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DEVELOPMENT OF A METHOD FOR ASSESSING AIR DUSTINESS IN THE MAIN FAIRING OF THE LAUNCH VEHICLE

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The object of this study is the process of thermostating the main fairing with a satellite at the stage of prelaunch preparation of the launch vehicle. When thermostating, it is necessary to predict the risk of dust contamination of the satellite surface. Currently, there are no normative methods for solving this problem. A numerical model has been proposed that makes it possible to quickly predict the dynamics of pollution of any surface of the satellite.

A numerical model has been built for analyzing the zones of dust pollution of air in the main fairing of the launch vehicle during thermostating. The novelty of the model is the use of the Laplace equation for the speed potential, based on which the problem of aerodynamics is solved, namely, the flow rate in the main fairing is determined. Based on the model built, a computational experiment was conducted for dust particles with a diameter of 6 μm that fall into the main fairing during thermostating. The results of the research showed that the formation of areas of dust pollution near the satellite is influenced by the geometric shape of the satellite, which affects the formation of an uneven air velocity field in the main fairing and the organization of air supply to the main fairing.

Calculations are performed within a few seconds, which makes it possible during working day to conduct a set of studies into the rational choice of the organization of air exchange of the main fairing during its thermostating. The constructed numerical model can be used in design organizations to scientifically substantiate the thermostating mode of the main fairing, taking into consideration the characteristics of the satellite located in it

Keywords: dust pollution, satellite, thermostating, master fairing, numerical model, computational experiment

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1. Introduction

The rapid development of satellite communication systems leads to the intensive launch of a large number of spacecraft (satellites) into orbit. The satellite is located in space, which forms the main fairing (MF) of the launch vehicle (LV) (Fig. 1). One of the extremely important practical tasks is to provide «comfortable» conditions for the satellite

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in the volume of the LV MF at the stage of prelaunch preparation and during flight. This is the so-called thermostating task for the duration of pre-launch preparation and drainage during LV flight. The purpose of these operations and processes is to solve several far from trivial problems: normalizing the air velocity near the surface of the satellite during ventilation, normalizing the air temperature near the satellite, and normalizing the rate of pressure drop in the compartment during drainage. This practical problem is of considerable scientific interest as it is based on solving problems of two-dimensional and three-dimensional processes occurring in related fields of science. In the subfairing space, the air must comply with strict standards, one of which is the amount of dust per unit volume of air. This is a particularly important task – to ensure the purity of the air in the main fairing at the stage of prelaunch preparation [1]. One of the tasks is to ensure the purity of the air in the main fairing where the satellite is located at the stage of prelaunch preparation [1], namely, the amount of dust per unit volume of air must comply with the standard indicators of MPC. Now the assessment of air purity in the main fairing at the stage of design work has become an extremely important issue. This is due to the emergence of new requirements for the purity of the surfaces of modern satellites. In practice, it is very important to determine the zones of possible «danger» of especially «sensitive» surfaces of the satellite (optics, detectors, etc.) from dust pollution before starting the thermostating process.

Fig. 1. The location of satellite in the main fairing [2]

However, the theoretical solution to this problem is an extremely difficult task because, as one can see in Fig. 1, the satellite has a very complex geometric shape. Currently, there is no universal procedure for the scientifically based assessment of air dustiness in the main fairing for satellites of various configurations when thermostating the main fairing.

Therefore, studies aimed at devising methods for assessing the intensity of dust pollution in the main fairing at the stage of its thermostating are relevant. The availability of such method will improve the quality of work at the design stage of rocket and space technology.

2. Literature review and problem statement

In 1970, NASA standard established clear criteria for temperature standards and air purity class (dust pollution) for LV MF and in other so-called «dry» compartments of LV [3]. As a rule, modern general requirements for clean rooms are given in standards [4]. Currently, these and other conditions are given in special editions of the developers of LV and satellites. For example, in work [2], the thermostating parameters for MF in the Chinese rocket «Long March 3A» are given, and [5] gives the parameters for the American Falcon-class rocket; in [6] – for the French Ariane 5 rocket.

