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Research of thermal loading of the separated rocket design elements in the atmospheric phase of the descent trajectory

V. Trushlyakov, K. Zharikov*, M. Dron'*, Yu. Iordan*, D. Davydovich**
** Omsk State Technical University, av. Mira 11, Omsk, 644050, Russian Federation*
vatrushlyakov@yandex.ru;
kozharikov@yandex.ru;
u1tro@mail.ru;
iordanyuliya@gmail.com;
davydooovich@gmail.com

Abstract
The thermal load parameters by the example of payload fairing half when moving in the atmospheric phase of the descent trajectory are defined. The methods used to estimate the thermal load on the basis of a centred-set model (the motion of a material point), the distributed model (Navier-Stokes). The physical simulation of the experimental wind tunnel on the design element of the payload fairing made of carbon fiber was done. The pilot 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 analysis of the obtained results.

1. Introduction

When launching rockets in the boost phase of flight to separate the spent rocket design elements (RDE), such as boosters, steps, fairings, interstage compartments.
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 burning and destruction of different RDE types returning from space into the Earth's atmosphere having velocities of about 7 km/s, is described in the significant number of works [1 - 4]. 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 class RDE 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.
As possible technology, circuit and design solutions for minimizing the creation of space debris, on the example, of in the RDE question (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 [5-9].
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.
This paper presents theoretical and experimental studies of the thermal state of the RDE, made of polymer composite materials, like carbon fiber reinforced plastics on the basis of three methodological approaches for assessing the thermal loading: a) based on the concentrated model (the motion of a material point), b) based of the distributed model (Navier-Stokes), c) experimental studies in a wind tunnel. The pilot 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.

2. Statement of the problem research

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For realization of the proposed safety improve technology it is necessary to deliver the required amount of heat $Q_{\Sigma},(t_1,t_2)$ to the RDE at predetermined (selected) interval of flight time (t_1,t_2) on the atmospheric phase of the descent trajectory to height of Hpredetermined:

$$Q_{\Sigma},(t_1,t_2) = Q_{air}^{ht}(t_1,t_2) - Q_{air}^{ls}(t_1,t_2) + Q_{pc}(t_1,t_2,m_{pc}) , \tag{1}$$

providing the combustion of RDE with the mass equal to:

$$m = m_{erc} , \tag{2}$$

Where,

$Q_{air}^{ht}(t_1,t_2)$ – is the heat supplied to RDE due to aerodynamic heating,
$Q_{air}^{ls}(t_1,t_2)$ – is the heat entrained by the oncoming aerodynamic flow,
$Q_{pc}(t_1,t_2,m_{pc})$ – is the heat supplied to RDE thanks to the pyrotechnic composition combustion,
m_{pc} – is the mass of the pyrotechnic composition with required physical and chemical properties.
t_1,t_2 – are the time intervals on the trajectory of descent, determined by the condition of sufficient oxygen in flow for oxidation of the PC fuel composition.
The criterion of successful solution of the formulated problem is the PC mass.
To determine the amount of heat required for combustion (1) are discussed below ranging from aerodynamic heating $Q_{air}^{ht}(t_1,t_2)$, $Q_{air}^{ls}(t_1,t_2)$.

3. Assessment of RDE aerodynamic heating and heat loss

We consider the thermal state of the RDE on the basis of the equations of motion of RDE as a material point with the corresponding cross-section, mass and aerodynamic coefficient for to solve the problem of determination of aerodynamic heating $Q_{air}^{ht}(t_1,t_2)$ and heat loss $Q_{air}^{ls}(t_1,t_2)$.
As the equations describing the motion of the RDE centre of mass, we use differential equations in velocity coordinate system [10]:

$$\begin{gathered}
\frac{dV}{dt} = -\frac{F}{m} + g \cdot \sin\theta \ ; \\
\frac{d\theta}{dt} = -\frac{g}{V} \cdot \cos\theta + \frac{V}{r} \cdot \cos\theta + 2 \cdot \omega \cdot \cos\phi \cdot \sin\psi \ ; \\
\frac{d\psi}{dt} = \frac{V}{r} \cdot tg\phi \cdot \sin\psi \cdot \cos\theta + 2 \cdot \omega \cdot \left(\cos\phi \cdot \cos\psi \cdot tg\theta + \sin\phi \right) \ ; \\
\frac{d\phi}{dt} = \frac{V}{r} \cdot \cos\phi \cdot \cos\theta \ ; \\
\frac{d\lambda}{dt} = \frac{V \cdot \sin\psi \cdot \cos\theta}{r \cdot \cos\phi} \ ; \\
\frac{dh}{dt} = -V \cdot \sin\theta \ ;
\end{gathered} \tag{3}$$

