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An experimental investigation of convective heat transfer at evaporation of kerosene and water in the closed volume*

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An evaporation of kerosene and water was investigated based on convective heat transfer in the experimental setup simulating a typical volume of the fuel tank of the launch vehicle. Basic criteria of similarity used in choosing the design parameters of the setup, parameters of the coolant and model liquids, were numbers of Reynolds, Prandtl, Biot, and Nusselt. The used coolants were gases, including air and nitrogen; in addition, at the stage of preliminary experiments, products of combustion of hydroxyl-terminated polybutadiene (HTPB) were considered. Boundary conditions were taken for the liquid located on the plate in the form of "drop" and at its uniform film spread in the experimental model setup. On the basis of experimental investigations, the temperature values were obtained for the system "gas-liquid-wall", and areas of mass transfer surface and heat transfer coefficients of “gas-liquid” and “gas- plate” were determined for coolants (air and nitrogen) and for liquids (water and kerosene). The comparative analysis of the obtained results and the known data was carried out. Proposals for experiments using coolants based on HTPB combustion products have been formulated.

Keywords: heat and mass transfer, fuel tanks, gasification, fuel components.

Introduction

Unused fuel residues (up to 3 % or more of the initial fuelling) in the tanks of rocket stages with cruising liquid rocket engines (LRE) provoke explosions in the stages of launch vehicles (LV) 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 [1]. 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 based on coolant supply in respective fuel tanks [2–4]. For each fuel component, a special coolant is selected; it should have certain physical and chemical characteristics, namely, chemical composition, temperature, second mass flow, and the scheme of input into the fuel tank.

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In a fuel tank of LV, after a cruising LRE shutdown and brake pulse application at stages separation, the boundary position of the liquid fuel residues is random. Experimental studies in the tower of weightlessness [5] showed possible options of residual liquid location after a cruising LRE shutdown and brake pulse application. These studies served to accept possible variants of boundary conditions of the fluid determined by its location in the form of drop or uniform film spread on the plate [6].

To study the process of convective heat transfer occurring in the LV fuel tank, the authors have developed an experimental setup comprising the coolant production system, the experimental model unit (EMU), the system of measurement, registration and processing of measurement results, and connecting as well as shutdown valves [7].

Conditions of convective heat transfer in the fuel tank between the coolant, fluid, the tank walls and the pressurizing gas are significantly different from the conditions of occurrence of the known thermal processes, boundary conditions, and structural materials [8−14]. Therefore, the use of available heat transfer coefficients is impossible, and they must be determined experimentally for each implementation of the process of heat and mass transfer, defined by the coolant parameters, the boundary location of the liquid, the tank design, thermodynamic parameters inside the tank, etc. The need to determine the heat transfer coefficients is confirmed by the evaluation, using the developed mathematical model [6], sensitive to the changing coefficients of heat transfer from gas to coolant and liquid. The change of heat transfer coefficient by 1% leads to the 0.2 % error in the amount of energy input; the liquid evaporation rate is determined with an error of 1.6 %. Thus, correct determination of heat transfer coefficients is critical because of the degree of their influence on the accuracy of the results.

Figure 1 shows a general scheme of gasification of liquid fuel residues in the LV tanks at coolant supply into the fuel and oxidizer tanks.

For experimental studies of convective heat transfer, modeling the gasification of liquid fuel residues in the tank on the ground experimental stand, it is necessary to ensure the similarity of the process under study. To use the existing EMU the similarity criteria were fulfilled by providing the following basic parameters: the coolant temperature and the flow rate. Table 1 shows the values of the similarity criteria (Reynolds, Nusselt, and Biot) to assess the possibility of modeling the thermodynamic processes in the existing EMU by the example of kerosene gasification in the tank of the second stage of LV of the type of «Soyuz-2.1 b». From the table, it follows that choosing the coolant parameters (temperature, impingement rate, kinematic viscosity) for the existing EMU, it is possible to provide the similarity conditions of heat and mass transfer on the basic criteria (Re, Nu, and Bi).