To ensure the necessary thermostating conditions, forced ventilation of the main fairing is used: air supply through certain holes in the main fairing and air vent through drainage holes (Fig. 2). At the same time, it is necessary that regulatory requirements are met in the main fairing, primarily for dusting (purity) of air. Dust particles that can come with air during ventilation of the main fairing settle on the surface of the satellite. Therefore, the task of ensuring the cleanliness of the surfaces of the spacecraft is very important for its normal and long-term performance in orbit. It is especially important to predict the level of dust pollution where the «sensitive» surfaces are located, namely: in the area where the optics are located; in the aperture area; in the area where detectors are located.

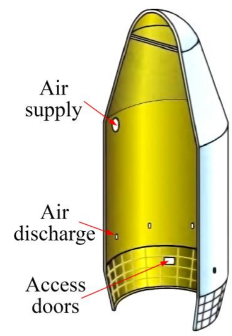

Fig. 2. Scheme of air supply to the main fairing during thermostating [2]

The deterioration of the characteristics of these devices can be caused by any particle of both organic and inorganic origin that has fallen into the volume of MF during ventilation. Thus, an important task of predicting the level of dust pollution in the volume of MF during thermostating has appeared.

In this regard, it is very important to note that there are no standard methods for solving a set of thermostating problems, and in particular, the task of assessing the level of dust pollution in the main fairing. Procedures for solving individual problems related to thermostating of the main fairing were developed. For example, in [7], the use of an experimental bench is considered to assess the efficiency of thermostating the main fairing and to determine the rational position of the ventilation holes. In that paper, the results of the experimental determination of the value of air velocity and temperature near the wall of the battery radiator are given but the issues of dust pollution in the main fairing have not been investigated. In [8], a methodology for express assessment of satellite surface contamination was devised. This procedure makes it possible to quickly calculate the number of dust particles that can settle on the surface of the satellite. The disadvantage of that procedure is the use of empirical dependences that can be applied only to the range of parameters at which the experiment was conducted. In addition, when assessing the level of contamination of the satellite surface, in that paper, the uneven dust field in the main fairing is not taken into consideration, which leads to uneven dust deposition on different parts of the satellite. In [9], an empirical model is proposed to estimate the number of dust particles that can be deposited on the surface of a satellite during thermostating. However, the proposed model does not take into consideration such a significant factor as the uneven distribution of dust particles inside the main fairing, which sexually affects the level of pollution of various components of the satellite.

It should be noted that to solve the problem of assessing dust pollutionin the main fairing, two problems should be solved. First, it is necessary to assess the level of dust pollution in the main fairing and, having such information, proceed to the assessment of dust pollution of the satellite surface.

For each satellite (package of satellites), it is necessary to carry out a separate calculation to determine the level of «dust» air pollution in the main fairing. In the absence of a universal methodology for solving this problem, there is a task of assessing the dustiness of air for satellites of various configurations. With different configurations of satellites, complex flow paths appear inside the main fairing, in which dust particles move. This makes it very difficult to assess the uneven dust field in the main fairing. Conducting experimental research requires a special place to organize the experiment, considerable time for setting up the experiment, conducting it, processing data, and summarizing the measurement results. In addition, the data of experimental studies can be used in the future, only for «similar» scenarios of the satellite location. In the case of the location of another satellite, such data can no longer be applied. It is also important to note that at the stage of prelaunch preparation, «implementation» in the volume of MF of sensors for assessing the speed of air flow near the satellite is excluded. Since the owner of the satellite requires guaranteed security. To do this, many tests are carried out at the preparatory stages, without a satellite or with its layout. Therefore, the use of experimental measurements to solve this problem is possible only in a limited range of studies. That is, we can say that an experiment cannot be a daily research tool in project organizations.

