Investigation of heat and mass transfer process in the closed volume with different types of impact on liquid

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Abstract. Theoretical and experimental investigations of liquid evaporation process under ultrasonic (US) and heat influences (HI) under conditions of reduced pressure are carried out. A mathematical model of the influence of US, HI and pressure of a vapor-gas mixture in a vacuum chamber (VC) on the temperature and rate of fluid evaporation is developed. A program and methods for conducting experiments have been developed, an experimental stand has been created, and an experimental program has been implemented. The experimental dependences of the change in the liquid temperature under combined US and HI under conditions of reduced pressure and under the influence of these factors were obtained separately. A comparative analysis of the calculated and experimental values of liquid temperatures was carried out, which showed a discrepancy of the results to 10%. The areas of parameters of US, HI, and pressure in a vacuum chamber are identified, at which the evaporation rate of the liquid varies significantly, for example, at a pressure of 3 ... 4.5 kPa, a sharp decrease in the liquid temperature is observed, up to the formation of ice crust. The combined use of US and HI in conditions of reduced pressure leads to an increase in the rate of liquid evaporation by 0.7 g / min than when using US and HI separately.

1. Introduction
Unused fuel residues (up to 3 % or more of the initial fuelling) in the tanks of rocket stages with liquid rocket engines provoke explosions in the stages of launch vehicles in orbits and fires in areas of their falls, and drastically deteriorate dynamic characteristics of spent rocket stages at their motion in the atmospheric phase of the descent trajectory.

For avoiding the negative impact of unused residual fuel in the tanks of spent stages of launch vehicles, an on-board system is developed to ensure the removal of these fuel residues by evaporation in carrier rockets [1].

Currently, there are various methods for the evaporation of liquids, including by direct heating of the surface on which the liquid is, the convective influence of gas flow on liquid, as well as US, vacuum, electromagnetic influences, etc.

The mechanism of liquid evaporation in US is fairly well studied, such as in [2]. Numerous experiments on the drying of various materials under the action of US confirm the fact that the velocity of the process depends on the magnitude of the US frequency and the pressure, for example, in [2], when the naphthalene evaporates from the surface of metal balls with a diameter of 3 ... 6 mm, the linear dependence of the flow mass on the US.
The dynamics of the liquids cavitation under US was considered in [3, 4], besides, the influence of the ultrasound frequency and amplitude f on the intensity of cavitation on the basis of the Nolting-Nepayras mathematical model was evaluated.

The results of theoretical and experimental investigations of liquid evaporation under various conditions have been obtained, including the following:

- various boundary conditions for the liquid location on a solid surface ("drop" and "mirror") [5, 6];
- gas flow influence on the liquid [7], with certain parameters (input angle, temperature, etc.) [8, 9] by using experimental stands [10, 11];
- use of various types of surfaces on which the liquid is located (micro- and nano-coatings) [12].

Since the existing investigations of liquids evaporation under US [13, 14] and HI [15, 16] are carried out under atmospheric or increased pressure conditions, a special interest is the investigation of US and HI effect on liquid evaporation under conditions of reduced pressure.

It is proposed to investigate the process of heat and mass transfer on liquid evaporation with a free surface under conditions of reduced pressure under combined US and HI, and under the influence of these factors separately.

2. Problem statement

Investigation of the liquid evaporation process with a free surface in the closed volume under US and HI under conditions of reduced pressure is proposed to be carried out in a limited range of parameters of the evaporated liquid, that are US and HI.

The solution of the task is:

- development of a mathematical model of the influence of US, HI and a vapor-gas mixture (evaporated liquid + gas in a volume) pressure in a closed volume on the process of liquid evaporation, conducting numerical experiments;
- development of a program and methodology for conducting experiments, the formation of requirements for the experimental stand and its development;
- conducting experiments and comparative analysis of the mathematical and physical modeling results.

Restrictions and assumptions are the following:

- distilled water is used as liquid;
- initial mass of the liquid (150 g) at the initial temperature of the liquid (14 ... 16 °C);
- liquid evaporation is considered up to the point of its freezing;
- change in pressure in the VC is from 101 kPa to 0.8 kPa with a constant pumping speed of 6.5 \( \text{dm}^3/\text{s} \);
- US frequency is 40 kHz, sound pressure is 120 dB;
- HI was carried out using an electric heater located in the volume of the evaporated liquid. Electric heater power is 30 watts. The surface area of heating is 3300 mm².

