DOI: 10.13009/EUCASS2017-115

Enhancement of fuel evaporation in microgravity conditions under the effect of ultrasound techniques

Trushlyakov V.I.[*], *Lesnyak I.Yu.*[**], *Galfetti L.*[***]
[*] *vatruslyakov@yandex.ru, Mira, h. 11 Omsk, Russian Federation, 644050*
** *lesnyak.ivan@gmail.com, Mira, h. 11 Omsk, Russian Federation, 644050*
[***] *luciano.galfetti@polimi.it, Via La Masa, 34, I-20156, Milan, Italy*

Abstract
This work investigates the process of evaporation of a liquid fuel in a small gravitational fields by using the experimental model bench (EMB), which simulates the allocated volume of the fuel in the rocket tank. A convective exchange between a gas carrier and the surface of the liquid fuel is supported by an acoustic device. To intensify the process of heat and mass transfer acoustic gas-jet generators (AGG) and magnetostriction emitters (MSE) are used. Investigations are carried out under different parameters of heat carrier, acoustic oscillations and liquid fuel properties. Heat and mass transfer coefficients are measured both using acoustic influence and without acoustic influence.

1. Introduction

To reduce the negative impact on the environment of fuel residues in the tanks of carrier rocket stages, an onboard system is developed, ensuring the gasification of fuel residues based on the supply of hot gases - heat carrier (HC) to the fuel tanks [1-3].
After turning off the liquid rocket engine and application of the brake pulse during the separation of the stages, the boundary position of the liquid fuel residues is random. The conducted experimental studies in a tower of zero gravity [4] showed possible variants of the location of liquid fuel residues after the shutdown of the liquid rocket engine and the application of the brake impulse. Based on these studies, possible options for the boundary conditions of the fluid ("mirror", "drop") [5] can be determined.
To study the process of convective heat and mass transfer occurring in the fuel tank of a rocket, an experimental stand was developed, including a system for producing a HC, an EMB, a system for measuring and recording data, and connecting and shut-off valves [6].
Previous theoretical and experimental studies of liquids evaporation [7] using the created experimental stand showed that a significant amount of energy is required for the evaporation of liquid rocket fuel residues. To decrease the energy expenses acoustic influence of the running heat carrier flow is used in addition to convection. As sources of acoustic waves for intensification of the heat and mass transfer process, AGG and MSE are used.
The effect of acoustic waves on heat and mass transfer in forced convection has already been studied in [8, 9]. On the basis of the experimental studies, generalized empirical formulas were obtained. The experiments described in [8, 9] were carried out in a narrow range of frequencies and intensities of acoustic oscillations.
The mechanism of the effect of sound vibrations on the processes of heat and mass transfer was considered in [10]. The need of studying the process of liquid evaporation under acoustic influence is determined by variations in thermal processes, materials, boundary conditions [11, 12]. Therefore, the use of existing heat and mass transfer coefficients is unsuitable and it is necessary to determine them experimentally for each variant of the heat and mass transfer process (HC parameters, frequency and intensity of acoustic oscillations, fluid boundary location, tank design, thermodynamic parameters inside the tank, etc.).
In this paper, experimental studies were carried out using EMB simulating the allocated volume of a rocket fuel tank. Table 1 shows the values of the similarity criteria of Reynolds, Nusselt and Bio to evaluate the possibility of simulating thermodynamic processes in the existing EMB using the example of the second stage tank of the «Soyuz-2.1v».

DOI: 10.13009/EUCASS2017-115

Table 1: Initial data for modeling the heat and mass transfer processes occurring in the rocket stage tank, for example, gasification of liquid in existing EMB

№	Parameters	Fuel Tank	EMB
1	Characteristic size, m	Tank length - 2,3	Plate length - 0,15
2	HC	Combustion products in the gas generator: kerosene + oxygen (1:0,7)	Air
3	Temperature HC, K	1470-1500	330-360
4	Velocity HC, m/s	5-6	2-4
5	Kinematic viscosity HC, m^2/s	$8.3 \cdot 10^{-5}$	$18 \cdot 10^{-6} - 20 \cdot 10^{-6}$
6	Reynolds number (Re)	$10^5 - 1.6 \cdot 10^5$	$1{,}8 \cdot 10^4 - 10^5$
7	Nusselt number (Nu)	350-440	330-420
8	Bio number (Bi)	0,005	0,005

As shown in table 1, by choosing the parameters HC (temperature, flow rate, kinematic viscosity) for the existing EMB (characteristic size), it is possible to provide the conditions for the similarity of the heat and mass transfer process according to the main criteria (Re, Nu, Bi).