where: V,m – are the RDE velocity and mass; h – is the flight altitude; ϕ,λ – are the longitude and latitude, respectively; θ – is the flight-path angle (the angle between the velocity vector and the local horizon); ψ – is the azimuth of the RDE movement; g – is the gravitational acceleration; $r = R + h$ – is the distance from the centre of the Earth to RDE; R – is the radius of the Earth; ω – is the angular velocity of Earth rotation; $F = 0,5 \cdot c_x \cdot \rho \cdot V^2 \cdot S$ – is the drag force; S – is the frontal area; c_x – is the drag coefficient.
Initial conditions and assumptions are the following:

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- Height $h_0 = 80\,\text{km}$, the flight-path angle $\theta = 0°$, azimuth $\psi = 28°$, longitude $\phi = -49{,}39°$, latitude $\lambda = 5{,}05°$ on the example of the payload fairing separated from the launch vehicle of the "Souz 2.1v" type [11].
- the RDE mass is constant;
- the change of the gravitational acceleration dependent on height is neglected.

The change in the quantity of heat received due to aerodynamic effects during the RDE descent, is described by the following expression:

$$c \cdot m \frac{dT}{dt} = dQ_{air}^{ht} - dQ_{air}^{ls} , \tag{4}$$

Where: c, m, T – are the RDE heat, mass, and temperature;
$Q_{air}^{ht} = S \cdot q_k$ – is the heat coming to RDE due to the aerodynamic heating;
$q_k = 0.635 \cdot 10^{-3} \cdot \left(\frac{2 \cdot \rho}{\rho_0 \cdot d}\right)^{0.5} \cdot V^{2.862}$ – is the density of the incoming heat flux;
$Q_{air}^{ls} = S \cdot q_a$ – is the heat entrained by the oncoming aerodynamic flow;
$q_a = \alpha \cdot (dT - dT_\infty)$ – is the density of the heat flux;
T_∞ – is the incoming flow (environment) temperature;
$\alpha = Nu \cdot \lambda / d$ – is the heat transfer coefficient.
λ – is the heat conductivity coefficient of the incoming flow;
Nu – is the Nusselt number [12-15];
$d = 4 \cdot S / \Pi$ – is the RDE equivalent diameter;
Π – is the perimeter of the RDE surface.

Numerical integration of differential equations system (3) together with equations (4-10) was performed by the Runge-Kutt fourth order method. Fig. 1 the results of velocity change calculation and altitude along the descent trajectory with initial velocities relative to the Earth $V_0 = 2$ km/s and $V_0 = 7$ km/s, mass 500 kg and the midsection area of 5.5 m^2, are shown.