3. Mathematical model

The main processes that consume energy with US and HI on the liquid are: a) cavitation; b) micro streams of liquid; c) vortex flows. These processes are manifested in the form of liquid heating [17], by heating the vapor-gas mixture in cavitating bubbles [18] and by dissipating acoustic energy on the inhomogeneities of various fluid layers that form when cavitation occurs and the liquid is stirred.

The total energy of the process is determined by the level of energy consumed and is calculated after measuring the voltage supplying on the ultrasound generator and the current consumed. The calculation takes into account the efficiency of the ultrasonic generator and the coefficient of electro-acoustic conversion. Acoustic energy is expended on the liquid heating and mixing.

For modeling the mixing process, we consider the variant of the turbulent flow and the body moving in the flow. Oscillation of the bottom of the container, in which the liquid is located, creating the effect of motion of the plane in the turbulent flow, allow us to estimate the power required to create this flow.
In accordance with the well-known formula [19], the power $P$ required for the motion of a body in a turbulent flow can be represented in the form:

$$P = c_S \rho / 2 \nu^3,$$

(1)

where $c_s$ is the coefficient that depends on the shape of the body and is a function of the Reynolds number; $S$ is the area of the plane in a stream, perpendicular to his direction; $\rho$ is the fluid density; $\nu$ is the relative velocity of fluid motion. This velocity consists of two components:

1) velocity $v_m$, which is associated with fluctuations of a bottom of a container at US:

$$v_m = 2\pi f A_m,$$

(2)

where $f$ is the frequency of US; $A_m$ is the amplitude of the oscillations;

2) velocity $v_k$, which is determined by the cavitation process and the flow velocity near the cavitating bubble, is estimated [3] by the following expression:

$$v_k = U_s^2 / 2\pi f R,$$

(3)

where $U_s$ is the radial velocity of bubble boundary; $R$ is the average radius of a cavitation bubble.

This expression is associated with the asymmetry of the processes of expansion and contraction of the cavitating bubble [4], and $U_s$ is also determined by the average bubble radius and the time of reduction of the liquid or gas pressure, which, with the asymmetry indicated above, is about 0.75 of the oscillation period.

$$U_s = R / 0.5 T = f R / 0.75,$$

(4)

where $T$ is the oscillation period.

$$v_k = 8 f R / 9 \pi.$$  

(5)

The resonance size of the bubble is determined from the known Minnert formula [20], which relates its size to the resonance frequency of the oscillations:

$$f = 1 / 2\pi R \sqrt{3 \gamma / \rho \left(P_0 + 2 \sigma / R \right)},$$

(6)

where $R$ is average radius of a cavitation bubble; $\gamma$ is the air adiabatic index; $\sigma$ is the surface tension of a liquid; $P_0$ and $\rho$ is the static pressure and density of liquid, respectively.

For simplification further transformations, we exclude the second member in brackets in the Minnert formula, as a second order quantity of smallness in comparison with the static pressure of liquid. Then the Minnert formula is transformed into an expression for the bubble size:

$$R = 1 / 2\pi f \sqrt{3 P_0 \gamma / \rho}.$$

(7)

Then the velocity $v_k$ will be determined:

$$v_k = 4 / 4 \pi^2 \sqrt{3 P_0 \gamma / \rho}.$$  

(8)

Respectively, the total relative velocity of the liquid:

$$v = v_m + v_k = 2\pi f A_m + 1 / \pi^2 \sqrt{3 P_0 \gamma / \rho}.$$  

(9)

Power $P$ required to create a turbulent flow:

$$P = c_S \rho / 2 \left(2\pi f A_m + 1 / \pi^2 \sqrt{3 P_0 \gamma / \rho} \right)^3.$$  

(10)

Knowing the power required for mixing and total acoustic power, it is not difficult to determine the part of the power $P_T$ that determines the heating of the liquid:

$$P_T = S_A c_p c S \rho / \left[2\pi f A_m + 1 / \pi^2 \sqrt{3 P_0 \gamma / \rho} \right]^{3/2}.$$  

(11)
where $S_a$ is the emitter surface area; $c_e$ is the speed of sound in water.