1. Problem statement

For the experimental determination of coefficients of heat transfer from gas mixtures, consisting of the coolant, pressurizing gas, and the evaporated component, to the liquid $\alpha_{\text{g-l}}$ and the plate $\alpha_{\text{g-pl}}$ on which the liquid is placed, it is necessary to develop an experimental stand. It should include a system of coolant production, EMU, the system of measurement, registration and processing of measurement results, and connecting and shutdown valves, and consider the similarity

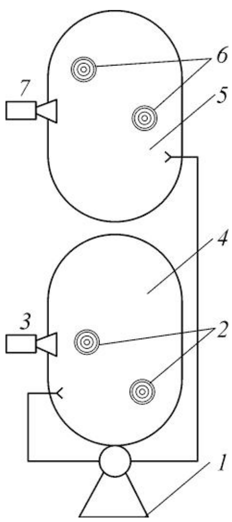


Fig. 1. Scheme of gasification of liquid fuel residues in LV tanks and utilization of gasified products.

1 — cruising LRE, *2* — liquid fuel residues (kerosene), *3* — gas generator feeding the coolant in the fuel tank, *4* — fuel tank (kerosene), *5* — oxidizer tank (liquid oxygen), *6* — oxidizer residues (liquid oxygen), *7* — gas generator feeding the coolant in the oxidizer tank.

Table 1

Source data for modeling heat and mass transfer processes occurring in the tank of LV stage by the example of kerosene gasification in the existing EMU

Item	Parameters	Fuel tank	EMU
1	Characteristic size, m	Tank length — 2.3	EMU diameter — 0.245
2	Coolant	Combustion products in gas generator: Kerosene + oxygen (1:0.7)	Nitrogen
3	Coolant temperature, K	1470–1500	373–423
4	Coolant velocity, m/s	5–6	8–15
5	Kinematic viscosity of the coolant, m^2/s	$8.3 \cdot 10^{-5}$	$36 \cdot 10^{-6}$
6	Reynolds number	10^5–$1.6 \cdot 10^5$	$9 \cdot 10^4$–$1.4 \cdot 10^5$
7	Nusselt number	350–440	330–420
8	Biot number	0.005	0.005

criteria given in Table 1. Moreover, the program of experiments and the source data for research should also be determined. The latter include: temperature, flow rate, chemical composition of the coolant as well as mass, temperature, boundary condition, and chemical composition of the model fluid in accordance with the parameters given in Table 1.

The heat transfer coefficients $\alpha_{\text{g-l}}$, $\alpha_{\text{g-pl}}$ were determined according to the formula proposed in [15]:

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

where Q_c is the convective heat flux from the coolant to liquid and plate, W; t_1 is the temperature of the coolant, K; t_2 is the temperature of the liquid or the plate, K; F is the area of the surface of the liquid or the plate, m^2; and i are the elements involved in the heat transfer of gas–liquid or gas–plate.

Using the obtained values of heat transfer coefficients, thermal conductivity of the coolant, and the plate size, the Nusselt numbers were determined by:

$$\mathrm{Nu} = \alpha_i d_{\text{pl}} / \lambda_{\text{clnt}} \,, \tag{2}$$

where d_{pl} is the plate diameter, m; λ_{clnt} is the thermal conductivity coefficient of the coolant, W/(m·K).

The calculated scheme for evaluating the parameters of the plate–liquid heat transfer using the Bi number, given the fact that the liquid is on the plate of finite dimensions in a stationary state, is presented in the handbook of heat transfer [16].

In the experiments, the following restrictions and assumptions were made:

1. Temperatures of the EMU walls, both metal and glass, of gas in the EMU volume, and of the liquid on the plate are taken averaged for each heat transfer actor, i.e., the temperature gradient is virtually absent.

2. Thermodynamic effects (convective heat transfer) on the liquid are considered based on the coolant supply on the liquid surface inside the EMU; chemical interaction is not taken into account.

3. The evaporation assumes the “frozen” state of the liquid, i.e., fixed, with no fluctuations of the free liquid surface.