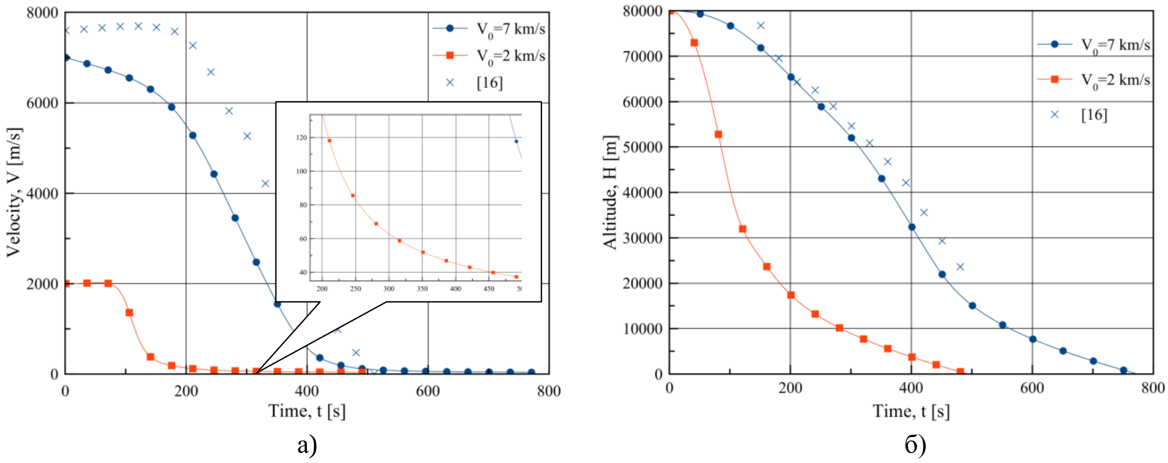

Figure 1: Change of velocity (a) and height (b) during the RDE descent in the atmosphere

The obtained parameters of the trajectory (Fig. 1a and 1b) are in good agreement with the nature of changing the same parameters given in [16].
Figure 2 shows the change of heat fluxes density (the heat coming to RDE and entrained by the oncoming aerodynamic flow) depending on the RDE shape and initial velocities.

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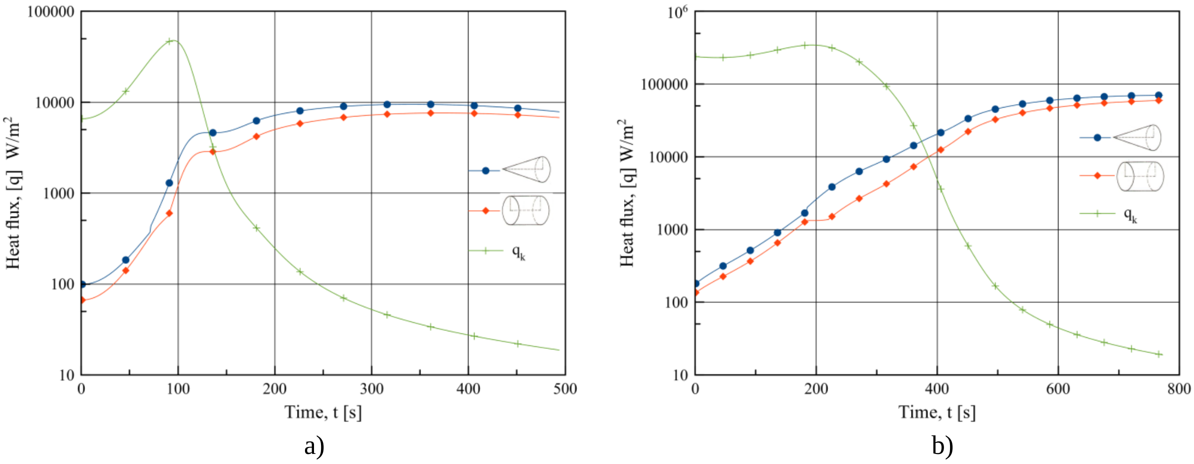

Figure 2: Changes of heat fluxes (the heat coming to RDE and entrained by the oncoming aerodynamic flow) during the descent in the atmosphere with initial velocities $V_0 = 2$ km/s (a) and $V_0 = 7$ km/s (b)

Figure 2 shows convective aerodynamic flow peak. The peak value of heat coming to RDE when the initial velocity of $V_0 = 2$ km/s is up to approximately 50 kW/m2 to 98 s, which corresponds to a height of about 44 km. For RDE moving with an initial velocity of $V_0 = 7$ km/s, the peak value of heat coming to RDE is equal to 350 kW/m2 to 201 s, which corresponds to a height of about 65 km.

The change of the heat flow q_a entrained by the oncoming aerodynamic flow has a monotonously growing character. When exceeding the values of heat flow q_a entrained by the oncoming aerodynamic flow – the value of heat coming q_k to RDE, there is observed the outflow of heat from the RDE surface, reducing the RDE surface temperature (Fig. 3a).

Otherwise, the same is the situation with the entrainment of heat from the surface of RDE during the descent with an initial velocity of $V_0 = 7$ km/s, the magnitude of the heat outflow in the order of smaller values of the density of the oncoming heat flux (see Fig.2, b). Resulting in maximum heating of the surface RDE (see Fig.3, b).

