Experimental investigations of the parameters of liquid evaporation process under acoustic-vacuum exposure

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Abstract. Experimental investigations of the process of liquid evaporation under conditions of acoustic-vacuum exposure were conducted. Based on the obtained values of the evaporating liquid mass and the liquid vapor pressure in a closed container, a resonance effect is revealed. The emergence of the resonance effect is characterized by the active boiling of the liquid when the frequency of the system "steam-gas mixture + cupola + vacuum chamber + liquid layer" coincides with the frequency of the acoustic exposure under conditions of reduced external pressure. To measure the vapor pressure of the liquid, a cupola was introduced into the experimental stand, which makes it possible to increase the vapor pressure of the liquid and register its value with the equipment used. The calibration characteristic of laboratory scales is obtained as a dependence of the change of cargo weight on the pressure values in the vacuum chamber. Using the obtained calibration characteristic of laboratory scales operating under acoustic-vacuum exposure, the values of liquid mass change are obtained at different values of external pressure in the vacuum chamber. The results obtained can be applied in the field of acoustic-vacuum drying and cleaning of different surfaces.

1. Introduction

The evaporation of a liquid under acoustic-vacuum exposure is characterized by a metastable state with periodic heating, cooling, boiling, and, ultimately, freezing of the liquid. Since acoustic and vacuum exposure accelerates the process of heat and mass transfer, they are often used in many industries, for example, for food drying [1, 2], seawater desalination [3], drying of contaminated wastes, including nuclear ones [4], etc.

The conducted patent information review showed that most of the works are aimed at the separate study of the acoustic or vacuum effects on the process of heat and mass transfer during liquid evaporation. At the same time, the joint acoustic-vacuum effect has practically not been studied. For example, in works [5, 6] it is shown that acoustic impact in the evaporator at constant external atmospheric pressure increases the heat transfer coefficient by 15–20%. In [7] a one-dimensional mathematical model of instantaneous evaporation of a liquid at depressurization of an evaporation chamber without acoustic influence has been developed.

The investigations of the evaporation process of liquids under joint acoustic-vacuum exposure were carried out in [8–10]. A mathematical model of the process under study was developed [8, 9], the effect of a sudden short-term "boiling" of the liquid surface (distilled water, alcohol mixture) at certain values of the frequency of acoustic exposure and pressure in the vacuum chamber (VC) was revealed [10]. For example, for distilled water, this effect is observed at acoustic exposure frequencies of 22 kHz and 30 kHz and pressure in the VC of 4–6 kPa; for alcohol mixture, it is 30 kHz at a pressure of 3–4 kPa. This effect is not observed during the evaporation of kerosene TS-1.
The results of existing investigations are limited by the values of temperatures and pressures of the investigated medium under acoustic and vacuum exposure. In this case, the mass of an evaporating liquid is an important parameter in the process under investigation, which shows the evaporation intensity at different values of external pressure and parameters of acoustic exposure (frequency, amplitude). To determine the mass of the evaporating liquid under acoustic-vacuum exposure is a difficult task. This is due to the formation and destruction of a large number of bubbles, in which drops are ejected and a liquid film separates from the bottom of the bath in which the liquid is placed. In addition, a change in external pressure affects the operation of the metrological equipment (laboratory scales) and, as a consequence, the readings of the mass values of the evaporated liquid. Therefore, experimental results are often presented as the initial and final mass of the liquid [7, 11]. Intermediate values are selected based on forecasting using the results of mathematical modeling [7].

Another no less important parameter of the investigated process is the pressure of the steam-gas mixture above the liquid surface, according to the values of which it is possible to estimate the dynamics of the liquid evaporation process and to reveal the resonance effect arising at the coincidence of the frequency of the system "steam-gas mixture + cupola + vacuum chamber + liquid layer" and the frequency of acoustic exposure under low external pressure.

2. Problem statement
It is proposed to investigate experimentally the dynamics of the evaporation process of a liquid under acoustic-vacuum exposure to identify the resonance effect by determining the following parameters:
- the mass of the evaporating liquid;
- the pressure of the steam-gas mixture above the liquid surface.