4. For EMU, there are no heat flows between the fluid and the EMU wall, as the model fluid is placed on the plate, and heat flows between the plate and the EMU wall are negligible due to installed heat insulators.

5. The heat transfer coefficient from the coolant to gas is constant over the process time $\left(\alpha_{\text{clnt}} = \text{const}\right)$ and is not defined at this stage of the experiment.

2. Experimental stand

Experimental studies for determining heat transfer coefficients (1) were performed using the experimental setup in the SPLab laboratory of Milan Technical Unviersity (Politecnico di Milano) (Fig. 2), created on the basis of the similarity theory (Table 1). This setup, developed by joint efforts, allows studies using coolants of different composition, including air, nitrogen, and products of solid fuel combustion. At the present stage of research, we use solid fuel of hydroxyl-terminated polybutadiene, HTPB, which is applied as rocket fuel. The experimental stand consists of the following parts:

– coolant production systems based on the combustion of solid fuel of HTPB type (with combustion temperature up to 1073 K and pressure in the combustion chamber up to 0.5 MPa) or using a compressor with receiver or gas cylinders (nitrogen) and heater (with coolant temperature in the range from 293 to 423 K and second flow rate up to 25 l/min);

– EMU with height of 0.135 m, diameter of 0.245 m, wall thickness of 0.005 m and with available device for coolant supply (excessive pressure inside reaches 0.2 MPa);

– systems of measurement, registration, and processing of measurement results, consisting of mobile temperature sensors, pressure and flow rate sensors, videocamera, and oscilloscope;

– connecting and shutdown valves, which represent a system of hoses, fittings, and ball valves, ensuring the tightness of connections at a pressure up to 0.5 MPa.

The evaporated liquids in the experimental research were the aviation kerosene Jet A-1 (C12H23) and the model liquid (water). The model liquid was located on the plate made of aluminum. The plate parameters were as follows: the wall thickness $\delta = 0.002$ m, its diameter $d = 0.06$ m, and the blackness degree of the plate surface $\varepsilon \approx 0.11$.

Diagram of the coolant input and gas output (consisting of evaporated liquid, coolant and pressurizing gas in the EMU) in EMU is shown in Fig. 3. 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.

3. Experimental results

3.1. Liquid evaporation at its uniform film spread on the plate ("mirror")

The process of liquid evaporation at its uniform film spread on the plate is realized with the following parameters: the initial temperature of air inside the EMU equal to 295 K, the coolant temperature (nitrogen, air) at the inlet to EMU equal to 373 ± 2 K, ambient temperature of 295 K, and the coolant flow rate (nitrogen, air) of up to 25 l/min. The evaporated liquid, whose volume was 7.5 ml, consisted of kerosene Jet A-1 and water.

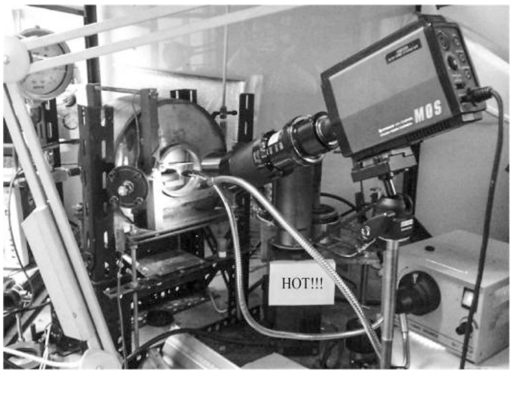
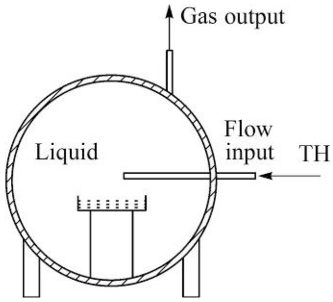


Fig. 2. Experimental stand for studying liquids evaporation.

Fig. 3. Diagram of the coolant flow input and gas output (evaporated liquid + coolant + pressurising gas in the EMU) from EMU.