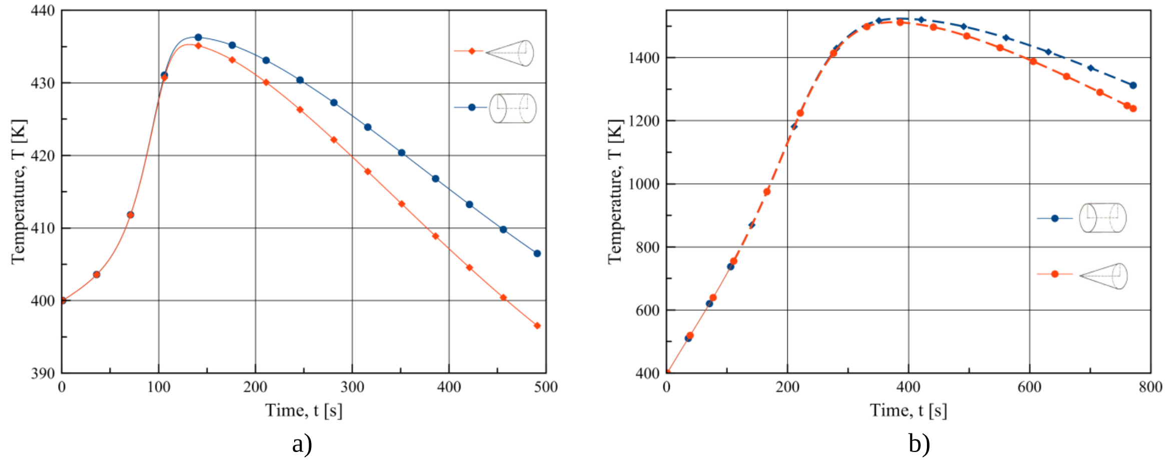

Figure 3: RDE surface temperature change during the descent in the atmosphere with an initial velocity of $V_0 = 2$ km/s (a) and $V_0 = 7$ km/s (b). The dotted line shows the methodological value of the surface temperature RDE. (In real conditions the temperature will not be achieved, because the temperature of destruction of elements cannot exceed 780 K)

At lower velocities (<2 km/s) the sufficient heating or combustion is out of the question, due to the fact that the value of heat flow entrained by the oncoming aerodynamic flow is a lot more (100 times) than the value of heat coming to RDE (Fig. 2, 3). For destruction (combustion and dispersion), an additional supply of a certain amount of energy is required.

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4. Mathematical modelling of heat exchange process based on the Navier-Stokes equations

In p.3 for evaluation of the heat transfer process folds of the head fairing at various velocities entering the atmosphere based on centred-set models of the motion and heat transfer. The heat transfer coefficient was adopted according to [12-15] for two specific forms of blown surfaces: cone and cylinder.
The purpose of mathematical modelling based on the Navier-Stokes equations (distributed model) is the determination of process parameters of heat transfer, including heat transfer coefficient at a constant flow of gas for RDE in the form of a plate made on carbon fiber for the velocity corresponding to the range from 70 m/s and below.
Mathematical modelling based on the solution of Reynolds averaged Navier-Stokes equations together with the equation of energy using the ANSYS FLUENT software. For completion the Reynolds equations was used turbulence model Shear Stress Transport k-omega consists of four differential equations [17]: a transport equation for the turbulent kinetic energy, transport equation for specific dissipation rate of turbulent energy, transport equation for intermittency and a transport equation for the Reynolds number of the beginning of the laminar-turbulent transition. The model is based on a hybrid modelling of the Shear Stress F. Menter. Compared with other currently used models are the Menter approach shows quite high performance in the calculations of flow around solid bodies [18].
The main assumptions adopted in the simulation:
1) The object of the study presents the carbon fiber plate, which is the RDE model.
2) Is considered 2D (two-dimensional) formulation of the problem.
3) Heating of the sample was stopped before the start of the blowing, thus, is modelled the case without a constant influx of heat.
4) On the output boundary condition is set free exit and equality to zero of excess pressure.
5) Thermophysical parameters of the incoming flow in the modelling process do not change.
6) External leakage to the RDE model, chemical and ablative processes are neglected.
Initial and boundary conditions:

- RDE model dimensions – 40x40mm;
- Oncoming flow parameters: temperature 295 K; pressure 101325 PA; density of 1.22 kg/m^3; flow velocity from 10 to 70 m/s, perpendicular to the plane of the RDE model.