The laboratory scales used during experimental investigations under acoustic-vacuum exposure operate with an error in measuring the mass of the evaporating liquid, depending on the values of the external pressure in the VC. Therefore, before carrying out the main experiments, it is necessary to determine the calibration characteristic of the laboratory scales used at various values of the external pressure in the VC.

The following data are taken as initial ones: an evaporating liquid is water; the weight of water is 5 g; pressure in the VC is 101–0.4 kPa; the mass of the acoustic radiator is 360 g; initial water temperature is 19 °C; frequency of acoustic exposure is 25 kHz; vibration amplitude of the bottom of the acoustic radiator is 1; 2 μm.

3. Physical model and process provision for measuring liquid evaporation process parameters
To solve the tasks, the existing experimental stand was modernized [8]. Its scheme is shown in figure 1.

![Figure 1](image-url)  
**Figure 1.** Scheme of the modernized experimental stand: 1 – glass cupola with a volume of 0.005 m³; 2 – VC with a volume of 0.463 m³; 3 – acoustic radiator with a bath; 4 – model liquid; 5 – differential pressure sensor (0 ... 10 kPa); 6 – thermocouple for determining the temperature of the model liquid;
7 – thermocouple for determining the gas temperature under the cupola; 8 – gas pressure sensor in the VC (0 ... 101 kPa); 9 – analog-to-digital converter (ADC); 10 – multichannel temperature meter; 11 – oscilloscope; 12 – computer; 13 – video camera; 14 – pneumatic valve; 15 – vacuum pump; 16 – generator of acoustic vibrations

Since no buoyant force of air acts on the weighed sample (liquid) under vacuum conditions, the readings of the used laboratory electronic scales VK 3000.1 in vacuum become higher than at atmospheric pressure. Moreover, the vacuum has a negative effect on the electronics of the laboratory scales used. Therefore, part of the laboratory scales with vacuum-sensitive electronic equipment is moved outside the VC, and the platform with the weighed sample is placed inside the VC (figure 2).

![Laboratory scales](image)

**Figure 2.** Laboratory scales. (a) Platform of laboratory scales with an acoustic radiator in the VC. (b) Case of laboratory scales with electronic equipment, located outside the VC

To correct the readings of the scales operating in a vacuum, experimental investigations were carried out to determine the calibration characteristic using standard weights. Before the start of the experiment, reference weights with a mass of 360 g are placed on the platform of the scales located in the VC, simulating the weight of the acoustic radiator. After that, the readings of the scales are reset to zero, and the standard weights of mass 2; 3 and 5 g are installed on the platform of the scales in turns, simulating the mass of the evaporated liquid. The forehead pump is switched on and the pressure in the VC decreases along a hyperbolic curve from 101 kPa to 0.4 kPa. Experiments with each weight (2; 3 and 5 g) are repeated at least three times. After that, the calibration characteristic is determined as the dependence of the change in the readings of the scales on the pressure values in the VC.

To determine the pressure of the steam-gas mixture above the surface of the liquid, a glass cupola with holes for the outlet of the liquid vapors is introduced into the experimental stand. The area of the hole is selected based on the condition that the pressure of the steam-gas mixture under the cupola is sufficient to be measured by the used pressure sensor with a measurement range of 0 ... 10 kPa. Figure 3 shows a glass cupola with an acoustic radiator located inside the VC.
4. Results and discussions

As a result of preliminary experiments carried out with reference weights of mass 2; 3 and 5 g under vacuum conditions, the dependences of the change in the readings of the scales on the pressure in the VC are obtained, as shown in figure 4.

As can be seen from the results presented in figure 4, the nature of the curves is the same for different initial masses of the reference weights. Therefore, it can be assumed that the readings of the scales under reduced pressure change according to the same law at different values of the mass of the cargo up to 5 g. In this case, the pressure in the VC always changes from 101 to 0.4 kPa in the same time period. The maximum mass of the reference weight is 5 g because when carrying out the main experiments, a liquid with a mass of not more than 5 g is used. When the masses of the reference weights are more than 5 g, the nature of the curves may have a different form. Based on the obtained experimental results, the calibration characteristic of laboratory scales was determined as the dependence of the change in the readings of the scales on the pressure values in the VC at the initial mass of the reference weight of 5 g:

\[ m = 10^{-4}P^4 - 0.0002P^3 + 0.0097P^2 + 0.0167P + 6.869, \]  

where \( m \) is scales indications, g; \( P \) is pressure in the VC, kPa.
As the result of the basic experiments on liquid evaporation, using the calibration characteristic (1), the dependences of the change in the mass of the liquid on the parameters of the acoustic exposure (frequency, amplitude) and pressure in the VC were obtained (figure 5).

