Investigation of the liquid evaporation process in a vacuum chamber with ultrasound influence

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Abstract. The investigations of the process of heat and mass transfer in the evaporation of model liquids (distilled water, alcohol mixture, kerosene TC-1) in a vacuum chamber (VC) under parametric ultrasonic influence (UI) and vacuum influence (VI) on a liquid with the purpose of using the obtained results for the development of a methods for designing the evaporation system of unused liquid residues of rocket fuel remaining in the launch vehicle (LV) tanks at the end of the mission. The initial data, variable parameters, assumptions and limitations have been determined. Experimental dependences of the temperature variation of model liquids and gas in a VC under UI under conditions of reduced pressure (up to 0.065 kPa) are obtained. The masses of evaporated model fluids and the rate of evaporation are determined. A comparative analysis of the experimental data obtained for various model liquids was carried out, which showed that the evaporation rate increases with increasing amplitude of the bath bottom vibrations, with the highest evaporation rate under the same conditions for kerosene TC-1.

1. Introduction

At present, the actual task is to reduce the technogenic impact of LV on the environment. This is due to the fact that fuel residues in fuel tanks of a rocket can be up to 3% of the initial fuel reserves after the mission is completed [1, 2], which leads to the risk of explosion of spent stages in orbits and to fires as a result of impact of the spent stage about the surface of the Earth in the region of the fall.

Based on the analysis of existing Russian and foreign methods for reducing the technogenic impact of spent stages in the areas of incidence and near-Earth space [3, 4], a technology based on gasification of rocket fuel in LV tanks [5, 6].

The proposed technology is implemented when the evaporation of the rocket fuel remains in zero-gravity conditions, due to the fact that the uncertainty of their phase state and the boundary location in the volume of the LV tank [5]. In this case, there are a number of limitations on the maximum pressure and temperature of gases in rocket tanks from the condition of thermal strength loading of the structure.

The available results of the theoretical and experimental studies on the evaporation of model liquids in a closed volume simulating the allocated volume of a real fuel tank [7] have shown that a considerable amount of energy is needed to evaporate a given mass of fuel.

To reduce energy costs, it is proposed to conduct studies on the evaporation of model fluids under reduced pressure and UI.

The existing results of theoretical and experimental investigations on the evaporation of liquids and drying of various materials [8, 9], including in the case of ultrasonic waves, have shown that the rate
of evaporation of a liquid depends on the frequency and amplitude of oscillations of ultrasonic waves, increased pressure, temperature, etc.

In work [8] results of researches on evaporation of water at heat influence and ultrasonic influence on a liquid with constant frequency and amplitude of oscillations in conditions of reduced pressure are presented.

It is proposed to carry out experimental investigations of the evaporation of various liquids (distilled water, alcohol mixture and kerosene TC-1) under reduced pressure with the introduction of a new factor - different values of the amplitude of oscillations of ultrasonic waves.

2. Problem statement
The aim of the proposed investigations is to determine the evaporation rate of distilled water, alcohol mixture and kerosene TC-1 in a vacuum chamber under the combined parametric UI and VI for different values of the amplitude of the oscillations of the bottom of the bath.

To solve this aim it is necessary to perform the following tasks:
– development of methods for conducting experiments;
– carrying out experiments and analyzing the results;
– evaluation of the influence of the investigated parameters (pressure in the VC, frequency and amplitude of UI) on the rate of evaporation of various model liquids.

Baseline data, assumptions and limitations:
– as model liquids used: distilled water, alcohol mixture and kerosene TC-1;
– initial mass of the model fluid is 5 g;
– initial temperature of the model liquid from 20 to 24°C;
– pressure in the VC from 101 kPa to 0.065 kPa;
– frequency of UI is 23 kHz;
– amplitude of the oscillations of the bottom of the bath is 1, 2, 3 μm.