The computational domain, boundary conditions and computational mesh, is presented in figure 4.

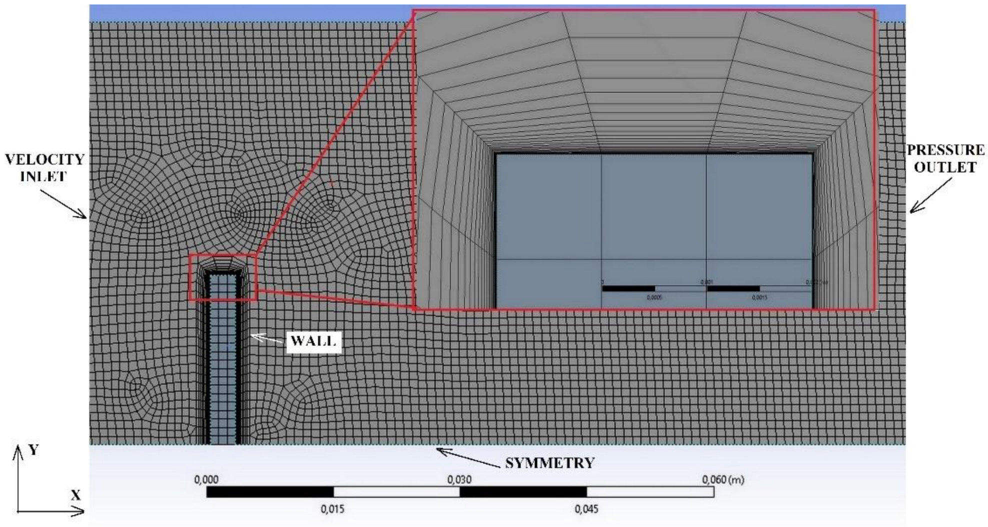

Figure 4: The computational domain and mesh in ANSYS FLUENT

A structured mesh was built using a tool Inflation. The boundary layer in the near-wall region close to the carbon fiber plate is resolved layers of prismatic elements. The value of Yplus parameter was provided <0.5, large values of this parameter lead to a significant overestimation of the heat transfer coefficient and, consequently, to not correct results of the calculation [19].
The heat flux density is calculated according to the formula:

$$q_w = \alpha\left(T_{wall} - T_{\infty}\right) , \tag{5}$$

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Where, α – is the heat transfer coefficient, T_{wall} – is the wall temperature, T_{∞} – flow temperature.
Thus, the heat transfer coefficient can be calculated using a function in Fluent-Pre – Custom Field Function according to the following formula:

$$\alpha = \left| \frac{total\ surface\ heat\ fluxes}{T_{wall} - T_{\infty}} \right| . \tag{6}$$

The initial temperature of the surface of a carbon plate is specified by the patch in Solution Initialization for the corresponding zone plate. Figure 5 shows the surface temperature variation of the RDE model when the blowing gas stream at an initial temperature of 423 K.

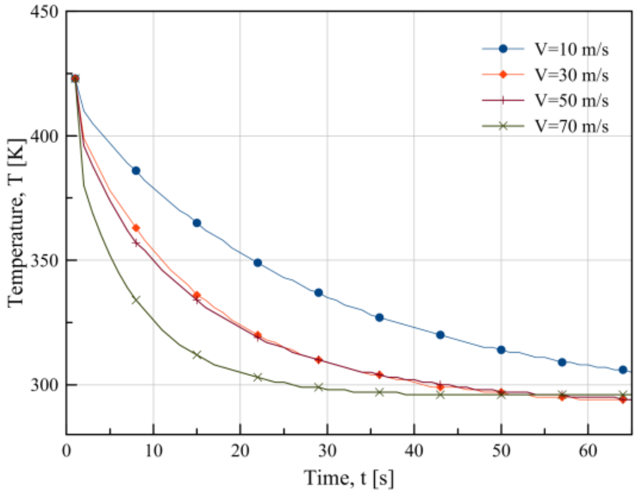

Figure 5: Graph of temperature change from blowing time at an initial temperature of $T = 423\,\mathrm{K}$

From the graph in Fig. 5 can be traced to the decrease of temperature in time, thus, the higher the flow velocity, the more rapid decrease in the temperature. With the same initial temperature 423 K during the experiment there is a decrease in temperature to the temperature of the oncoming flow.