Figures 4 and 5 show the graphs of changes in heating temperatures of liquid (kerosene and water), gas in the EMU volume and the EMU wall over the evaporation time of liquid evenly spread on the plate. Temperatures in the experiments were measured using three thermocouples installed on the EMU wall, on the liquid surface, and in the EMU volume. The comparative analysis of the experimental results (Figs. 4 and 5) has shown that water evaporation occurs faster than that of kerosene because of the high boiling point of kerosene (up to 573 K) compared to water. From the time of 1500 s (Fig. 4), the thermocouple is stripped off, and temperature sharply increases. The graph of Fig. 5 shows that the temperature of kerosene, gas, and the EMU wall increases smoothly, without jumps, until complete evaporation of the kerosene. The level of evaporated liquid (water, kerosene) is registered during the experiment using high-speed cameras and specially installed measuring devices in the form of a cylinder with a scale of 1 mm.

Line 1 in figures 6 and 7 shows experimental data of changes in the levels of water and kerosene located on the plate ($\overline{h} = h / h_{\text{init}}$), which correspond to the time of the experiment ($\overline{t} = t / t_{\text{tot}}$). The initial level of water and kerosene on the plate is $h_{\text{init}} = 0.0035$ m. Line 2 is quadratic approximations of the change in the level of water h_{w} and kerosene h_{k} on the plate, written in the form of polynomials of second degree

$$h_{\text{w}} = (-0.8636\overline{t}^2 - 0.1818\overline{t} + 1.0118)\, h_{\text{init}} \tag{3}$$

and

$$h_{\text{k}} = (0.5606\overline{t}^2 - 1.5788\overline{t} + 1.0173)\, h_{\text{init}}. \tag{4}$$

To obtain the approximation formulas (3) and (4), it was necessary to determine the respective coefficients of determination $R^2 = 0.9931$ and $R^2 = 0.9875$ showing the percentage of dispersion of experimental points of changes in the level of water and kerosene due to measurement errors.

3.2. Evaporation of a drop of liquid located on the plate

The evaporation of a liquid drop located on the plate was realized at parameters given in section 3.1 at evaporated liquid volume (kerosene Jet-A1) from 0.03 to 0.05 ml.

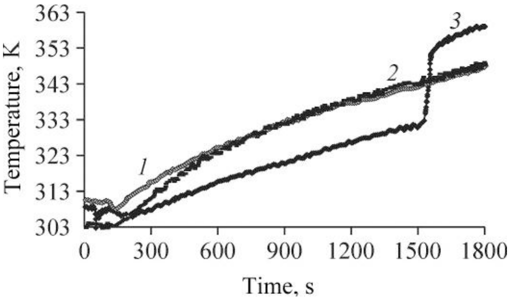


Fig. 4. Graph of changes in temperatures of water, gas, and EMU wall.
Temperatures of gas (1), wall (2), and water (3).

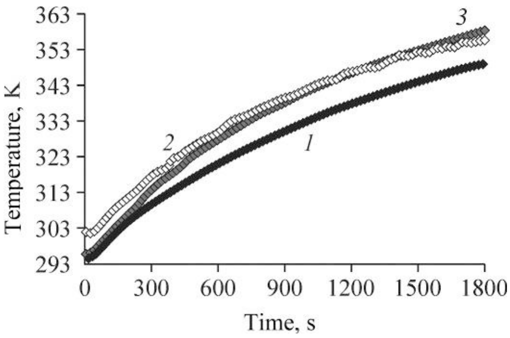


Fig. 5. Graph of changes in temperatures of kerosene, gas, and EMU wall.
Temperatures of gas (1), wall (2), and kerosene (3).

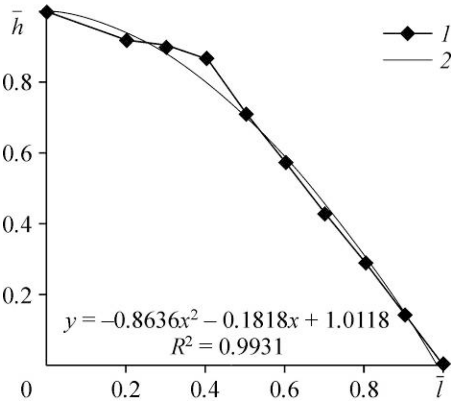


Fig. 6. Graph of water level change on the plate.

