Experimental research of thermal loading of the rocket payload fairing element during the atmospheric phase of the descent trajectory

V Trushlyakov, Yu Iordan, D Davydovich and K Zharikov, M Dron’

Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia

e-mail: u1tro@mail.ru

Abstract. The thermal loading physical simulation in the experimental wind tunnel on the design element of the payload fairing made of carbon fiber was done. The experimental study is given in the speed range below 70 m/s, which corresponds to the interval of heights of the descent trajectory of the payload fairing half below 10 km. The values of heat transfer coefficient are obtained. The analysis of the results is carried out.

1. Introduction
When launching rockets in the boost phase of flight the spent rocket design elements (RDE), such as boosters, steps, fairings, interstage compartments separate.

The fall of the separated parts of the Earth’s surface is a source of economic, environmental and social issues arising in the implementation of space-rocket activity. The speed of the separated parts to the atmosphere is significantly different from 1 km/s to 7 km/s, which leads to various environmental impacts: from the fall almost as much as RDE, for example, fairings to almost complete combustion of RDE (boosters the second and third steps) in the dense layers of the atmosphere.

At the present time, the problem of RDE destruction returning from space into the Earth's atmosphere having velocities of about 7 km/s, is described in the significant number of works [1–2]. The developed mathematical models include the estimation of the centre of mass and around centre of mass motion parameters, the thermal load from aerodynamic effects and assess the RDE strength. The specificity of this RDE class is that their parameters while entering the atmosphere (velocity of entrance and entrance angles) are within the range of velocities about 1.0 km/s. Because of their aerodynamic characteristics, the velocity in the dense layers of the atmosphere significantly decreases, reaching values about several tens of m/s, respectively, the aerodynamic heating of RDE is significantly lower and RDE reaches the Earth's surface without a lot of destruction. It leads to the necessity of providing large territories for their impact areas [3].

2. Statement of the research problem
As possible technology, circuit and design solutions for minimizing the creation of space debris, on the example of the RDE (payload fairing halves and adapter sections), their combustion on the atmospheric phase of the descent trajectory after separation from the launch vehicle using the installation of additional heat sources, for example, pyrotechnic composition (PC) producing the required quantity of heat, is proposed [4].
At the first stage of the research, with the purpose to estimate the amount of the required heat, providing RDE combustion or destruction into fine particles (fine dispersion) on the atmospheric phase of the descent trajectory, it is necessary to define the heat fluxes determined by the aerodynamic heating, including heat loss and heat coming from the PC burning. [5]

The article presents experimental research of the thermal state of the RDE, made of polymer composite materials: carbon fiber KMU-4L, textolite PTK. The experimental study is given in the speed range below 70 m/s, which corresponds to the interval of heights of the descent trajectory of the payload fairing half below 10 km.

3. Physical experiments review
The purpose of the experiments is to determine the RDE surface temperature variation and, based on the calculation of heat transfer coefficients at aerodynamic loading in an experimental wind tunnel (EWT). The experimental bench described in [6] allows to simultaneously simulating the aerodynamic and thermal influences on the test sample.

The experimental stand consists of system for air preparation, EWT, measuring system, valves and control equipment.

In accordance with the conditions of the RDE aerodynamic load on the atmospheric phase of the descent trajectory, experimental stand and the EWT should implement the following conditions:

- the air flow rate in the range of 1...460 m/s (Mach 1.4);
- turbulence air flow $E_0 = 0.05...0.3$;
- the air flow temperature in the range of 260...295K;
- the flow compression $\varepsilon = 0.6...0.625$;
- the humidity of the air stream should not exceed 30%;
- the RDE blowing angles $0...90^\circ$
- the size of the EWT camera: 174mm x 50 mm;
- RDE specifications: overall dimensions must not exceed 40mm x 40mm x 15mm.

Measured parameters and measurement accuracy:

The temperature is measured in at three point (1 – is the flow temperature away from the sample; 2 – is the RDE temperature from the oncoming flow; 3 – is the RDE temperature on the back side).

Figure 1 shows a fragment of EWT. The EWT is a direct-flow type with a closed working part of circular cross-section with a diameter of 174 mm and a length of 280 mm. Aerodynamic flow to the working part has a medium level of turbulence ($E_0 = 0.1$) in the absence damping screen to provide more realistic conditions for the experiment.

The degree of flow compression is adjusted by replacing the nozzle to ensure a wide range of flow rates at the entrance to the working part with the same initial pressure.

The EWT consists of the working part (POS. 6) made of a welded cylindrical structures made of steel 41CrMO Steel, mounted on a pedestal. To the wall of the working part is welded to the diffuser main part. With the two screws (POS. 12) inside the working part includes a holder (POS. 7) for mounting the RDE (POS. 8) with screw clamps. On top of the case has 4 fitting (POS. 15) with a diameter of 6 mm for the installation of the thermocouples and measuring the temperature. To estimate flow velocity in front of the RDE envisaged the possibility of installation in the fitting (POS. 2) velocity sensor. Additionally, in horizontal section, has two fitting symmetrically relative to each other. The first is to measure the pressure in the working part, the second for supplying power from the power source to the heating element (POS. 1) in the plate form.