2. Problem definition

To evaluate the influence of ultrasound on the intensification of liquid evaporation process, it is necessary to experimentally determine the coefficients of heat transfer α and mass transfer β without acoustic influence and with acoustic influence.
To carry out experimental studies to determine the coefficients of heat and mass transfer, it is necessary:
- to develop a program and methods for conducting experiments taking into account the use of ultrasonic radiators of AGG and MSE;
- to collect data for carrying out researches:
a) temperature and mass flow HC;
b) frequency and intensity of acoustic waves;
c) the mass, temperature, boundary condition and the chemical composition of liquid according to the parameters specified in table 1.
The heat transfer coefficients between gas and liquid is given by the following [13-15]:

$$\alpha_i = Q/(t_1 - t_2)F\,, \tag{1}$$

where Q - convective heat flow from the HC to the liquid and the plate [W];
t_1 - temperature HC [K];
t_2 - temperature of liquid or plate [K];
F - surface area of liquid or plate [m^2];
i - the elements participating in heat transfer (gas-liquid; gas - plate).
In accordance with (1), to calculate the heat transfer coefficients, it is necessary to determine:
- temperatures of HC, liquid and a plate with use of mobile and stationary sensors of temperature;
- area of the liquid.
Nusselt number (Nu) is determined using the obtained heat transfer coefficient values, as well as heat conductivity HC and plate sizes:

$$Nu = \alpha_i l / \lambda_{HC}, \tag{2}$$

where l - length of a plate [m];
λ_{HC} - coefficient of heat conductivity HC [W / mK].

DOI: 10.13009/EUCASS2017-115

To calculate the mass-transfer coefficients β [13, 14], it is necessary to determine:
- the humidity of the gas at the outlet from the EMB using a hygrometer;
- temperature of liquid using mobile temperature sensors;
- area of mass-transfer surface of liquid.

$$\beta = \frac{\dot{M}RT}{(p - p_p)F} = \frac{\dot{M}RT}{p(1-\varphi)F}, \qquad (3)$$

where R - is the gas constant [J/(kg K)];
T - liquid temperature [K];
p - pressure of saturated steam of liquid in the range of temperatures 290... 310 K, [Pa];
p_p - partial pressure of liquid vapor in a EMB [Pa];
F - area of the mass-transfer surface [m^2];
$\varphi = \frac{p_p}{p}$ - relative humidity [%].
The calculation scheme of the heat exchange process between a plate and a liquid using the number Bi is presented in [16].
Limitations and assumptions used in the experiments:
1. The temperatures of the walls of the EMB (metal and glass), of the gas in the volume of the EMB, of the liquid on the plate are accepted as average for each participant in the heat exchange, i.e. practically no temperature gradient.
2. The thermodynamic effect (convective heat transfer) on the liquid is considered on the basis of the supply of HC to the surface of the liquid inside the EMB, without chemical interaction.
3. In the evaporation process a "frozen" condition of liquid is assumed, i.e. fixed, without oscillation of the free surface of the liquid.
4. For the EMB, thermal flow between liquid and a wall of the EMB are absent, as the liquid is located on a plate and thermal streams between the plate and the wall of the EMB are negligible due to the use of thermal insulators.
5. The heat transfer coefficient between HC and gas is constant $\alpha_{HC} = const$ with respect to the time of the process and is not determined at this stage of the experiment.

3. Experimental stand

Experimental studies to determine the coefficients of heat transfer (1) and mass transfer (3) were carried out using an experimental stand (Figure 1). The main design parameters of the stand are determined taking into account the similarity theory (Table 1).

Figure1: Experimental stand

DOI: 10.13009/EUCASS2017-115

The experimental stand includes:
- a system for obtaining a HC, based on the use of a compressor with a receiver and a heater (the temperature of the HC is in the range from 293 K to 423 K, a second flow rate up to 400 l / min);
- EMB (height 0.5 m, length 0.5 m, width 0.2 m, excessive pressure to 0.2 MPa, input device HC);
- a system for measuring, recording and processing measurement results (mobile temperature sensors, pressure, flow, humidity, speed sensor, video camera);
- the connecting and shut-off valves consist of hoses, fittings, valves, which ensure the tightness of the joints at an overpressure of up to 0.5 MPa.

