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Analysis of Temperature Field in the Transport Compartment of the Launch Vehicle

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Abstract

The development of satellite linkage systems is based on the satellite's transportation in space. The transportation of a satellite into orbit is carried out by a launch vehicle. The satellite is located in the transport compartment inside the main fairing. At the stage of the pre-launch preparation, it is necessary to fulfill very strict environment conditions inside the main fairing. Namely, it is very important to predict temperature field in the transport compartment inside the main fairing during its forced ventilation at the stage of pre-launch preparation. To calculate the temperature field formed by the ventilation of the transport compartment and release of heat from different elements of the satellite, the energy equation was used. This equation took into account the intensity of heat release from different parts of satellite, air flow pattern over the satellite, heat transfer in the transport compartment. The non-uniform field of the air flow velocity in the transport compartment was calculated on the basis of the potential flow model. The finite difference schemes were used for numerical integration of modeling equations. The computer code has been developed that implements the proposed numerical model. The results of computational experiments to estimate the temperature regime in the main fairing of the launch vehicle for different satellites is presented.
KEY WORDS: *satellite, transport compartment, main fairing, temperature field, stage of pre-launch preparation*

1. Introduction

Nowadays, satellites play a significant role in improving the level of people`s life. Satellite systems determine the development of all branches of science, technology, industry, agriculture, banking sector, transport and the environment. A booster is an onboard system that delivers a payload from the earth to suborbital, orbital or interplanetary space. The payload is usually placed in a spacecraft or satellite, which is located in the transport compartment of the launch vehicle in the main fairing. At the stage of pre-launch preparation, an important stage is the calculation of the temperature field, which is formed under the influence of forced ventilation of the transport compartment and with the simultaneous release of heat from various technological elements inside the satellite. Measuring the heat flux from a satellite is difficult, since almost every element inside the satellite generates heat through its work. A significant increase of temperature can lead to overheating of the internal elements of the satellite, which reduces the risk of a trouble-free launch of the satellite into orbit. The study of temperature control processes of the main fairing remains an urgent task. Its solution allows determining the rational position of the holes to improve ventilation near the satellite.

The results of experimental studies of the temperature distribution field in different blocks of the main fairing during temperature control are given in the work [1]. The analysis of the characteristics of the internal flow in the main fairing was carried out using CFD modeling based on the Navier-Stokes equations and the turbulence model [2]. Based on the solution of differential equations of gas dynamics by numerical methods, an analysis of the ventilation and location of the spacecraft in the main fairing during flight was carried out [3]. However, with this simulation, the velocity and temperature fields in the main fairing were not obtained. Studies of the features of pressure changes in the main fairing under flight conditions have been carried out [4]. The work [5] shows the influence of the location of the drainage holes to study the characteristics of the gas flow in the compartment under the main fairing. The calculations of the temperature field and the velocity field in the flow past the block, where the onboard instruments are located, were carried out based on CFD models of the Ansys Fluent software package [6], which requires a lot of computer time.

In this paper, a method has been developed for numerically calculating the field of air flow velocity and temperature in the main fairing, where the satellite is located at the stage of prelaunch preparation. Mathematical modeling was carried out using finite difference methods. A program has been created for carrying out computational experiments that do not require large expenditures of computer time. These studies can be useful at the stage of designing the ventilation system inside the main fairing when placing a payload in it.

2. Statement of the Problem and its Solution

2.1. Mathematical Model

A method is considered for calculating the temperature field of the air flow in the main fairing of a launch vehicle during heat emission from the satellite surface and from forced ventilation. The scheme of the computational domain is shown in Fig. 1.

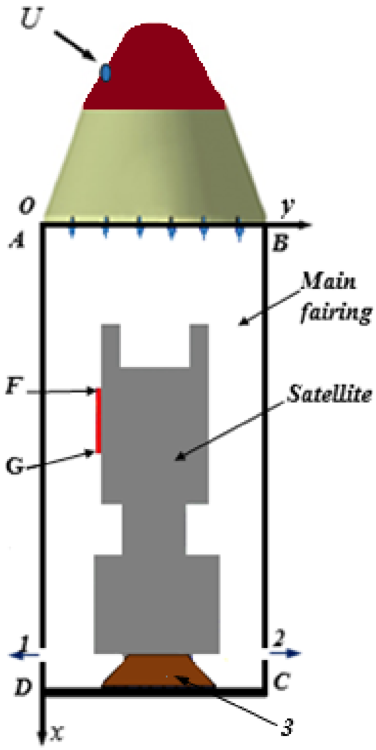


Fig. 1 The scheme: *1*, *2* – air outlets; *3* – adapter; *ABCD* – boundaries of the calculated domain; *FG* – heat release zone

For mathematical modeling of the process of formation of the air temperature field in the head main fairing, the energy equation is used (1):

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}=\frac{\partial}{\partial x}\left(a_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(a_y\frac{\partial T}{\partial y}\right)=0, \tag{1}$$

where T – air temperature [°C]; a_x, a_y – thermal diffusivity [m^2/s]; u, v – components of the air flow velocity vector, [m/s]; (x_i, y_i) – coordinates, [m]; t – time, [s].