Therefore, it became necessary to build mathematical models for express assessment of the field of dust pollution of the air environment in the main fairing during thermostating. Designers need mathematical models of ventilation of the main fairing, making it possible to obtain a solution to the gas-dynamic problem and the problem of dust mass transfer within a few minutes of computer time. The use of such mathematical models will make it possible within one working day to calculate a dozen scenarios for placing spacecraft in the main fairing and quickly investigate the level of dust pollution near the satellite. Further, after such an express calculation, several scenarios will be selected, which at the next stage can be investigated in detail using software packages such as «ANSYS».

Analysis and research of the processes of thermostating MFs is a specific task associated, first of all, with the closeness of topics on space research of countries with facilities for the design and creation of rocket and space technology. Minimization of scientific publications in this area is also due to the fact that in many cases satellites are commercial objects and the publication of materials related to the task of thermostating is closed. However, our review of open publications [10–19] on this topic made it possible to identify a number of issues that need to be improved.

In [10], the results of experimental studies of temperature distribution in different blocks of the main fairing during thermostating are reported. Plots of the dependence of air temperature in the main flow are given. However, there are no data on the study of dust pollution near the satellite.

In [11], a three-dimensional CFD analysis of the characteristics of the internal flow in the main fairing of the launch vehicle was carried out. Numerical research was obtained using the OVERFLOW program, in which the solution to the aerodynamic problem is obtained based on the Navier-Stokes equations. During the calculations, the Spalart-Allmaras turbulence model with three different values of Re numbers was used. The disadvantage is the provision of calculation results only to the conical part of the fairing.

In article [12], an analysis of the ventilation of the spacecraft location in the main fairing of the launch vehicle in flight was carried out. Attention was paid to the influence of ventilation holes on this process since the launch vehicle performed the flight task. To solve this problem, the solution to nonlinear zero-dimensional differential equations of gas dynamics was used. Numerical modeling was carried out using the fourth-order Runge-Kutta method. The simulation required a small expenditure of computer time but, with this simulation, it is impossible to obtain the field of speed, pressure, and temperature in the main fairing. This is a disadvantage of the model used. The disadvantages of these calculations include the lack of clarity of the reported results.

Work [13] shows the features of the change in pressure in the volume of the main fairing under rapidly changing external flight conditions. It has been shown how the pressure at the satellite's location decreases under the condition of the isothermal state of the medium. When simulating the process, the concentration of dust content was not taken into consideration and the air flow velocity field near the satellite was not calculated. Given the features of the mathematical model, it was not possible to build a visualization of the process of changing pressure.

Article [14] studied the quantitative characteristics of gas flows in the compartment under the main fairing, taking into consideration the leakage of the main fairing of the launch vehicle. The mathematical model is compiled taking into consideration dimensionless pressure coefficients. In that paper, an analytical dependence of dimensionless pressure coefficients depending on the Mach number is proposed. The disadvantage is the inability to take into consideration the formed currents and their vortices in the area of placement of the spacecraft and the lack of solution to the problem of assessing the field of dust concentration.

In [15], the results of experimental research for the SpaceX Dragon Trunk launch vehicle are reported. A physical experiment was conducted that simulated depressurization of the payload compartment. The experiment in the vacuum chamber was recognized as the best way to ensure the safety of the payload. The experiment paid attention to the rate of pressure drop and methods for releasing air masses from individual parts of the spacecraft. However, the results of the experiment are «special» in nature and cannot be applied to other conditions (other satellite layout, etc.).

In [16], the influence of contamination of cold and cryogenic surfaces of spacecraft was experimentally studied. Pollution levels in the early stages of satellite development and preparation (ground operations) were estimated. The methodology applies the results obtained by the method of thermographic analysis. The disadvantage is the lack of assessments of the influence of external factors on the intensity of molecular contamination of the satellite.

