_{lcl} + m_{rcr}}. \quad (14)$$

The coefficient  $K$  in formula (14) is included in the product  $\rho_m C_m$  (5).

A comparative analysis of the mathematical modeling results with and without the refinement coefficients  $K$  and  $K_p$  (shown in figure 5) showed that the temperature of the liquid differs by more than 200 °C.



**Figure 5.** Comparative analysis of the mathematical modeling results considering the use of refinement coefficients and the experimental studies results with an ultrasonic oscillations amplitude of 2  $\mu\text{m}$

The maximum temperature of the liquid, when using coefficients, is 33.5 °C (the liquid freezes at 5 minutes), and without them it is 239.8 °C (shown in figure 5), while the liquid freezes after 8 minutes.

A comparative analysis of the mathematical modeling results considering the use of refinement coefficients and experimental investigations findings (shown in figure 5) has shown that the curves of changes in the liquid temperature almost converge. From the initial time point, the liquid temperature increases sharply from 27.7 °C to 32.8 °C, and then, when the pressure in the vacuum chamber reaches 50 kPa, it gradually decreases until an ice crust forms on the surface of the liquid. From the initial time moment to 3rd minute, the maximum discrepancy of the results is 8%. From the time point of 3rd minute to the freezing point of the fluid, the discrepancy is up to 50% (shown in figure 5). This can be explained by the fact that when conducting experiments from 3rd minute to the freezing point of the

liquid, an active formation of cavitation bubbles is observed on the liquid surface, which affects the reliability of thermocouple readings.

## 5. Conclusions

As a result of theoretical and experimental investigations, the dependences of the change in the relative load on the oscillations amplitude have been obtained for the radiator bath bottom at the pressure change in a closed volume. These data made it possible to determine the coefficients improving the thermal physical-mathematical model for the influence of the UE amplitude and the reduced external pressure on the temperature of the evaporated liquid. The reliability of the mathematical modeling results in terms of the refinement coefficients obtained is confirmed by the experimental investigations findings. The discrepancy between the obtained temperatures of the evaporated liquid is 8%. The influence of the UE amplitude on the liquid leads to an increase in the liquid temperature to a certain value of external pressure (approximately 50 kPa), while a reduced external pressure leads to a decrease in the partial pressure of liquid vapor above the free surface and a decrease in the boiling point.

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