The computational area in the head main fairing has an ABCD boundary (Fig. 1). To solve Eq. (1) boundary conditions are set:

1. $T\big|_{AB}=T_{entrance}$, where $T_{entrance}$ – the known air flow temperature, which is supplied by ventilation in section AB, i.e. the temperature of the air flow at the entrance to the computational domain.

2. $\left.\frac{\partial T}{\partial \vec{n}}\right|_{CD}=0$, where $\vec{n}$ – unit vector of the outer normal at the boundary of the air flow outlet from the holes in the main fairing;

3. $\left.\frac{\partial T}{\partial \vec{n}}\right|_{surface}=q$, where q – the known value of the heat flux from some part of the satellite surface that is heating up;

$\left.\frac{\partial T}{\partial \vec{n}}\right|_{surface} = 0$, if there is no heat release from some part of the satellite surface;

4. $\left.\frac{\partial T}{\partial \vec{n}}\right|_{surface} = 0$ – on the walls of the main fairing.

For the moment of time $t = 0$, the initial condition is written as follows $T_{t=0} = T_0$, where T_0 – the known air flow temperature inside the head main fairing.

To calculate the temperature field based on Eq. (1) we need to know the distribution of the air flow velocity field components inside the main fairing. The potential flow Eq. (2) is used to simulate the movement of the air flow:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0, \tag{2}$$

where P – air flow velocity potential.

Appropriate boundary and initial conditions are set for the solution Eq. (2):

1. $\left.\frac{\partial P}{\partial \vec{n}}\right|_{AB} = U$ – the Neumann condition, at the boundary *AB* the air flow enters the transport compartment at a speed U. When performing computational experiments, a uniform air flow is set at the boundary *AB*: $U = const$;
2. $P = P_0 + const$ – Dirichlet condition, where P_0 – arbitrary constant. This condition must be met at the border of the air flow outlet from the transport compartment;
3. $\left.\frac{\partial P}{\partial \vec{n}}\right|_{surface} = 0$, where $\vec{n}$ – the unit vector of the outward normal to the solid surface. This condition must be satisfied on the surface of the satellite, on the walls of the main fairing;

The components of the air flow velocity vector are related to the potential of the air flow velocity based on dependencies [7]:

$$u = \frac{\partial P}{\partial x}, \; v = \frac{\partial P}{\partial y}. \tag{3}$$

To determine the potential field of the air flow velocity, it is necessary to solve Eq. (2). The obtained values of the velocity potential make it possible to calculate the components of the air flow velocity vector based on dependencies (3). The found components of the air flow velocity are used to determine the temperature field of the air flow when solving Eq. (1).

2.2. Numerical Model

Consider the methodology for constructing a numerical model based on the equations Eq. (1) – Eq. (3). Numerical integration of modeling equations is carried out on a rectangular difference grid $(x, y)_{i,j} = (i \cdot \Delta x, j \cdot \Delta y)$, $i, j \in \text{integer}$.

For numerical integration of the equation an explicit finite-difference scheme of numerical integration is used. Laplace Eq. (2) reduces to an equation of the evolutionary type:

$$\frac{\partial P}{\partial \eta} = \frac{\partial^2 P}{\partial^2 x} + \frac{\partial^2 P}{\partial^2 y}, \tag{4}$$

where η is the dummy time, when $\eta \to \infty$, the solution of Eq. (4) goes to the solution of Laplace Eq. (2). The stationary solution of Eq. (2) is the boundary case of solving the non-stationary Eq. (4). In this case, the solution of Eq. (4) ceases to change in time and reaches the stationary regime, which is the solution of Eq. (2). To solve this equation it is necessary to specify the initial condition, the potential field at $\eta = 0$. For example, you can take $P_{\eta=0} = 0$ to the entire calculation area.