In [17], a method of quantitative and qualitative monitoring of pollution has been developed. This is an important issue of reducing the risks caused by pollution. Pollution levels in place and in real time are performed with great accuracy using quartz microscales. A numerical tool for automatic processing of experimental data of thermogravimetric analysis/mass spectrometry has been developed. This makes it possible to determine the contribution of each species and obtain the mass spectrum of each of these species. A probable disadvantage is the application of the developed method to the molecular type of pollution.

In [18], the results of numerical modeling of the air flow velocity field in the main fairing at the location of different satellites are reported and the results of the numerical calculation and experiment are compared. The results of that work show the wide possibilities of the method of numerical modeling. However, the issue of dust pollution on the main fairing was not considered.

In [19], patterns of the temperature field and vector diagrams of velocities during the flow around a block containing instruments for work in space are obtained. The calculations are made taking into consideration the numerical model, using the Ansys Fluent CFD software package. The disadvantage is that the implementation of this numerical model requires the use of a very powerful computer, which is not always available for design organizations.

Based on the review of scientific publications, it can be argued that issues related to the analysis, calculation of processes in the main fairing are disparate and cover only individual technical problems. At the same time, there are no methods to theoretically solve an extremely important problem that is tackled during the design work – assessing the level of dust pollution in the main current in order to ensure the trouble-free operation of the satellite in orbit.

3. The aim and objectives of the study

The aim of this work is to build numerical models that require several seconds to solve the problem of assessing the dustiness level of the main fairing of the launch vehicle during its forced ventilation during thermostating. This will make it possible to reduce the time spent at the stage of design and calculation operations given that the calculation based on the «ANSYS» software package would take several hours to solve this problem.

To achieve the set aim, the following tasks have been solved:

– to build a numerical model for calculating the air flow velocity field in the main fairing of the launch vehicle during its forced ventilation;

– to build a numerical model for calculating the dustiness of air in the main fairing of the launch vehicle, which makes it possible to take into consideration the complex geometric shape of the satellite located there;

– to conduct computational experiments based on constructed numerical models.

4. The study materials and methods

The object of this study is the process of dust pollution of the surfaces of the satellite in the main fairing during its thermostating. The main hypothesis assumes that a change in the aerodynamics of the movement of air flow in the main fairing affects the level of dustiness of its sensitive surfaces. The assumption is that the viscosity of the air does not affect the formation of concentration fields of dust in the main fairing. When building models, the following simplifications are accepted: only the diagonal components of the tensor of diffusion coefficients are taken into consideration; it is accepted that the air flow is vortexless.

The development of a method for assessing the level of dustiness in the main fairing of the launch vehicle during its forced ventilation is based on the construction of a numerical model of the propagation of dust particles in the main fairing where the satellite is located. The basis for building a method for assessing the level of dust in the main fairing of the launch vehicle is two-dimensional numerical models. The construction of numerical models is based on the application of the finite differences method to solve the differential equations of aerodynamics and mass transfer [20].

5. Results of the study on building a method for assessing the level of dust in the main fairing of the launch vehicle

5. 1. Construction of a two-dimensional numerical model for calculating the air velocity field in the main fairing of the launch vehicle during thermostating

The construction of a method for calculating the air flow velocity field in the main fairing during its ventilation at the stage of prelaunch preparation is considered. The scheme of the estimated region is shown in Fig. 3.

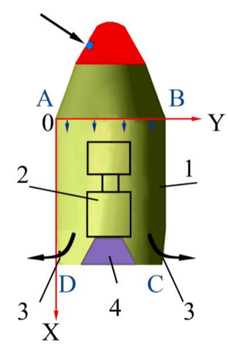

Fig. 3. Estimation scheme:
1 – main fairing; 2 – satellite; 3 – openings for air release; 4 – adapter; ABCD – estimated region

To determine the concentration of dust in the main fairing, one needs to consistently solve the following problems:

1. Calculate the dust concentration field in the main fairing.

2. Calculate the number of dust particles that settle on the «sensitive» surface.

Consider the methodologies for solving these problems. The estimated area in the main fairing is limited to the *ABCD* boundary. To estimate the velocity field in the main fairing during its ventilation at the stage of prelaunch preparation, a model of the potential flow is used:

$$\frac{\partial P^2}{\partial x^2}+\frac{\partial P^2}{\partial y^2}=0, \qquad (1)$$

where P is the speed potential.