Change of temperature of liquid:

$$\Delta T = P_t t / (m_i c_i + m_c c_e),$$

(12)

where $t$ is the time; $m_i$ is the mass of liquid; $c_i$ is the specific heat of the liquid; $m_c$ is the container weight; $c_c$ is the specific heat of container material.

On the other hand, the heating process is accompanied by the evaporation of liquid, especially under reduced pressure. In accordance with the laws of thermodynamics, the evaporation process is accompanied by the absorption of energy, which can be determined through the specific heat of vaporization:

$$Q = q m,$$

(13)

where $q$ is the specific heat of vaporization; $m$ is the mass of vaporized liquid.

This process leads to a change in the temperature of the liquid:

$$\Delta T = (P_t t - q m)/(m_i c_i + m_c c_e).$$

(14)

The ass of vaporized liquid is as follows:

$$\dot{m} = c S_s (p_n - p)/p_0,$$

(15)

where $\dot{m}$ is the amount of liquid converted into steam in 1 second; $c$ is the coefficient of proportionality (hereinafter, determined experimentally); $S_s$ is the evaporation surface area; $p_n$ is the saturated vapor pressure; $p$ is the vapor pressure of a liquid above its free surface; $p_0$ is the external barometric pressure.

After transformation expression for the velocity of evaporation rate of liquid will look:

$$\dot{m} = c S_s (1 - \varphi) p_0,$$

(16)

where $\varphi$ is the relative humidity.

As experiments are made in the vacuum chamber in the conditions of the decreasing pressure, expression for mass of the liquid passing into steam will be defined as follows:

$$m = \int_0^t \dot{m} dt = \int_0^t c S_s (1 - \varphi)/p_0(t) dt$$

(17)

and, accordingly, the expression for changing the temperature of the liquid under US and HI under conditions of decreasing pressure:

$$\Delta T = \left(P_t t - q \int_0^t c S_s (1 - \varphi)/p_0(t) dt \right) / (m_i c_i + m_c c_e).$$

(18)

At substitution in the received expression formula for the power of US defining liquid heating, we will receive:

$$\Delta T = \left[S_a \rho c_e 2\pi^2 f^2 A_m - c_s S \rho / 2 \left(2\pi f A_m + 1/\pi^2 \sqrt{5P_{ef} / \rho}\right) t - q c S_s \int_0^t p_n (1 - \varphi)/p_0(t) dt \right] / (m_i c_i + m_c c_e).$$

(19)

4. Experimental stand

Experimental investigations for determining the temperature and mass of the vaporized liquid with a free surface in a closed volume under US and HI under conditions of reduced pressure were performed using the developed and created experimental stand shown in Figure 1.
The experimental stand includes:
- VC with a volume of 0.463 m³;
- container for placing a liquid with a protective film from splashing drops (length 0.150 m, width 0.085 m, height 0.065 m, weight 762.9 g, material: stainless steel);
- piezoceramic radiator (frequency 40 kHz, sound pressure 120 dB);
- electric heater (power 30 W, surface area of heating 4400 mm²);
- for vacuum pump (pumping speed 0.0065 m³ / s, ultimate residual pressure 1 Pa);
- system for measuring, recording and processing measurement results (mobile thermocouples, pressure sensor, video camera);
- connecting and shut-off valves (system of hoses, fittings and pneumatic valves).

During the experimental investigation, distilled water was used as the evaporated liquid.

The measurement error for temperatures of the walls, gas, and liquid obtained using a multichannel temperature meter MIT-12 and thermocouples THA is ± 1 °C.

The process of liquid evaporation with a free surface in the VC at US and HI was carried out with the following initial parameters: gas temperature inside the VC is 17 ... 19 ° C; mass of the evaporated liquid is 150 g; water temperature 17 ... 20 °C; initial pressure in VC 101 kPa.

The experiments were carried out for 7 minutes with the joint US and HI, and under the influence of these factors separately under conditions of constantly decreasing pressure in the VC from 101 kPa to 0.8 kPa.