The counterpart is made in the form of a cover with nozzles (POS. 9), which is connected by means of bolted connections (POS. 10) with the working part. The tightness of the seals (POS. 11).

The working part is connected with a supply line and a gas receiver by means of the pipe to straighten the flow. After straightening the flow, gas for RDE blowing flows through set vortex flowmeter "EMIS Vortex 200".

Between the pipe (POS. 3) and the working part, replacement set of critical nozzles (POS. 4) made of polymer materials in the 3D printer.
Figure 2 shows photographs of the working parts and nozzles with critical cross-section of 8 and 20 mm.

**Figure 1.** Scheme of the EWT working part.
1 – is the heating element; 2 – is the fitting for the velocity measuring; 3 – is the flow straightener; 4 – is the replacement of critical nozzles; 5 – is the seal; 6 – is the case of the working part; 7 – is the holder; 8 – is the RDE; 9 – is the counterpart; 10 – is the counterpart fixture; 11 – is the counterpart sealing; 12 – is the holder fixture; 13 – is the fitting; 14 – is the heating element power strip; 15 – fitting for temperature measuring.
The methodology of the experiments involves the following sequence:

- pre-purging of air receivers, the possible withdrawal of moisture from the tanks;
- injection receivers gas to a pressure up to 1.5 MPa;
- installation of RDE on the holder and connect the heating element plate;
- testing, installing, configuring, thermocouples and velocity sensors;
- check the metering data on flow, pressure, velocity and temperature measuring-computing complex;
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- connect the power source to the heating element;
- conducting experiments;
- saving and processing of the received data after the end of the experiment, disconnect power from the stand, removal of the RDE, purge the system and release residual pressure from the receivers.

The study was conducted series of experiments, where pre-heating of RDE to the established temperature, with subsequent input of the oncoming flow.

In all cases, RDE was a plate of rectangular cross section. As the test materials were chosen two of the most used: carbon fiber KMU-4L, textolite PTK.

In all cases RDE in the form of plate with a side length of 29 mm to 33 mm, thickness 2 mm. It was placed vertically at an angle of attack equal to 90 at a distance of 180 mm from the critical section (figure 3). With RDE clamps it is attached to the heater for maximum contact area.
Samples of RDE are pre-heated to a temperature of 423 K on the outer surface (600K to side of heater) at a flow velocity of V= 0 m/s. After reaching the set temperature the samples were submitted by the oncoming flow at various velocities V: 0 m/s, 30 m/s, 50 m/s, 70 m/s. The temperature measurements were made at three points: in the place of the air flow on the RDE, directly from the heater surface (as occurs contact heat transfer can be considered that the temperature on the back side of the RDE is equal to the temperature of the heater) and in the area of lack of RDE. The experiment was completed after the establishment of constant temperature on RDE during blowing the air flow.

Processing of the obtained results was carried out using a number of dependencies, described in [7]:

- The temperature is recalculated in the values of the excess temperature $\Delta T$, [K] as the temperature difference;
- Define the values of $\ln(\Delta T)$ with accuracy to the third decimal place;
- Plot the $\ln(\Delta T)=f(\tau)$;
- Through the points of the graph are averaging line and its slope is determined by the cooling rate:

$$m = \frac{\ln(\Delta T_2) - \ln(\Delta T_1)}{\tau_2 - \tau_1};$$

(1)

- Indices 1 and 2 refer to any two points lying on a straight averaging.

The total heat transfer coefficient is determined from the equation:

$$\alpha_z = \frac{M}{F} C_f m,$$

(2)

where: $M/F=2.01$ [kg/m3] is the constant of the sample (assuming that the mass and size of the sample does not change during the experiment); $C_f$ [J/(kg·K)] – is specific heat capacity; $m[\text{c-1}]$ – is the cooling rate specified in the graphic.

Given the constancy of the coefficients entering in (2):

$$\alpha_z = 49.245 \cdot m.$$

(3)

The average value of the radiation heat transfer coefficient is determined by the average temperature during the experiment. As the environmental temperature we accept temperature of a room:

$$\alpha_R = C \left( \frac{T_s}{100} \right)^4 - \left( \frac{T_f}{100} \right)^4 \frac{T_s - T_f}{T_s - T_f},$$

(4)
where $C=4.762 \text{ W/(m}^2\cdot\text{K}^4)$ is the emissivity coefficient of the plate surface (the degree of blackness for the material of 0.84); $T_f$ [K] is the environmental temperature far from the plate; $T_s$, [K] is the mean value of temperature during the experiment.