For this equation, the following boundary conditions are set (Fig. 3):

– at the boundary A–B – the air flow enters the transport compartment at speed U, the boundary condition is

$\partial P/\partial x=U$ (Neumann's condition). When conducting a computational experiment, a uniform air flow is set at this limit, that is, U=const;

– at the interface of the air flow exit from the transport compartment: $P=P_0$+const, where P_0 is an arbitrary constant (Dirichlet condition);

– on solid boundaries (satellite surface, walls of the main fairing) under non-flow conditions: $\partial P/\partial n=0$, n – unit vector of the outer normal to the solid limit.

The components of the air flow velocity vector are associated with the velocity potential via a dependence:

$$u=\frac{\partial P}{\partial x},\ v=\frac{\partial P}{\partial y}. \qquad (2)$$

For numerical integration of the velocity potential equation, a rectangular difference grid is used. Previously, the Laplace equation (1) is brought to the form [21]:

$$\frac{\partial P}{\partial \eta}=\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}, \qquad (3)$$

where η is fictitious time.

At $\eta\to\infty$, the solution to equation (3) seeks to solve equation (1).

To start the calculation according to the difference schemes (4) and (5), it is necessary to set the «initial» condition for the fictitious time η. During the calculations, it was believed that P=0 in the entire estimated region for the time point $\eta=0$.

For the numerical integration of equation (3), two difference schemes were used. The first difference scheme takes the form [21]:

$$P_{ij}^{n+1}=P_{ij}^{n}+\Delta t\frac{P_{i+1,j}^{n}-2P_{ij}^{n}+P_{i-1,j}^{n}}{\Delta x^2}+$$
$$+\Delta t\frac{P_{i,j+1}^{n}-2P_{ij}^{n}+P_{i,j-1}^{n}}{\Delta y^2}. \qquad (4)$$

To construct the second difference scheme, a geometric splitting of equation (3) is carried out [21]:

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial x^2}, \qquad (5)$$

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial y^2}. \qquad (6)$$

For the numerical integration of equation (5), the following difference scheme is used [21]:

$$P_{i,j}^{n+1}=P_{i,j}^{n}+\Delta t\frac{P_{i+1,j}^{n}-P_{i,j}^{n}}{\Delta x^2}+\Delta t\frac{-P_{i,j}^{n}+P_{i-1,j}^{n}}{\Delta x^2}. \qquad (7)$$

For the numerical integration of equation (6), the following difference scheme is used [21]:

$$P_{i,j}^{n+1}=P_{i,j}^{n}+\Delta t\frac{P_{i,j+1}^{n}-P_{i,j}^{n}}{\Delta y^2}+\Delta t\frac{-P_{i,j}^{n}+P_{i,j-1}^{n}}{\Delta y^2}. \qquad (8)$$

The calculation ends when the condition is met:

$$\left|P_{i,j}^{n+1}-P_{i,j}^{n}\right|\le\varepsilon,$$

where ε is a small number; n is the iteration number.

Both difference schemes are used when conducting computational experiments to control the computational process since the calculation is carried out in areas that have a very complex geometric shape where the loss of stability of difference schemes is possible.

After calculating the velocity potential field, the components of the air velocity vector are calculated as follows:

$$u=\frac{P_{i+1,j}-P_{i,j}}{\Delta x},\ v=\frac{P_{i,j+1}-P_{i,j}}{\Delta y}. \qquad (9)$$

The software implementation of the considered numerical models is completed in the Fortran environment.

Markers are used to form the estimated region and the geometric shape of the satellite [20].