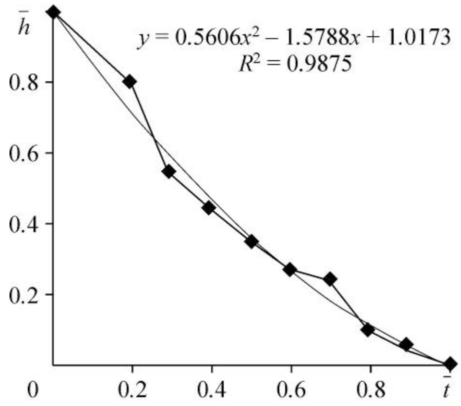


Fig. 7. Graph of kerosene level change on the plate.

Since kerosene is a liquid with high wettability, a thermocouple was used to obtain a drop of kerosene. It helped to avoid the drop outflow on the plate, and allowed determining its temperature change. Figure 8 shows a graph of changes in the temperature of a drop of kerosene over evaporation time. Analysis of the research results on gasification of a drop of kerosene shows that from the initial time up to 390 s, the drop temperature does not change; from the time of 390 to 750 s, a sharp increase by 30 % is observed; and from the time of 750 s, there is a sharp decrease in temperature due to the thermocouple stripping-off and its closure with the plate surface.

Figure 9 shows video frames of the evolution of a drop of kerosene in the process of heating and evaporation.

Line *1* in Fig. 10 shows experimental data on the change in the area of the evaporated drop of kerosene S_k, located on the plate ($\bar{S} = S_k/S_{init}$), corresponding to the time of the experiment ($\bar{t} = t/t_{tot}$), and line 2 is a quadratic approximation of the change in the area of the drop of kerosene S_k, written as a polynomial of the second degree (5)

$$S_k = (-0.1166\bar{t}^2 - 0.9525\bar{t} + 1.0534)\cdot S_{init}, \tag{5}$$

where S_{init} = 50 mm^2 is the initial area of the contact spot of a drop of kerosene. For the obtained approximation formula (5), we defined the coefficient of determination R^2 = 0.9771, showing the proportion of dispersion of experimental points of change of the contact spot area of a drop of kerosene due to measurement errors. Approximation formulas (3)–(5) are used to refine the mathematical model of water and kerosene evaporation.

The obtained results allowed a preliminary assessment of the change of heat transfer coefficients at various coolant velocities (Table 2).

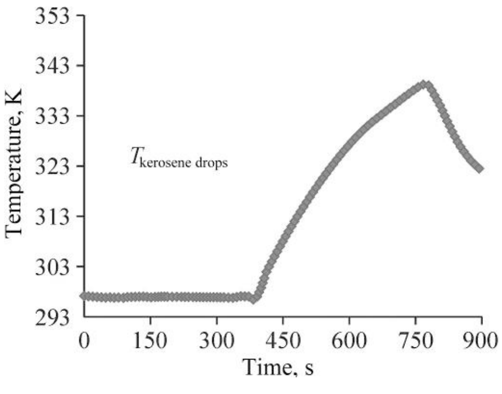


Fig. 8. Graph of temperature changes of a drop of kerosene.