As sources of acoustic waves are used:
- AGG (frequency 33 kHz, sound intensity - 130 ÷ 145 dB), presented in Figure 2;
- MSE (frequency 40 kHz, sound intensity - 120 dB) with a generator (power 35 W), presented in Figure 3.

Figure 2: AGG

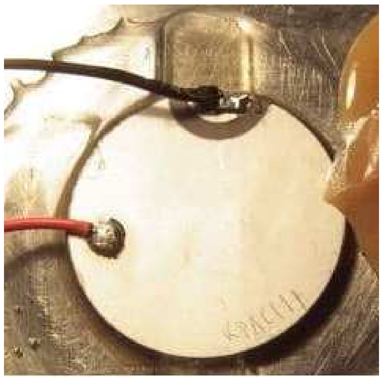

Figure 3: MSE

The scheme of the input of the flow of HC through the AGG and the gas outlet (evaporated liquid + HC) from the EMB is shown in Figure 4.

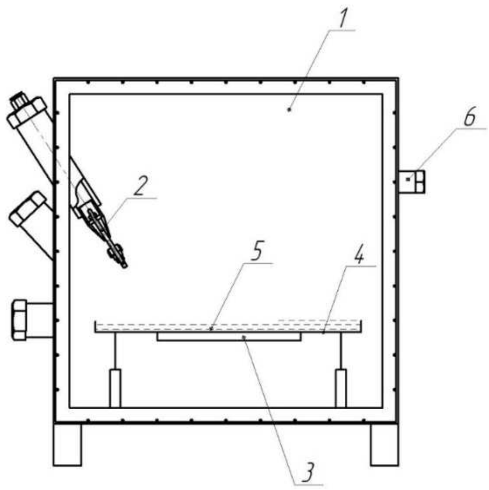

Figure 4: Scheme of the input of the flow of HC through the AGG and the gas outlet from the EMB:
1 – EMB; 2 - AGG-4; 3 - MSE; 4 - plate; 5 - model liquid; 6 - outlet fitting

The error in measuring the humidity of the gas at the outlet from the EMB and the gas and liquid temperatures using a multichannel temperature meter MIT-12 and thermocouples THA is 1%. The error in measuring the frequency and amplitude of sound using the noise announcer "Assistant" is 0.7%.

When carrying out experiments, the second law of thermodynamics has to be observed (transfer of heat from a warmer to a colder body). For verification of this law, according to the readings of the temperature sensors, the temperature of the HC and other heat exchange participants (EMB walls, plate, liquid) is compared, and in the event of a violation of the condition:

DOI: 10.13009/EUCASS2017-115

$$T_{HC} \geq T_i,\ \text{i=1…N}, \tag{4}$$

where N - is the number of installed temperature sensors inside the EMB, the experiment is terminated and faults are detected in the measurement and data recording system.
The temperature of the HC T_{HC} at the entrance to the EMB must correspond to a predetermined temperature with a minimum deviation.
When carrying out experiments, relative humidity of gas in volume of the EMB is measured and the partial pressure is calculated at the gas temperature in the EMB:

$$p_p = \varphi \cdot p, \tag{5}$$

the obtained value is compared with the table value p_p^0:

$$\left| p_p^0 - p_p \right| \geq E, \tag{6}$$

where E includes instrumental and methodological errors, and if this condition is met, the experiment is terminated and faults are detected in the measurement and data recording system.

4. Technique and program of experiments

The scheme of the experimental stand for the investigation of ultrasound influence on the intensification of the liquid evaporation process is shown in Figure 5.