3. Theory
Experimental studies on the evaporation of distilled water, alcohol mixture and kerosene TC-1 with UI and VI were carried out using the experimental stand created, presented in Figure 1.
**Figure 1.** Experimental stand: 1 - VC; 2 - pre-vacuum pump; 3 - control panel for pneumatic valves and thermocouples; 4 - oscilloscope; 5 - viewing window in VC; 6 - ultrasonic radiator and laboratory scales.

The experimental stand (Figure 2) consists of:
- volume of the VC is $0.463 \, m^3$;
- cylindrical bath for placing the model liquid (diameter 0.035 m, height 0.01 m, material: stainless steel);
- piezoceramic radiator (PCR) and generator (amplitude of the oscillations of the bottom is from 1 to 3 $\mu m$);
- an oscilloscope for determining the amplitude of the oscillations of the bottom of the bath;
- for vacuum pump (evacuation rate $6.5 \, dm^3/s$, ultimate residual pressure 1 Pa);
- multichannel temperature meter MIT-12 and mobile temperature sensors THA with measurement error of 1 °C;
- stinger CVM211GCL pressure sensor with a measurement error of 2.5%;
- laboratory scales VM-510 DM-II with an error of measurements of 0.05g.

**Figure 2.** The scheme of the experimental stand: 1 – VC; 2 – bath; 3 – model liquid; 4 – PCR; 5 – generator; 6 – pre-vacuum pump; 7 – mobile temperature sensors; 8 – pressure sensor.

The method of carrying out the experiments consists in feeding UI and VI into the closed volume and measuring the pressure and temperature of the liquid, the walls of the vacuum chamber and the gas in order to establish later the dependence of the evaporation rate of various model liquids on the parameters of the UI (frequency and amplitude of the oscillations of the bottom) and the pressure in the VC.

The fixed time of the experiment is determined, which is determined by the output of the measured parameters to the steady state. The formation of ice is not a sufficient condition to stop the experiment, which instead happen to the moment of complete evaporation.

Before to the start of the experiment, PCR (4) with the bath (2) are placed on a platform of laboratory scales, after which the selected model liquid (3) (distilled water, alcohol mixture or kerosene TC-1) is poured into bath (2) to the set value of mass, namely 5g.

Then PCR (4) with model liquid (3) is placed in VC (1). After that, the pre-vacuum pump (6) starts and the pressure in VC (1) gradually decreases. Simultaneously with the inclusion of the pre-vacuum pump (6), a PCR (4) is switched on. Using the generator (5) and an oscilloscope, the required amplitude of the oscillations of the bottom of the bath (2) (from 1 to 3 $\mu m$) is established.
The temperatures of the model liquid (3) and the gas inside the VC (1) are determined by means of mobile temperature sensors (7). The pressure in VC (1) is determined by means of a pressure sensor (8).

The experiment stops after 10 minutes from the start, the fore-vacuum pump (6) and PCR (4) are switched off. PCR (4) with the bath (2) and the remnants of the model liquid is placed on a platform of laboratory scales to determine the mass of the residuals of the model liquid, followed by calculation of the average evaporation rate of the model liquid.

4. Experimental results

In Figure 3 – 5 are presented the experimental results about the evaporation of various model liquids (distilled water, alcohol mixture and kerosene TC-1) at an amplitude of the bottom of the bath 2 μm under conditions of constantly decreasing pressure in the VC.

![Figure 3](image1.png)

**Figure 3.** Change of temperatures of model liquids: 1 – distilled water; 2 – alcohol mixture; 3 – kerosene TC-1.

![Figure 4](image2.png)

**Figure 4.** Change of gas temperatures in VC during evaporation of model liquids: 1 – distilled water; 2 – alcohol mixture; 3 – kerosene TC-1.
Figure 5. Change in pressure in the VC during experiments.

The values of the average evaporation rates of model liquids and the masses of evaporated model fluids, depending on the amplitude of the oscillations of the bottom of the bath with constantly decreasing pressure in the VC, are shown in Table 1.