5. 2. Construction of a numerical model for calculating the field of dust pollution in the main fairing of the launch vehicle

To predict the level of dust pollution in the main fairing of the launch vehicle, during the thermostating procedure, the equation for the transfer of dust particles is used:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C}{\partial y}\right), \qquad (10)$$

where C is the number of dust particles in m^3, particles/m^3; u, v – components of the air flow velocity vector in the main fairing, m/s; t – time, s; μ_x, μ_y – diffusion coefficients, m^2/s.

For the mass transfer equation (10), the following boundary and initial conditions are set:

1. At the input to the estimated region (the hole through which ventilated air is supplied): $C=C_{in}$, where C_{in} is the known concentration of dust particles.

2. At the exit boundary of the air flow from the main fairing: $\partial C/n\partial=0$ (n – the unit vector of the outer normal to the boundary).

3. On solid limits: the surface of the satellite, the walls of the main fairing, the following condition is set: $\partial C/n\partial=0$.

4. The initial condition is $C=C_h$, where C_h is the known concentration of dust particles in the air inside the main fairing.

To construct a numerical model of the process of transferring dust particles, equation (10) is split into two equations (11) and (12):

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}=0, \qquad (11)$$

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C}{\partial y}\right). \qquad (12)$$

From a physical point of view, equation (11) describes the transfer of dust particles due to speed, and equation (12) describes the transfer of dust particles due to diffusion.

Since the solution to modeling equations (10) or (11), (12) is determined in a region that has a complex geometric shape, the only solution is to use numerical methods.

For the numerical integration of equation (11), the following transformations are performed:

$$\frac{\partial C}{\partial t}\approx\frac{C_{ij}^{n+1}-C_{ij}^{n}}{\Delta t},$$

$$\frac{\partial uC}{\partial x}=\frac{\partial u^{+}C}{\partial x}+\frac{\partial u^{-}C}{\partial x},\ \frac{\partial vC}{\partial y}=\frac{\partial v^{+}C}{\partial y}+\frac{\partial v^{-}C}{\partial y},$$

$$\frac{\partial u^- C}{\partial x} \approx \frac{u^-_{i+1,j} C^{n+1}_{i+1,j} - u^-_{i,j} C^{n+1}_{i,j}}{\Delta x} = L^-_x C^{n+1},$$

$$\frac{\partial u^+ C}{\partial x} \approx \frac{u^+_{i,j+1} C_{i,j} - u^+_{i,j} C_{i-1,}}{\Delta x} = L^+_x C^{n+1},$$

$$\frac{\partial v^+ C}{\partial y} \approx \frac{v^+_{i,j+1} C_{i,j} - v^+_{i,j} C_{i,j-1}}{\Delta y} = L^+_y C^{n+1},$$

$$\frac{\partial v^- C}{\partial y} \approx \frac{v^-_{i,j+1} C_{i,j+1} - v^-_{i,j} C_{i,j}}{\Delta y} = L^-_y C^{n+1},$$

where

$$u^+ = \frac{u+|u|}{2}, u^- = \frac{u-|u|}{2}, v^+ = \frac{v+|v|}{2}, v^- = \frac{v-|v|}{2}.$$

At the next stage, a four-step difference scheme is applied:

– step 1, $k=1/4$:

$$\frac{C^{n+k}_{ij} - C^n_{ij}}{\Delta t} + \frac{1}{2}\left(L^+_x C^k + L^+_y C^k\right) = 0; \quad (13)$$

– step 2, $k=1/2$, $c=n+1/4$:

$$\frac{C^k_{ij} - C^c_{ij}}{\Delta t} + \frac{1}{2}\left(L^-_x C^k + L^-_y C^k\right) = 0; \quad (14)$$

– step 3, $k=n+3/4$, $c=n+1/2$:

$$\frac{C^k_{ij} - C^c_{ij}}{\Delta t} + \frac{1}{2}\left(L^-_x C^k + L^-_y C^k\right) = 0; \quad (15)$$