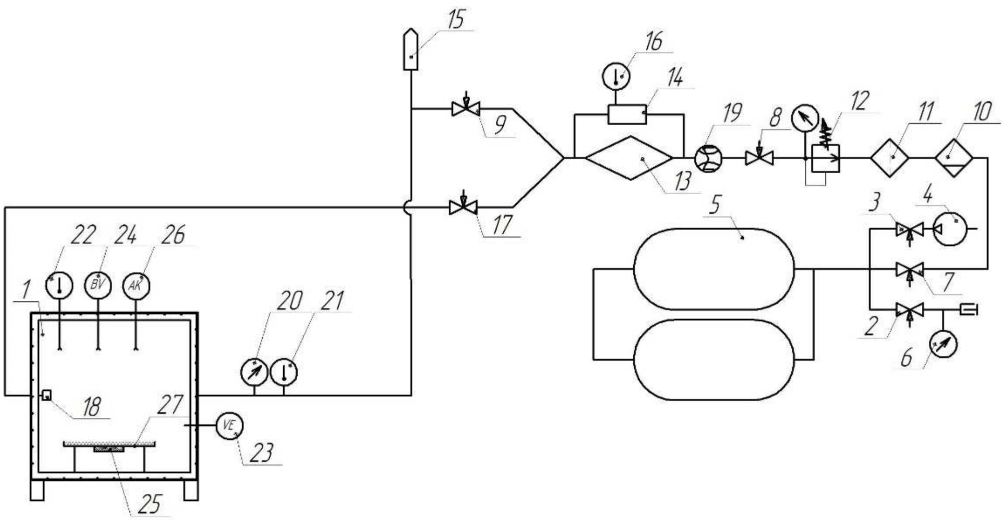

Figure 5: The scheme of the experimental stand:
1 - EMB; 2, 3, 7, 8, 9, 17 - valve; 4 - compressor; 5 – receivers; 6, 20 - pressure sensors; 10 - water separator; 11 - filter; 12 - valve with pressure sensor; 13 - electric heater; 14 - temperature regulator; 15 - outlet nozzle; 16, 21 - stationary temperature sensors; 18 - AGG; 19 - flowmeter; 22 - mobile temperature sensor; 23 - flow velocity sensor; 24 - gas humidity sensor in the EMB (hygrometer); 25 - MSE; 26 - analyzer of noise and vibrations; 27 – plate

Each group of experiments is conducted with acoustic influence and without acoustic influence with the use of AGG and MSE.
Parameters of the studied process are the following:
1. Liquid parameters:
- temperature with an accuracy of 1%;
- volume of liquid, determined using a high-speed video camera (60 frames / s);
- evaporation time.
2. HC parameters:
- temperature with an accuracy of 1%;
- mass-second flow with accuracy up to 0.3%;

DOI: 10.13009/EUCASS2017-115

- angle of input;
- velocity of flow of HC over the surface of the liquid with an accuracy of 4%.

3. Parameters of acoustic influence (AGG + MSE):

- frequency and amplitude of sound with an accuracy of 0.7%.

The efficiency of the liquid evaporation process was determined from the residual volume of liquid on the plate and the rate of evaporation of the liquid.

Measurement of the liquid volume was carried out using a high-speed video camera and a special measuring device located on the wall of the plate in the form of a scale with a division step of 1 mm.

5. Results of experiments

The evaporation process of a liquid uniformly spread on a plate was carried out with the following parameters: initial air temperature inside the EMB 22 °C; temperature HC (air) at the entrance to the EMB $56 \pm 2\,^0$C; ambient temperature 22 °C; consumption of HC (air) 200 l/min; evaporated liquid: water; volume of the evaporated liquid 250 ml; initial liquid temperature $15 \pm 1\,^0$C.

Figure 6 shows the graphs of the temperature change of the liquid (water) located uniformly on the plate with different evaporation options:

1 – without acoustic impact, only convective influence of the oncoming flow of HC;
2 – with acoustic influence with periodic inclusion of the generator MSE;
3 – with acoustic influence when using only AGG;
4 – with acoustic influence when using AGG and MSE.

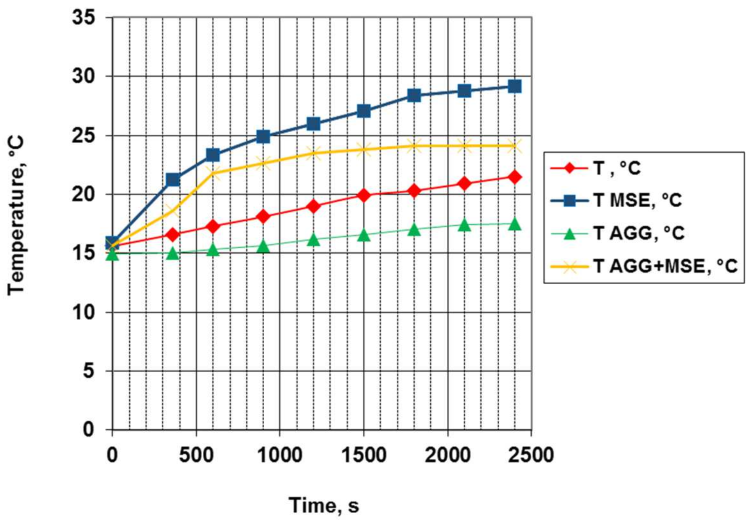

Figure 6: Graph of the temperature change of the liquid under acoustic influence with the use of AGG and MSE and without acoustic influence