5. Experimental results
As a result of mathematical modeling and carried out experiments, the dependence of the temperature change of the liquid at US and HI under conditions of reduced pressure was obtained (Fig. 2).
Figure 2. Comparative analysis of the experimental investigations and mathematical modeling results:
1 – US (mathematical model); 2 – US (experiment); 3 – HI (mathematical model); 4 – HI (experiment); 5 – US and HI (mathematical model); 6 – US and HI (experiment)

As can be seen from the results shown in Figure 2, the temperature of the liquid from the initial time to 3.5 ... 4 minutes is smoothly increased by 4.6 ... 9.6 °C, as in the joint US and HI (graphs 5, 6), and using these factors separately (graphs 1 - 4). Constantly decreasing pressure in the VC leads to active boiling of the liquid and the formation of large collapsing bubbles from the 4th minute of the experiment. At the same time, the temperature of the liquid decreases sharply until the end of the experiment by 13 ... 17 °C, and the pressure decreases to 0.8 kPa.

US and HI on the liquid lead to an increase in its temperature to a certain pressure value. Consequently, there are areas of the parameters of US, HI, and pressure at which the evaporation rate of the liquid varies substantially.

Table 1 shows the values of evaporated liquid mass and evaporation rate for separately US and HI, as well as for combined use of US and HI under conditions of reduced pressure.

| Type of action on the liquid | Mass of the evaporated liquid, g | Evaporation rate, g / min |
|-----------------------------|---------------------------------|--------------------------|
| US                          | 7.75                            | 1.1                      |
| HI                          | 8.6                             | 1.23                     |
| US and HI                   | 12.8                            | 1.83                     |

On the basis on the analysis of the data presented in Figure 2 and in Table 1 the following main research results are formulated:
– US and HI on the liquid lead to an increase in its temperature to a pressure value in the vacuum chamber of 3 ... 4.5 kPa. From 4.5 kPa to 0.8 kPa, the temperature of the liquid and the rate of evaporation of the liquid decrease. Consequently, there are areas of the parameters of US, HI, and pressure at which the evaporation rate of the liquid varies substantially;
– sharing of US and HI in conditions of reduced pressure leads to an increase in the rate of evaporation of the liquid by 0.7 g/min than when using US and HI separately;
– with joint US and HI under conditions of reduced pressure, the mass of the evaporated liquid will be greater than when using US and HI separately.

6. Discussion of the obtained results
The obtained results of theoretical and experimental investigations showed a close compliance of the change in the liquid temperatures at US and HI under conditions of reduced pressure. The discrepancy between the results of mathematical modeling and experimental investigations is no more than 10%.

Investigated US and HI on liquids under reduced pressure, which showed:
– there are areas of parameters of US, HI and pressure at which the evaporation rate of a liquid varies significantly, for example, at a pressure of 3 ... 4.5 kPa, bubbles are observed on the surface of the liquid and the liquid temperature decreases, until the ice crust forms;
– as follows from Table. 1, with the joint US and HI under conditions of reduced pressure, the mass of the evaporated liquid will be greater than when these factors are individually affected;
– at the same energy costs, the use of US leads to an increase in the liquid temperature by 9.6 °C (Fig. 2, graphs 1, 2), and the use of HI at 5.8 °C (graphs 3, 4);
– the use of US and HI in conditions of reduced pressure reduces the freezing point of the liquid.

Further recommendations on theoretical and experimental investigations are the following:
– to estimate intensity of US at various frequencies and amplitudes, and also at use of other liquids;
– investigations to determine the optimal combination of factors of US, pressure, temperature, affecting the efficiency of the evaporation process;
– carrying out experimental investigations on the evaporation of a drop of liquid to compare the results obtained with the results presented in [21, 22] with subsequent evaluation of the US and HI use effectiveness.

7. Conclusions
A mathematical and physical model for estimating the influence of US, HI and pressure on the liquid temperature and its evaporation rate is developed.

Experimental investigations of the process of liquid evaporation at US and HI under conditions of low pressure have been carried out. The reliability of the obtained results of the investigated process mathematical modeling is confirmed.

The areas of US, HI and pressure parameters are determined, under which the evaporation rate of the liquid varies substantially.

The recommendations for further theoretical and experimental investigations are formulated.

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