– step 4, $k=n+1$, $c=n+3/4$:

$$\frac{C^k_{ij} - C^c_{ij}}{\Delta t} + \frac{1}{2}\left(L^+_x C^k + L^+_y C^k\right) = 0. \quad (16)$$

For the numerical integration of the diffusion equation, the method of total approximation is used. The difference dependences are two steps long and take the following form:

$$\frac{C^{n+1}_{i,j} - C^{n+\frac{1}{2}}_{i,j}}{\Delta t} = \left[\frac{C^{n+1}_{i+1,j} - C^{n+1}_{i,j}}{\Delta x^2}\right] + \left[\frac{C^{n+1}_{i,j+1} - C^{n+1}_{i,j}}{\Delta y^2}\right], \quad (17)$$

$$\frac{C^{n+\frac{1}{2}}_{i,j} - C^n_{i,j}}{\Delta t} = \left[\frac{-C^{n+\frac{1}{2}}_{i,j} + C^{n+\frac{1}{2}}_{i-1,j}}{\Delta x^2}\right] + \left[\frac{-C^{n+\frac{1}{2}}_{i,j} + C^{n+\frac{1}{2}}_{i,j-1}}{\Delta y^2}\right]. \quad (18)$$

Thus, to calculate the unknown value of the dust concentration C, equations (13) to (18) are sequentially solved. It is important to note that the value of the concentration C from each equation is derived according to an explicit formula. This allows for a simple software implementation of the constructed numerical model.

The dust concentration field, calculated based on dependences (17), (18), makes it possible to calculate the number of dust particles that «settled» on a particular surface of the satellite. To calculate the number of dust particles that have a size of more than 5 µm and fall on the horizontal surface, an empirical model is used [9]:

$$C_s = c \cdot p \cdot C_n^{0.773} \cdot t, \quad (19)$$

where t is the time, $c=1.076$ is the empirical coefficient, $p=2.851$ is the empirical coefficient [9]; C_n – the concentration of dust in the air in the calculated cell adjacent to the surface. This concentration is calculated based on the constructed numerical model. Note that this parameter has a dimensionality [particles/foot^3]. The calculation using dependence (19) gives the value of the number of dust particles deposited per day on the surface with an area of 0.1 m^2. If a vertical surface is considered, the number of dust particles falling on it is 10 % of the value of C_s.

FORTRAN was used to program the considered numerical model; the code «SPUT-2» was developed.

5. 3. Conducting computational experiments based on the constructed numerical models

Below are the results of solving two model problems based on the constructed numerical models. The tasks differed in the shape of the satellite, which was located in the main fairing. During the computational experiment, the estimated region had dimensions: length $B–C$ – 4.99 m, width $A–B$ – 4 m. (Fig. 3). At the boundary $A–B$, uniform air flow was set at a speed of $U=2$ m/s. The concentration of dust entering with air through the boundary $A–B$ was equal to $C=10^5$ particles/m^3, diameter of dust particles – 6 µm. Satellite length, 3.4 m; width, 2.2 m.

The first problem is to assess the level of dust pollution in the main fairing when the satellite is located according to the «scheme number 1» (Fig. 4). This is a satellite of a «simple» geometric shape, such as a «rectangle». Two scenarios were considered. The first scenario is that the air entered the main fairing only from above (direct-flow air supply at the border $A–B$). The second scenario is that the air entered the main fairing additionally from the side (the place of additional feed is indicated by the number 3 in Fig. 4), the air flow was supplied without impurity, at the same speed (Fig. 4, zone 3). That is, in zone 3, there is an air blow at a speed of $U=2$ m/s.