When using AGG to brake a HC stream over the liquid surface the speed decreases from 3,3 m/s to 2,5 m/s. This explains the lower temperature and the dynamics of fluid heating when using AGG. The effectiveness of the AGG used depends on its correct location in the EMU to provide resonant force and uniform distribution of ultrasonic vibrations.

When using MSE there is a movement and a separation of bubbles from the surface of the evaporated liquid. This leads to the spraying of humidity in the volume of the EMB and its removal through the outlet and the convective component of the HC flow. The humidity level in the volume of EMB for different evaporation devices is shown in Figure 7.

DOI: 10.13009/EUCASS2017-115

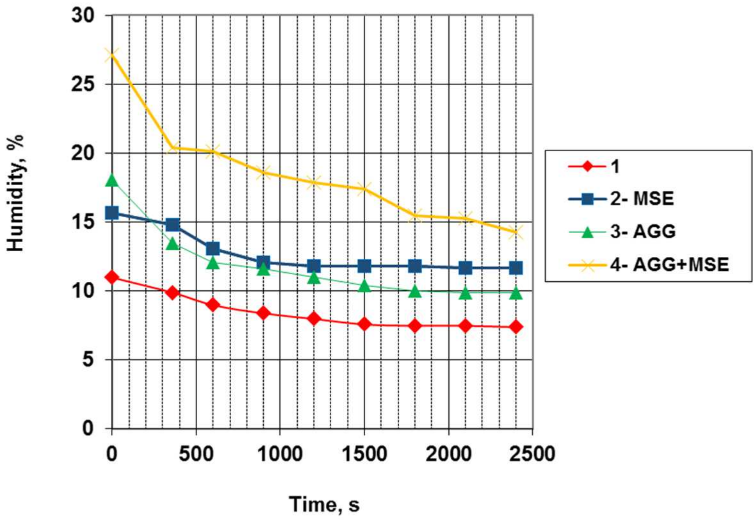

Figure 7: Humidity change in the volume of EMB under acoustic influence with the use of AGG and MSI and without acoustic influence

Figure 8 presents a comparative analysis of the change in the volume of the liquid for different evaporation options.

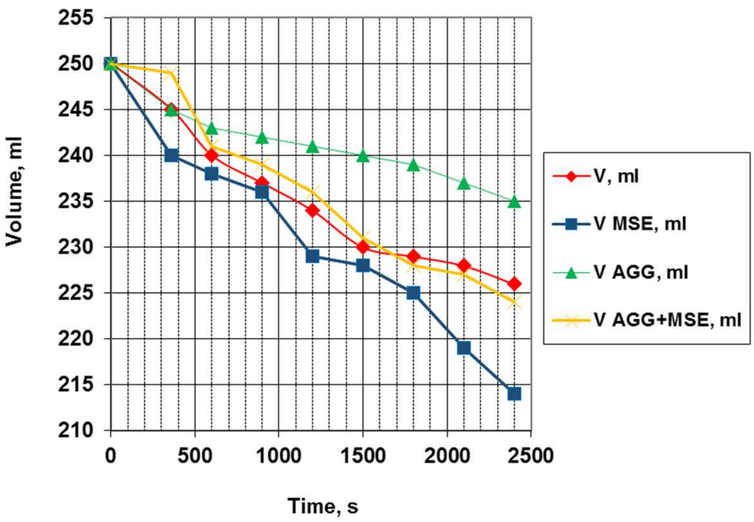

Figure 8: Change in the volume of liquid under acoustic influence with the use of AGG and MSE and without acoustic influence

The duration of the experiment is 2500 seconds due to the need to obtain more accurate results, since a scale with a division value of 1 mm is used to determine the liquid level, which is 10 ml of liquid.
From figure 8 it follows that exposure to ultrasonic vibrations using MSE allows an increase in evaporation rate from 0.5 to 0.9 ml/min. The rate of evaporation increases with increasing temperature and flow HC velocity.
The obtained results made it possible to make preliminary estimates of the change in the heat and mass transfer coefficients between the evaporated liquid and the HC for different evaporation options of the liquid (Figure 9, 10).