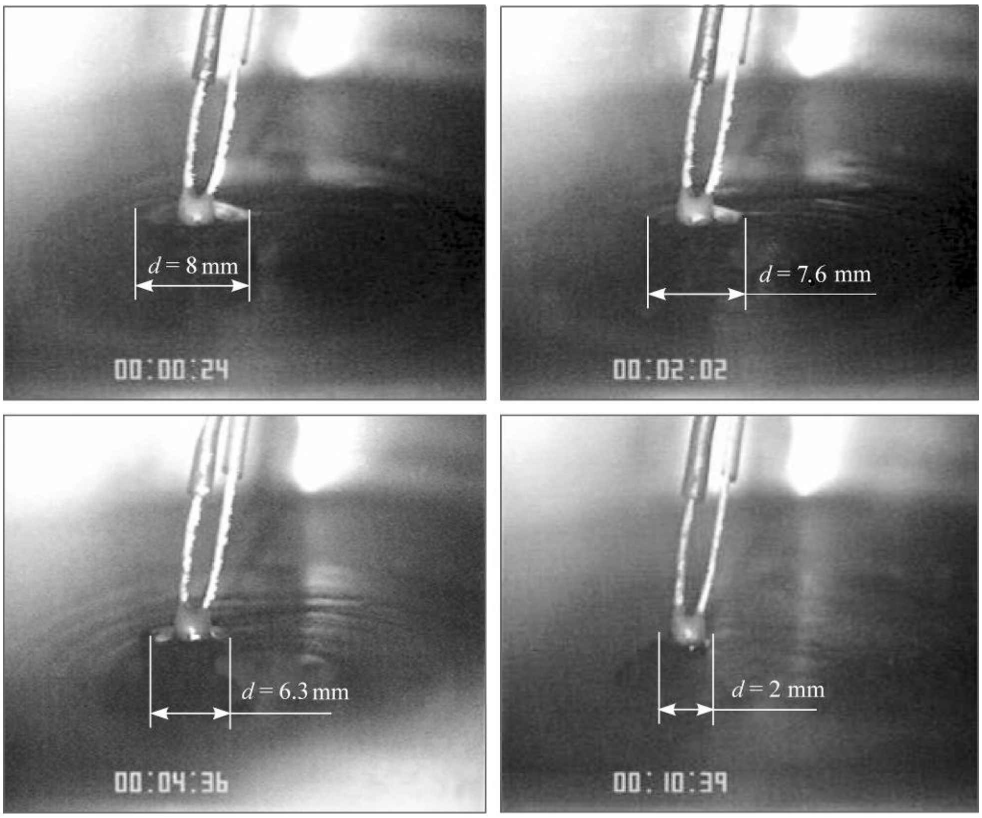


Fig. 9. Fragments of videoshooting of heating and evaporation of a drop of kerosene.

To refine dependencies in the form of criterial equations, using experimental data, we built graphs of lg Re – lg Nu and lg (Nu/Re) – lg Pr, which served to determine the values of coefficients *C* and the exponential factors *m* and *n*:

$$\mathrm{Nu} = C\,\mathrm{Re}^{m}\,\mathrm{Pr}^{n}\,. \tag{6}$$

Thus, on the basis of experimental studies, the following refined criterial equations may be proposed:

– from gas to plate: $\mathrm{Nu} = 0.05\,\mathrm{Re}^{0.65}\,\mathrm{Pr}^{0.43}$, (7)

– from gas to kerosene (“mirror”):

$$\mathrm{Nu} = 0.04\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}, \tag{8}$$

– from gas to kerosene (“drop”):

$$\mathrm{Nu} = 0.05\,\mathrm{Re}^{0.75}\,\mathrm{Pr}^{0.43}, \tag{9}$$

– from gas to water (“mirror”):

$$\mathrm{Nu} = 0.05\,\mathrm{Re}^{0.57}\,\mathrm{Pr}^{0.43}\,. \tag{10}$$

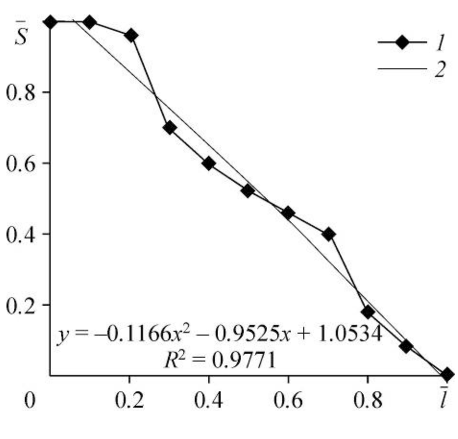


Fig. 10. Graph of changes in the area of a drop of kerosene on the plate.