Based on the method of numerical integration [7-8], the calculated dependence for solving equation (16) has the form:

$$P_{ij}^{n+1} = P_{ij}^{n} + \Delta t \frac{P_{i+1,j}^{n} - 2P_{ij}^{n} + P_{i-1,j}^{n}}{\Delta x^2} + \Delta t \frac{P_{i,j+1}^{n} - 2P_{ij}^{n} + P_{i,j-1}^{n}}{\Delta y^2}. \tag{5}$$

With the help of this explicit dependence, the velocity potential field in all internal cells of the computational domain is determined. The calculation of the velocity potential ends when the condition: $\left|P_{ij}^{m+1} - P_{ij}^{m}\right| \le \varepsilon$, where ε – a small number ($\varepsilon = 0.001$); m – iteration number.

The value of the velocity potential is determined in the centers of the difference cells, the value of the components of the velocity vector is calculated on the sides of the difference cells:

$$u_{ij} = \frac{P_{ij} - P_{i-1,j}}{\Delta x}\,;\; v_{ij} = \frac{P_{ij} - P_{i,j-1}}{\Delta y}\,. \tag{6}$$

For numerical integration of the equation Eq. (1), it is split into two Eqs. (7) − (8):

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} = 0\,; \tag{7}$$

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(a_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(a_y \frac{\partial T}{\partial y}\right). \tag{8}$$

Further, the following transformations and approximations of derivatives are performed [8]:

$$\frac{\partial uT}{\partial x} = \frac{\partial u^{+}T}{\partial x} + \frac{\partial u^{-}T}{\partial x}\,;\; \frac{\partial vT}{\partial y} = \frac{\partial v^{+}T}{\partial y} + \frac{\partial v^{-}T}{\partial y}\,; \tag{9}$$

$$u^{+} = \frac{u + |u|}{2}\,;\; u^{-} = \frac{u - |u|}{2}\,;\; v^{+} = \frac{v + |v|}{2}\,;\; v^{-} = \frac{v - |v|}{2}\,; \tag{10}$$

$$\frac{\partial u^{+}T}{\partial x} \approx \frac{u_{i+1,j}^{+} T_{i,j}^{n+1} - u_{i,j}^{+} T_{i-1,j}^{n+1}}{\Delta x} = L_x^{+} T^{n+1}\,;\; \frac{\partial u^{-}T}{\partial x} \approx \frac{u_{i+1,j}^{-} T_{i+1,j}^{n+1} - u_{i,j}^{-} T_{i,j}^{n+1}}{\Delta x} = L_x^{-} T^{n+1}\,; \tag{11}$$

$$\frac{\partial v^{+}T}{\partial y} \approx \frac{v_{i,j+1}^{+} {T^{n+1}}_{i,j} - v_{i,j}^{+} {T^{n+1}}_{i,j-1}}{\Delta y} = L_y^{+} T^{n+1};\; \frac{\partial v^{-}T}{\partial y} \approx \frac{v_{i,j+1}^{-} {T^{n+1}}_{i,j+1} - v_{i,j}^{-} {T^{n+1}}_{i,j}}{\Delta y} = L_y^{-} T^{n+1}. \tag{12}$$

Taking into account these transformations, the splitting scheme for Eq. (7) has the form:

– first step, $\dfrac{T_{i,j}^{k} - T_{i,j}^{n}}{\Delta t} + {L^{+}}_{x} T^{k} + {L^{+}}_{y} T^{k} = 0$;

– the second step, $\dfrac{T_{i,j}^{n+1} - T_{i,j}^{k}}{\Delta t} + {L^{-}}_{x} T^{n+1} + {L^{-}}_{y} T^{n+1} = 0$.

The temperature value is determined at each computational step of the solution.

For numerical integration of equation (8) an explicit difference scheme is used [7]:

$$T_{i,j}^{n+1} = T_{i,j}^{n} + \Delta t \frac{T_{i+1,j}^{n} - 2T_{i,j}^{n} + T_{i-1,j}^{n}}{\Delta x^2} a_x + \Delta t \frac{T_{i,j+1}^{n} - 2T_{i,j}^{n} + T_{i,j-1}^{n}}{\Delta y^2} a_y\,. \tag{13}$$