DOI: 10.13009/EUCASS2017-115

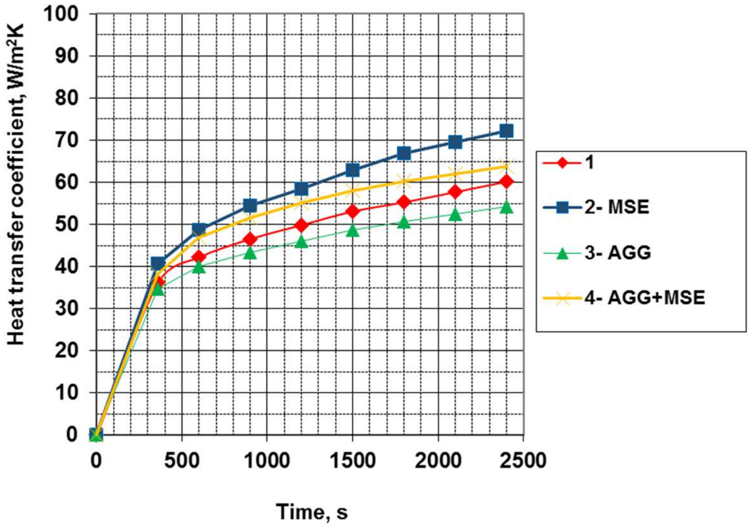

Figure 9: Change in the heat transfer coefficient under acoustic influence using AGG and MSE and without acoustic influence

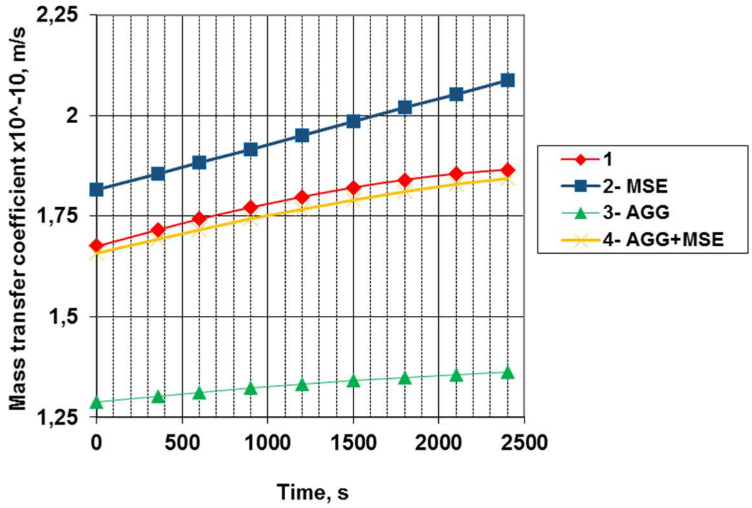

Figure 10: Change in the mass transfer coefficient under acoustic influence with the use of AGG and MSE and without acoustic influence

From figure 10 it follows that ultrasound with the use of MSE increases the mass transfer coefficient by 12%. The use of the AGG has practically no effect on the change in the mass transfer coefficient, due to the loss of velocity and temperature of the flow of HC on the AGG.

6. Conclusions

1. An experimental stand has been designed and realized that satisfies the similarity criteria for Nu, Re, Pr and Bi, allowing simulations of thermodynamic processes occurring in rocket tanks under zero-gravity conditions. A program and a procedure for conducting experiments using the AGG and MSE have been developed.
2. A series of experimental studies of liquid evaporation under acoustic influence and without acoustic influence was carried out. Values of temperatures of liquid and gas in volume of the EMB, and also changes of volume of the evaporated liquid are defined. The obtained results made it possible to determine the coefficients of heat and mass transfer at different stages of evaporation of the liquid.
3. The analysis of the obtained research results is carried out, which testifies the ineffectiveness of evaporation of a liquid using AGG. The reason for this is the imperfection of the design of the AGG used for existing boundary conditions and the existing capacitance that does not provide the resonant force of ultrasonic vibrations. The form of the container in which evaporation of the liquid takes place (EMB) should provide a resonant force and a uniform

distribution of the ultrasonic vibrations emitted by the AGG, while it is important to specify the correct direction of the airflow in the EMB [12].