Table 2

Values of heat transfer coefficients in gas-liquid and gas-plate systems at different values of coolant flow velocity in EMU and boundary conditions of liquid location on the plate

Coolant flow velocity, m/s	Re	Gas-plate		Gas-kerosene "mirror"		Gas-water "mirror"		Gas-kerosene "drop"	
		Nu	α_{g-pl}, W/m^2·K	Nu	α_{g-l}, W/m^2·K	Nu	α_{g-l}, W/m^2·K	Nu	α_{g-l}, W/m^2·K
8	$5.69 \cdot 10^4$	343	44.1	353	45.4	366	51.6	343	48.3
9	$6.04 \cdot 10^4$	367	47.2	378	48.6	392	55.2	366	51.6
10	$7.11 \cdot 10^4$	390	50.1	402	51.7	416	58.6	389	54.8

To confirm the reliability of the research results the obtained criterial equation (7) was compared with the dependence (11) for heat transfer in turbulent streamlining of a flat plate by a forced flow [15, 17]:

$$\mathrm{Nu} = 0.037\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}. \tag{11}$$

The results of the comparative analysis are shown in Fig. 11.

The values of the coefficient $C = 0.05$ and the exponent $n = 0.43$ and $m = 0.65$ depend on the flow regime (laminar, transitional, or turbulent). In this case, the flow regime is turbulent, as $\mathrm{Re} > \mathrm{Re}_{cr}$, and is $9 \cdot 10^4 - 1.4 \cdot 10^5$. The experimental value of exponent $n = 0.43$ of the Prandtl number (Pr) corresponds to the exponent of the known relationship (11), since in both cases, air, for which Pr = 0.68, is used as a coolant flow.

In Fig. 11, curves (1) and (2) are close to each other, and the discrepancy of Nu numbers is up to 10 %, so assumably, the obtained results are close to be accurate.

Table 3 presents a comparative analysis of coefficients *C* and exponents *m* and *n,* the obtained refined dependence (7), and the known dependence (11). The realized comparative analysis presented in Table 3 has showed that the deviation of the coefficient *C* from the known dependence (11) is 26 %, and that of the exponent *m* is 42.9 %, which may be explained, first, by a structural difference in experimental setups, secondly, by the type and scheme of coolant supply, and thirdly, by the experimental methodology.

3.3. Model liquid evaporation at the use of combustion products of solid fuel as coolants

The model fluid evaporation at its uniform film spread on the plate was carried out with the following parameters: coolant is the products of solid fuel combustion (HTPB), the initial temperature of gas inside the EMU is 295 K, ambient temperature is 295 K, the model liquid is water, and the volume of evaporated model liquid is from 18 to 20 ml.

Figure 12 shows the graph of temperature change of coolant, gas in the volume of EMU, and the EMU wall during evaporation.

Analysis of the results of studies of liquid evaporation using combustion products of solid

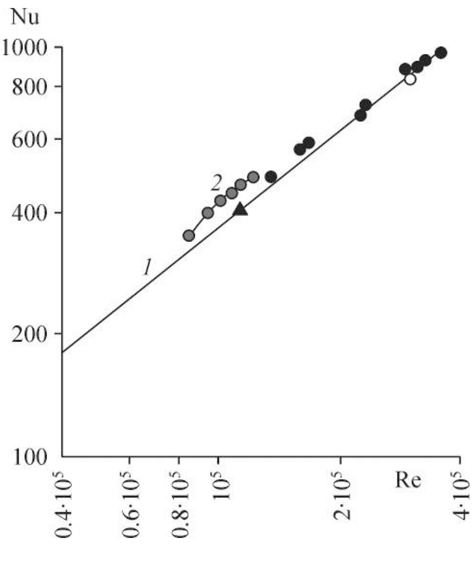


Fig. 11. Comparative analysis of experimental data for heat transfer at turbulent streamlining of a flat plate by a forced flow and the known dependence.