![Figure 5](image-url)

**Figure 5.** Results of experimental investigations: 1 – mass of liquid with an amplitude of vibrations of the bottom of the bath of the acoustic radiator of 1 μm; 2 – mass of the liquid with an amplitude of vibrations of the bottom of the bath of the acoustic radiator of 2 μm; 3 – pressure in the vacuum chamber

In figure 5, a change in the mass of the liquid is observed at vibrations amplitude of the bottom of the acoustic radiator bath of 1 and 2 μm, under conditions of a constantly decreasing external pressure in the VC. With an amplitude of oscillations of the bath bottom of 1 μm, the change in the liquid mass from 5 to 4.2 g is smooth. With an amplitude of vibrations of the bath bottom of 2 μm, the change in the liquid mass can be divided into 3 sections:

1. from 0 to 140 seconds, characterized by a decrease in the liquid mass by 0.7 g with a sharp decrease in pressure in the VC from 101 kPa to 12 kPa;
2. from 140 to 320 seconds which is "plateau", characterized by the minimum evaporation of the liquid, at which the liquid mass practically does not change. The pressure in the VC in this section decreases from 12 kPa to 1.14 kPa;
3. from 320 to 440 seconds, characterized by a decrease in the liquid mass by 2.4 g with the active boiling of the liquid. The pressure in the VC in this section decreases from 1.14 kPa to 0.46 kPa.

The change in the pressure of the steam-gas mixture above the liquid surface as a function of the pressure in the VC at the vibration amplitude of the bottom of the acoustic radiator bath of 2 μm is shown in figure 6.
Figure 6. Results of experimental investigations: 1 – pressure of the steam-gas mixture above the liquid surface; 2 – pressure in the vacuum chamber

Figure 6 shows the emergence of a resonance effect in the interval from 280 to 440 seconds, at which the pressure of the steam-gas mixture increases sharply from 5 Pa to 180 Pa and has an oscillatory character when the pressure in the VC is less than 2 kPa and the vibration amplitude of the bottom of the acoustic radiator bath is 2 μm. When the amplitude of the vibrations of the acoustic radiator bath bottom is 1 μm, the resonance effect is not observed. It should be noted that in this time interval from 280 to 440 seconds, the mass of the liquid sharply decreases (figure 5). The sharp increase in differential pressure at 430 seconds is associated with freezing of the liquid.

5. Conclusions
1. Experimental investigations of the parameters of the liquid evaporation process under the conditions of acoustic-vacuum exposure have been carried out, and the values of the mass of the evaporating liquid and the pressure of the steam-gas mixture above the liquid surface have been obtained.
2. To measure the vapor pressure of a liquid, a cupola is introduced into the experimental stand, which makes it possible to increase the vapor pressure of a liquid and register its value with the equipment used. The calibration characteristic of the laboratory scales is determined as the dependence of the change in the scales indications on the external pressure in the VC.
3. The resonance effect is revealed, which arises when the frequencies of the system "steam-gas mixture + cupola + vacuum chamber + liquid layer” coincide with the frequency of acoustic exposure at external pressure in the VC less than 2 kPa, acoustic exposure frequency of 25 kHz and vibration amplitude of the bottom of the acoustic radiator bath of 2 μm. In this case, the boiling of the liquid is observed, as well as a sharp increase in the pressure of the steam-gas mixture from 5 Pa to 180 Pa, and a decrease in the mass of the liquid by 2.4 g.

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Acknowledgments
This work was supported by the Russian Federation Ministry of Education and Science within the public contract with subordinate educational organizations, the project “Improvement of environmental safety and economic efficiency of launch-vehicles with cruising liquid rocket engines”, application No. 9.1023.2017/PCh.

The authors are grateful to engineer K. Lezhnin, an employee of the "Branch of the Joint Stock Company" United Propulsion Corporation - Saturn", for his help in conducting the experiments.