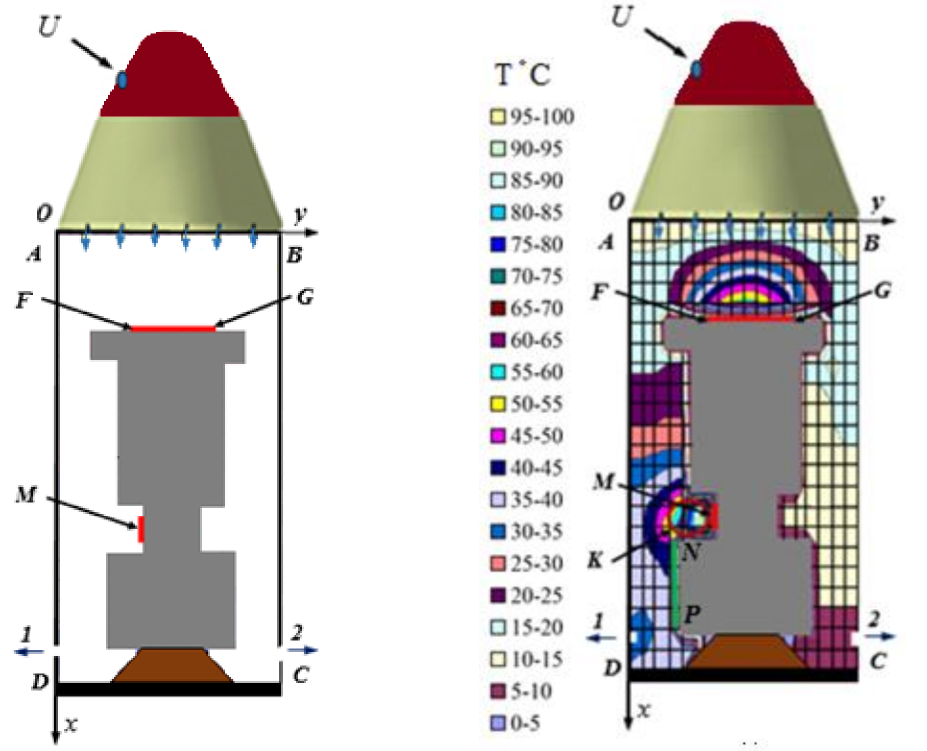
For computational experiments "SATELLITE-2" was created in the FORTRAN programming language.

2.3. Results of Computational Experiments

This section presents the results of solving two model problems based on the developed method for numerically calculating the temperature field in the transport compartment of the main fairing of the launch vehicle. Computational experiments were carried out for satellites of various shapes. The computational domain had dimensions: the length *BC* was 4.99 m, the width *AB* was 4 m. A uniform air flow was set at the *AB* boundary, with a velocity of 2 m/s and a temperature of 20°C. The geometric dimensions of the satellite were: length – 3.4 m, width – 2.2 m Fig. 2 − Fig. 3.

For model problem 1 (scenario 1), a heat flux q =300 W was set on the *FG* section of the satellite surface and a point heat flux q =100 W located in the *M* zone on the satellite surface Fig. 2, a. For model task 2, only the heat flux q = 300 W was set in the *FG* section of the satellite side surface Fig. 3, a.

The calculation program allows to calculate the temperature field in the entire transport compartment of the main fairing Fig. 2, b − Fig. 3, b.



a b

Fig. 2 The results of calculating the thermal regime inside the main fairing for model task 1: a – scheme of the computational domain, b – temperature field, *T*°C