5. Physical simulations

Requirements for experimental stand

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 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 Eo = 0.05...0.3;
- the air flow temperature in the range of 260...295K;
- the flow compression ε = 0.6...0.625;
- the humidity of the air stream should not exceed 30%;
- the RDE blowing angles 0...90 °
- 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).

Requirements for the methodology of processing experimental measurements

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The results of measurements of surface temperature EC, flow, flow rate in accordance with the methodology [20] should be determined the coefficients of heat transfer with an inaccuracy of measurements not more than 10% in the considered range of flow velocities.

The EWT design and the methodology of the experiments

Figure 6 shows a fragment of EWT. The ETA 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 (Eo = 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 7 shows photographs of the working parts and nozzles with critical cross-section of 8 and 20 mm.

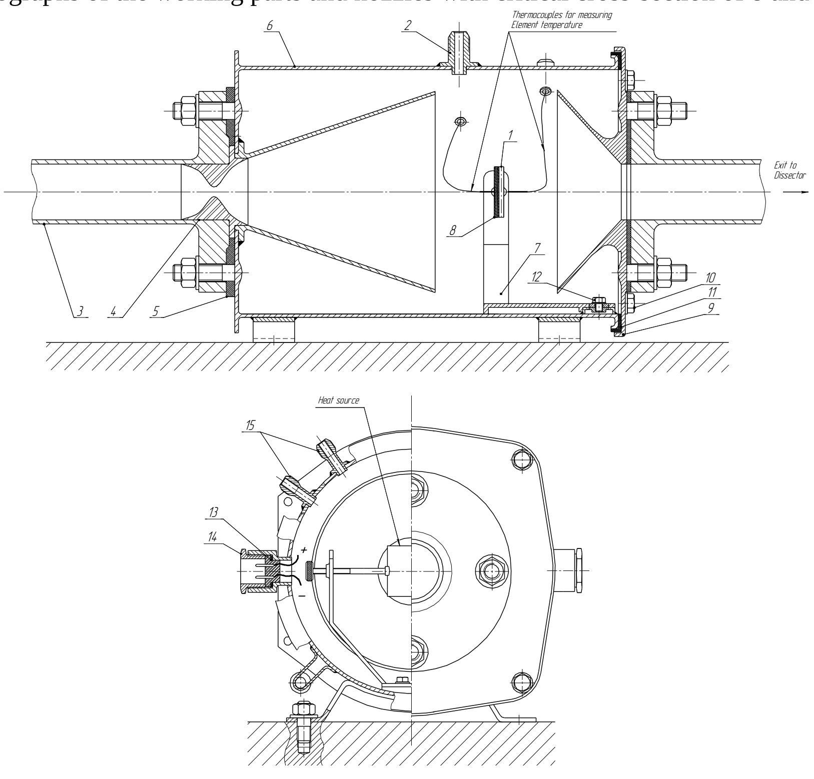

Figure 6: Scheme of the EWT working part.

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.

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а) б)

Figure 7: the elements of EWT: a) The EWT with a registration system of measurement; b) The nozzles

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;
- installing cover and tightening the connection;
- 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 in the form of a square plate made of CFRP with a side length of 29 mm to 33 mm, thickness 2 mm weight 2 gr. It was placed vertically at an angle of attack equal to 90 at a distance of 180 mm from the critical section (Fig. 8, 9). With RDE clamps it is attached to the heater for maximum contact area.