1 — known dependence $\mathrm{Nu} = 0.037\mathrm{Re}^{0.8}\mathrm{Pr}^{0.43}$.
2 — refined dependence $\mathrm{Nu} = 0.05\mathrm{Re}^{0.65}\mathrm{Pr}^{0.43}$.

Table 3

Comparative analysis of coefficients *C* and exponents *m* and *n* of the obtained refined dependence (7) and the known dependence (11)

Criterial equations	Determined parameters		
	C	*m*	*n*
The known $Nu = 0.037Re^{0.8} Pr^{0.43}$ (11)	0.037	0.8	0.43
The refined $Nu = 0.037Re^{0.65} Pr^{0.43}$ (7)	0.05	0.56	0.43
Deviation from the known dependence (E). %	26	42.9	0

fuel (HTPB) as coolant has shown that the temperature of coolant supplied in the EMU increases sharply, thus slightly increasing the temperature of gas, liquid, and EMU walls. After the entire combustion of HTPB, the flow rate and the temperature of coolant sharply decrease to zero. Determining the values of temperature and area of evaporated liquid surface is not possible because of the formation of precipitate of solid fuel combustion products on the plate.

It should be noted that the duration of the evaporation process depends on the amount of burnt HTPB; ensuring the constant coolant temperature and flow rate with existing equipment is difficult.

4. Discussion of the obtained results

Based on the analysis of the results of experimental research, it may be concluded that the coefficients of heat transfer from the gas to the plate and different fluids, in this case water and kerosene, have different values that is due to changes in heat transfer surface parameters at forced convection in a closed volume of EMU.

Considering that the Nu criterion changes depending on the Re criterion, and that the characteristic size and the thermal conductivity of the elements involved in heat transfer maintain constant values for the whole series of experiments, it becomes obvious that the variability of Nu is caused by the changing heat transfer coefficient α_i. In turn, the heat transfer coefficients depend on the temperature change of the system "gas–liquid–wall", the area of mass transfer surface of the evaporated liquid, and parameters of the supplied coolant (temperature, velocity, specific heat, and thermal conductivity).

The resulting value of changes in the level of mass transfer surface of water and kerosene at additional determination of gas wettability allows determining the mass transfer coefficient at subsequent stages of the research.

Analysis of the results obtained for liquid evaporation using the coolant as HTPB has shown that during HTPB combustion, a significant precipitation on the plate and a short and sudden increase in the coolant temperature occur. Ensuring the constancy of the coolant temperature and flow rate at this stage of the research is difficult.

Conclusions

The experimental setup, including the EMU, the system of coolant production, the system of measurement, registration, and processing of measurement results,

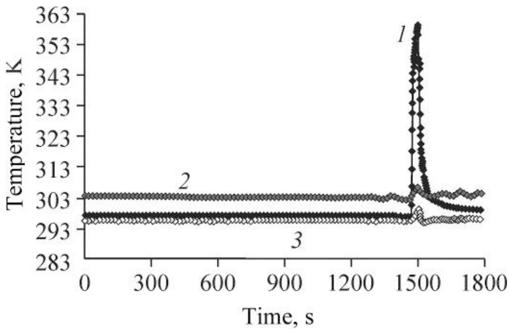


Fig. 12. Graph of temperature change of coolant (*1*), wall (*2*), and gas inside the EMU (*3*).

and the connecting and shutdown valves has been developed. The experimental stand that satisfies the similarity criteria (Nu, Re, Pr, and Bi) allows simulating the thermodynamic processes occurring in the tanks of the launch vehicle stages in terms of weightlessness.

A series of experimental studies has been performed, and the results have been obtained in the form of values of temperature of fluid (water, kerosene), EMU walls and gas in the EMU volume consisting of the coolant, air and products of vaporization as well as the area of mass transfer surface of the evaporated liquid. The obtained results allow determining the coefficient of heat transfer from gas to liquid and plate and criterial equations at this stage of the research.

The obtained criterial equation for heat transfer in the turbulent flow around the plate surface due to the forced flow has been compared with the known dependence; as a result, the discrepancy in the Nusselt numbers is obtained to be equal to 10 %.

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