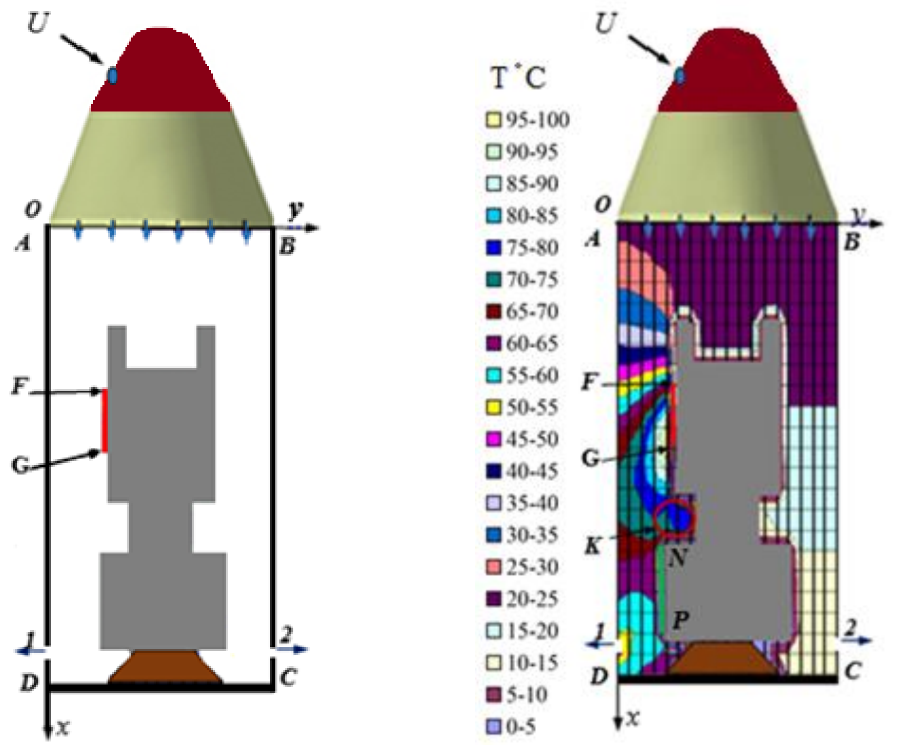


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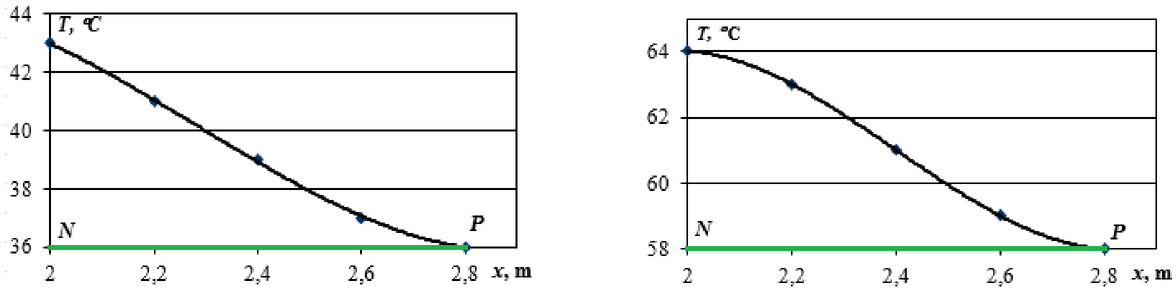
Fig. 3 The results of calculating the thermal regime inside the main fairing for model task 2: a – scheme of the computational domain; b – temperature field, *T*°C

Both scenarios are characterized by an asymmetric temperature field. The analysis of the temperature field for the model task 1 Fig. 2 shows that in zone *K* (highlighted in a circle) a high temperature of 75-82°C is observed. This is due to the fact that intense heat is released on the surface of the satellite in zone *M*, and heat removal from the surface of the satellite in zone *M* is minimal, since this area is located in the stagnant zone *K*. As is known, the stagnant zone is a recess and is characterized by a low speed of movement air in it. In this regard, the temperature in this zone *K* exceeds the threshold value *T* = 70°C, which may affect the operation of the satellite.

An analysis of the temperature field for model problem 2 Fig. 3 shows that an elevated temperature zone is also observed in zone *K* (circled), although there is no point source of heat release, as in the previous scenario. This is due to the influence of the heat source located in the *FG* section of the satellite side surface, above zone *K*. The movement of heat flow in the direction of air movement inside the transport compartment and the minimum air movement inside the cavity leads to the fact that an increased temperature is observed in the zone of cavity *K* in the range of 65-75°C.



a b

Fig. 4 Temperature distribution *T*°C along the NP satellite surface area: a – scenario 1; b – scenario 2

Also, the calculation program "SATELLITE-2" makes it possible to analyze the distribution of air temperature near the surface of the satellite Fig. 4. Fig. 4 shows the change in air temperature along the *NP* region of the satellite Fig. 2, b − Fig. 3, b. Fig. 4 shows that the temperature of the *NP* region is higher for scenario 2, since the heat release zone *FG* Fig. 3 is located on the same side of the satellite surface, closer to the studied *NP* region. For scenario 1, the temperature in the *NP* section is lower, since the heat release zone *FG* is located perpendicular to the investigated *NP* region, and the local source *M* Fig. 2 is located in the cavity, so the heat flow is more concentrated in zone *K*.

In this study, on the basis of the developed method, the model problems were solved in order to show the wide possibilities of using this method. This method of calculation, based on the analysis of the temperature field in the transport compartment of the head main fairing, makes it possible at the stage of prelaunch preparation to make constructive decisions regarding changing the temperature control mode or measures to reduce heat release from the satellite surface in the elevated temperature zone.

3. Conclusions

An efficient numerical method for calculating the thermal regime inside the main fairing during temperature control is proposed. This method allows to take into account: the complex geometric shape of the satellite, the location of the ventilation holes; heat release zones on the surface of the satellite. The developed program "SATELLITE-2" makes it possible to carry out computational calculations in a short time, about 5 seconds.

The developed method can be used for the initial assessment of the temperature regime in the main fairing at the stage of justifying the temperature control regime for a particular satellite or satellite system.

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