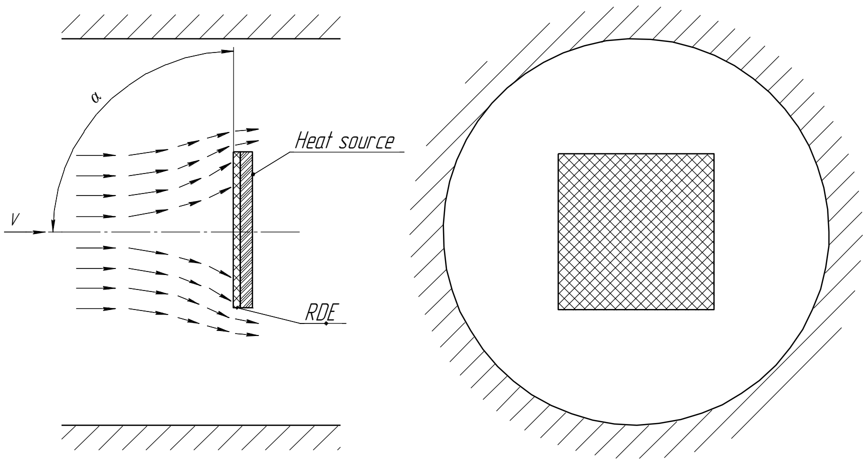

Figure 8: A scheme of the aerodynamic loading

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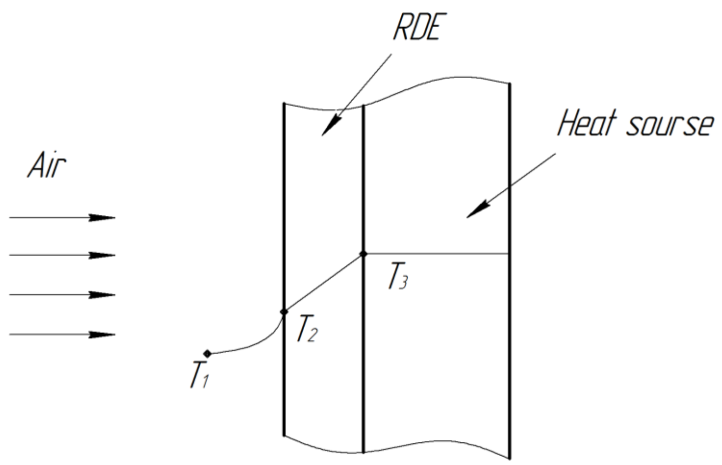

Figure 9: The scheme of temperature change

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: 10 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. In a series of experiments revealed a drastic temperature decrease of RDE in the process of blowing, depending on the flow velocity (Fig. 10)

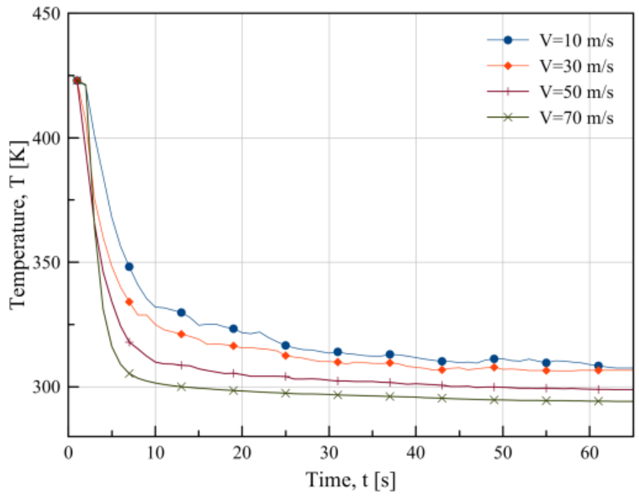

Figure 10: Graph of temperature change from time blowing

at an initial temperature of $T = 423K$

Processing of the results

Processing of the obtained results is conducted in accordance with [20]:

- the temperature is recalculated in the values of the excess temperature *ΔT*, [K] as the temperature difference;
- define the values of *ln(ΔT)* c accuracy to the third decimal place;
- plot the *ln(ΔT)=f(τ)* in the scale;
- through the points of the graph are averaging line and its slope is determined by the cooling rate:

$$m = \frac{\ln(\Delta T_1) - \ln(\Delta T_2)}{\tau_2 - \tau_1}\ ; \qquad (7)$$

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

The total heat transfer coefficient is determined from the equation:

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$$\alpha_{\Sigma} = \frac{M}{F} C_f m \quad , \tag{8}$$

Where: M/F=2,01 [kg/m3] constant of the sample (assuming that the mass and size of the sample does not change during the experiment); C_f =1470 [J/(kg·K)] – specific heat capacity of CFRP; m[c^{-1}] – the cooling rate specified on graphics,
Given the constancy of the coefficients entering in (8):

$$\alpha_{\Sigma} = 49,245 \cdot m \,, \tag{9}$$

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,

$$\alpha_R = C \frac{\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_f}{100}\right)^4}{T_s - T_f} \quad , \tag{10}$$

Where C=4.762 W/(m^2·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:

$$\alpha = \alpha_{\Sigma} - \alpha_R \quad , \tag{11}$$

The total error of determination does not exceed ±5%.
As a result of processing of results data were obtained are presented in table 1 and the values of heat transfer coefficient in the mathematical modelling obtained in section 4.