Table 1. Average speed of evaporation of model liquids in different amplitudes of batch down vibrations under condition of reducing pressure in VC.

| No | Model fluid  | Evaporation rate, g / min | Mass of evaporated model liquid, g |
|----|--------------|---------------------------|-----------------------------------|
|    |              | 1 μm | 2 μm | 3 μm | 1 μm | 2 μm | 3 μm |
| 1  | Distilled water | 0.341 | 0.353 | 0.397 | 1.7  | 1.76 | 1.98 |
| 2  | Alcohol mixture | 0.410 | 0.830 | 1.250 | 2.05 | 4.15 | 5   |
| 3  | Kerosene TC-1 | 0.770 | 1.0  | -    | 3.85 | 5   | -   |

5. Discussion of the results
In Figure 3 the nature of temperature changes of all model liquids is the same. The temperatures of the model liquids increase sharply from the initial instant of time and after 1 ... 1.5 minutes they begin to decrease smoothly until the end of the experiment. This can be explained by the fact that the UI is characterized by cavitation, microcurrents of fluid and eddy currents. At the same time, the explosion of the bubbles causes a decrease in the partial pressure of liquid vapor and a decrease in the boiling point, so that the temperatures of the model fluids begin to decrease after 1 ... 1.5 minutes of the experiment, until the crust is formed, as seen in Figure 6.

Figure 6. Formation of the crust of ice in the PCR bath with distilled water.
Formation of the crust of ice during the evaporation of distilled water occurs in 7 ... 8 minutes after
the beginning of the experiment, depending on the amplitude of the oscillations of the bottom of the
bath. This is because the freezing point of the liquid shifts to the left of the zero at VI, and when the
liquid is heated the freezing point shift to the right. The total displacement of the freezing point
depends on the type of liquid, its mass, the intensity of the UI, the magnitude of the explosion.

As a result of the experiments, the amplitude of the vibrations of the bottom of the bath was 2 μm
and the reduced pressure in the VC (Figure 3), the kerosene TC-1 evaporates in 5 minutes, the alcohol
mixture in 6 minutes, and the distilled water does not completely evaporates and after 7 minutes
passed into the solid phase. This is due to the fact that the kerosene TC-1 needs to transmit less heat to
dissipate it. For example, the specific heat of kerosene at constant pressure and temperature of 20° C is
2050 J / (kg K), the alcohol mixture is 2500 J / (kg K) and distilled water is 4183 J / (kg K).

The temperature of the gas in the VC (Figure 4) decreases sharply from the initial time to 2.5
minutes, which is due to a change in the pressure in the VC (Figure 5). After the pressure becomes
close to a constant (after 3 minutes of the experiment), the gas temperature gradually increases until
the end of the experiment.

With an increase in the vibration amplitude of the bottom from 1 to 2 μm, the evaporation rate
of distilled water increases by approximately 3.5%, the alcohol mixture by 100% and kerosene TC-1 by
30%. With an increase in the vibration amplitude of the bottom from 1 to 3 μm, the evaporation rate of
distilled water increases by approximately 16%, the alcohol mixture by 200% (Table 1).

Experiment on evaporation of kerosene TC-1 at an amplitude of oscillations of the bottom of a bath
of 3 microns did not succeed because of a significant part of the liquid at the initial moment of time
splashed out of the bath. This is due to large fluctuations in the surface of the liquid at 3 μm and with
the fact that kerosene TC-1 with a mass of 5 g has occupied the entire volume of the bath, due to its
low density.

6. Conclusions
1. The technique of carrying out experiments is developed and experemts are conducted.
2. Experiments on the evaporation of various model liquids (distilled water, alcohol mixture,
kerosene TC-1) were performed at different parameters of the UI and pressure in the VC.
3. Experimental dependences of the temperature variation of model liquids and gas in the VC at UI
have been obtained under conditions of constantly decreasing pressure (up to 0.065 kPa). The masses
of evaporated model fluids and the average evaporation rate are determined.
4. A comparative analysis of the experimental data obtained for various model liquids with the
results presented in [8] was carried out. They showed that the rate of evaporation increases with
increasing amplitude of the oscillations of bath. The highest rate of evaporation under the same
conditions for kerosene TC-1.

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