In the end, the heat transfer coefficient can be calculated:

$$\alpha = \alpha_e - \alpha_R.$$  \hspace{1cm} (5)

The total error of determination does not exceed ±10%.

4. The results of the experiments

In tables 1 and 2 are the values of the heat transfer coefficient is set $\alpha_{se}$ for two types of materials (textolite PTK and carbon fiber KMU-4L).

The last column shows the comparison of the simulation results obtained in [8].

Table 1. The results of experimental studies material: textolite PTK

| The velocity flow, $V$ [m/s] | $T_f$/T_2 [K] | The experiment time [s] | The cooling rate, $m$ [s$^{-1}$] | $\alpha_e$, [W/m$^2$\cdot K] | $\alpha_R$, [W/m$^2$\cdot K] | $\alpha_{se}$, [W/m$^2$\cdot K] | $\alpha_{teor}$, p. 3 [W/m$^2$\cdot K] |
|--------------------------|----------------|--------------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 10                       | 600/423        | 65                       | 0.0277                        | 85.097                      | 10.968                      | 74.129                      | 70.362                      |
| 50                       | 600/423        | 65                       | 0.0341                        | 104.758                     | 11.613                      | 93.145                      | 98.166                      |
| 70                       | 600/423        | 65                       | 0.0383                        | 117.661                     | 11.955                      | 105.706                     | 101.645                     |

Table 2. The results of experimental studies material: KMU-4L

| The velocity flow, $V$ [m/s] | $T_f$/T_2 [K] | The experiment time [s] | The cooling rate, $m$ [s$^{-1}$] | $\alpha_e$, [W/m$^2$\cdot K] | $\alpha_R$, [W/m$^2$\cdot K] | $\alpha_{se}$, [W/m$^2$\cdot K] | $\alpha_{teor}$, p. 3 [W/m$^2$\cdot K] |
|--------------------------|----------------|--------------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 10                       | 600/423        | 90                       | 0.0280                        | 113.475                     | 12.913                      | 100.562                     | 90.231                      |
| 30                       | 600/423        | 90                       | 0.0333                        | 134.928                     | 13.249                      | 121.679                     | 112.875                     |
| 50                       | 600/423        | 90                       | 0.0388                        | 157.005                     | 13.583                      | 143.422                     | 135.002                     |
| 70                       | 600/423        | 90                       | 0.0420                        | 170.005                     | 13.888                      | 156.117                     | 150.226                     |

where: $T_2$ and $T_3$ is initial temperature in accordance with figure 3.

Figures 4a and 5a present the results of experimental studies for the above materials. For comparison, in figures 4b and 5b the results of calculations of temperatures from the time of leakage flow [8].
**Figure 4.** Graphs of temperature change from the blowing time of the material Textolite PTK at an initial temperature of $T = 423$ K: a) experimental, b) theoretical [8].
5. Results and discussion

The difference of heat transfer coefficients, defined based on numerical [8] and an experimental simulation is less than 10%.

A theoretical model [8], which compared the proposed airflow physical model to the various surfaces, was calculated under the same initial conditions as in the case of the experiment.

Initial and boundary conditions:

- RDE model dimensions – 30 x 30 mm;
- The heat capacity of the PTK material – 1470 J/kg·K;
- The heat capacity of the KMU-4L material – 1300 J/kg·K;
- Oncoming flow parameters: temperature 295 K; pressure 101325 PA; density of 1.22 kg/m³; flow velocity from 10 to 70 m/s, perpendicular to the plane of the RDE model.

In terms of reliability, as with any land-based studies (trials) in wind tunnels, the model remains motionless, and the energy expended for receiving the gas stream flowing around the model.

When modelling external flow around a jet area \( F_C \) several times more cross sectional area of the model \( F_0 \):

\[
f_3 = \frac{F_c}{F_0}
\]  \( \text{(6)} \)

The flow-cluttering coefficient is \( f_3 = 14.056 \).
According to the results of the data of physical modelling the insight into the values of heat transfer coefficients of the materials (PTK, KMU-4L) at low free-stream velocities is obtained.

It is planned to change in the angle of oncoming flow and expansion of the velocities range up to transonic velocities, the use of real PC as a source of thermal energy, the consideration of sandwich materials with honeycomb core with the addition of a real PC.

6. Conclusion

1. The formulation of experimental studies of the thermal loading RDE rocket fairing during the atmospheric phase of the descent trajectory, realizing the aerodynamic loading corresponding to the real conditions is carried out.
2. Experimental studies have shown the indicative requirements for the amount of heat flow from the PC is required to ensure the heating process to the RDE combustion temperature.
3. The experimental stand and experimental wind tunnel for studying the thermal regime of the RDE from an additional source of heat and aerodynamic inflow and entrainment of heat at free-stream velocities corresponding to the real values and experiments programme and methods of processing the results of experiments are developed. The direction for further research is obtained

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