4. The use of MSE leads to an increase in the heat transfer coefficient by 18%, while the evaporation velocity of the liquid increases from 0.5 to 0.9 ml/min. The use of AGG has practically no effect on the change in the mass transfer coefficient, while the velocity and temperature of the HC flow decrease, and the rate of evaporation of the liquid decreases from 0.9 to 0.37 ml/min as compared with the MSE.

Acknowledgments

Researches are conducted with financial support of the Ministry of Education and Science of the Russian Federation within the state task to the subordinated educational organizations, the *"Increase in ecological safety and economic efficiency of rockets with liquid rocket engines"* project application No. 9.1023.2017/PCh.

References

[1] Kudentsov V., Trushlyakov V. Developing of active onboard deorbiting, Kosmonavtika i raketostroenie (Cosmonautics and rocketbuilding). – 2009. - № 4 (57). pp. 109-117.
[2] Trushlyakov V.I. V. Kudentsov, I. Lesnyak, K. Rozhaeva, M. Dron, K. Zharikov, L. Galfetti. Gasification of liquid propellant residues in fuel tanks of upper stages to feed an onboard de-orbiting system // 6th European conference for aeronautics and space sciences (eucass), Krakow, 2015.
[3] Trushlyakov V.I., Kudentsov V.Yu., Lesnyak I.Yu., Lempert D.B., Zarko V.E. The modeling of unused propellant residues processes from a tank of rocket stage // Proceedings of the 56th Israel Annual Conference on Aerospace Sciences. Tel-Aviv & Haifa. Israel. 2016. ThL1T4.4.
[4] Trushlyakov V., Shalay V., Shatrov Ya. Decreasing of technological impact of SLV on liquid toxic components on the environment: Monograph / Ed. V.I. Trushlyakov, Omsk, OmSTU, 2004. 220 p. (in Rus.)
[5] Trushlyakov V., Lavruk S. Theoretical and experimental investigations of interaction of hot gases with liquid in closed volume // Acta Astronautica, 109, (2015) 241-247.
[6] Trushlyakov V., Kudentsov V., Lesnyak I. et al. Pat. 2474816 Russian Federation, MPK G01 N29/02. Method for modeling the process of gasification of residual liquid propellant and the device for its implementation.
[7] Trushlyakov V., Kudentsov V., Kazakov A., Kurochkin A., Lesnyak I. Experimental in: Omskiy nauchnyi vestnik (Omsk Science herald). – Omsk, 2011. – №2 (100). - pp. 150 – 153.
[8] Kubansky P.N. Intensification of heat transfer by acoustic currents in forced convection / Acoustic Journal, 1962, 8, 1, 85-90.
[9] Kubansky P.N. Influence of acoustic currents on the process of convective heat transfer / Acoustic Journal, 1959, 5, 1, 51-57.
[10] Physical basis of ultrasonic technology. Edited by prof. L.D. Rosenberg. Moscow: Nauka Publishers, 1969. - 689 p.
[11] Perminov S.A., Ermakov G.V. Boiling-up of superheated water and water solutions under ultrasound influence / Thermophysics and Aeromechanics, 2010. T. 17. № 1. C. 107-112.
[12] VN Khmelev, AV Shalunov, RV Barsukov, SN Tsyganok, AN Lebedev. Research of the efficiency of ultrasonic drying. Electronic journal "Technical Acoustics", http://ejta.org, 2009, 6.
[13] Theoretical bases of cold storage engineering. Heat and Mass Transfer: Textbook. Manual for universities on the specialty "Refrigeration and compressor machines and installations" / SN Bogdanov [and others]; Ed. E. I. Guigo, 1986. - 319 p.
[14] Lesnyak I.Yu., Lavruk S.A. Theoretical and experimental studies of thermodynamic processes in experimental model capacity / Dynamics of systems, mechanisms and machines: mater. IX Intern. Scientific-techn. Conf. - Book 2. - Omsk, OmGTU, 2014. - P.245-248.
[15] V.I. Trushlyakov, I.Y. Lesnyak1, L. Galfetti. Experimental investigation of convective heat transfer at evaporation of kerosene and water in the closed volume / Thermophysics and Aeromechanics, 2017, 6.
[16] Kutateladze SS, Borishansky VM Handbook of heat transfer. - Moscow: SEI, 1958. - 418 p.