Table 1: The results of experimental studies

The velocity flow, V [m/s]	**The initial temperature on the RDE surface, T_3/T_2 [K]/[K]**	**The experiment time [s]**	**The cooling rate, m [s^{-1}]**	α_{Σ} **, [W/m^2 ·K]**	α_R **, [W/m^2 ·K]**	α_{exp} **, [W/m^2 ·K]**	α_{teor} **, p. 4 [W/m^2 ·K]**
10	600/423	65	0.0277	85.097	10.968	74.129	53.967
30	600/423	65	0.0297	91.241	11.210	80.031	110.025
50	600/423	65	0.0341	104.758	11.613	93.145	125.112
70	600/423	65	0.0383	117.661	11.955	105.706	132.214

6. Results and discussion

The difference of heat transfer coefficients, defined on the basis of numerical and experimental simulation of up to 15 %, which is considered acceptable for thermal evaluations.
In p. 3 presents a centred-set model the airflow over different surfaces. To confirm the reliability of this method were calculated RDE temperature during the experiments in the EWT with the use of heat transfer coefficients $\alpha_{эк}$ (tab. 1).
Initial and boundary conditions:

- RDE model dimensions – 40x40mm;
- the RDE model mass – 0.002 kg;
- the heat capacity of the RDE model material – 1470 J/kg·K;

- oncoming flow parameters: temperature 295 K; pressure 101325 PA; density of 1.22 kg/m^3; flow velocity from 10 to 70 m/s, perpendicular to the plane of the RDE model.

In Figure 11 shows the results of integrating equations (3), (4) to conditions of the airflow RDE in the EWT.

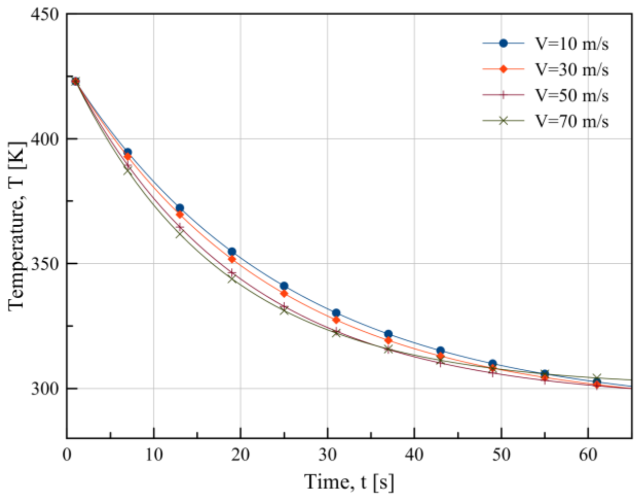

Figure 11: Graphs of temperature change from time blowing (when integrating the system of equations (3), (4) with the experimental values of the coefficients $\alpha_{\exp}$

The difference in the change of the RDE temperature values are shown in figures 10 and 11, due to the adopted assumptions in the development of a centred set on p. 2:

1) Not taken into account the effect of heat transfer from the surface of the RDE model in the form of radiation and heat conductivity;

2) The value of the heat flux, which is the equation (4) is obtained for velocities, M>1. For values of velocities of M<<1, it is necessary to introduce an additional correction factor.

In subsequent phases of the study, these assumptions will be eliminated.

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Conclusion

1. The formulation of theoretical and experimental researches of heat loading processes of RDE during the atmospheric phase of the descent trajectory is conducted.
2. The assessment of thermal loading of aerodynamic flows and entrainment heat from the RDE with the use of concentrated and distributed mathematical models is conducted.
3. The experimental stand and experimental aerodynamic setup 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 are developed. The experimental results are close to the calculated one obtained on the basis of mathematical modelling.

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