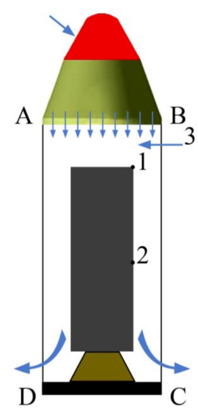

Fig. 4. Estimated «scheme No. 1»: 1–2 – surface of special «sensitivity»; 3 – additional air supply zone; ABCD – estimated region

Fig. 5, 6 show the dust concentration field in the main fairing for both scenarios. For the convenience of analyzing the polluted zone, the concentration of dust is shown in Fig. 5, 6 in percent of the maximum value of the dust concentration in the estimated region. Note that the maximum dust concentration is $C=10^5$ particles/m^3.

From the above Fig. 5, 6 one can see that near the top of the satellite there is a formation of zones of dust pollution with a high concentration gradient. This is due to a sharp reversal of the air flow flowing from above to the main part of the satellite.

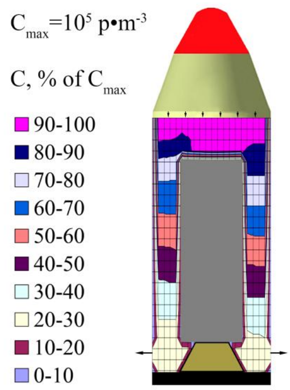

Fig. 5. The field of dust concentration in the main fairing when the satellite is located according to the «scheme number 1», the first scenario

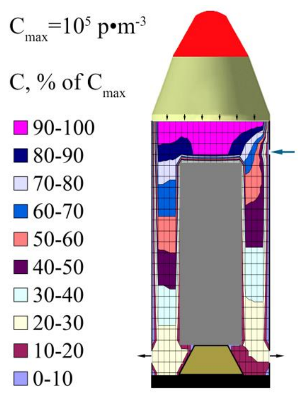

Fig. 6. Dust concentration field in the main fairing when the satellite is located according to the «scheme number 1», the second scenario (additional blowing)

Fig. 7 shows how many dust particles will «settle» on the vertical «sensitive» surface of the satellite (region 1–2, Fig. 4) per day.

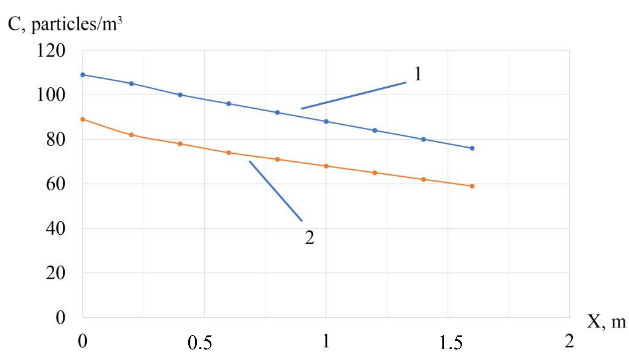

Fig. 7. The number of dust particles that «settled» on the vertical «sensitive» surface per day: 1 — scenario No. 1; 2 — scenario No. 2

As one can see from Fig. 7, the use of additional «blowing» air inside the main fairing can reduce, by about 20 %, the amount of dust deposited on the «sensitive» surface.

The second problem is to assess the level of dust pollution in the main fairing when the satellite is located according to «scheme 2» (Fig. 8). This is a satellite of «complex» geometric shape, such as «a set of rectangles.» The satellite has two surfaces of special «sensitivity»: the surface 1–2 on the side of the satellite and the surface 3–4 on the horizontal side of the satellite (Fig. 8).

Fig. 9 shows the dust concentration field in the main fairing for scenario No. 2. Here also, for the convenience of analysis, the pollution zone is shown as a percentage of the maximum value of dust concentration in the estimated region.

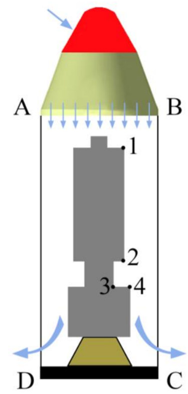

Fig. 8. Estimated «scheme No. 2»: 1—2 — the surface of a special «sensitivity» on the side of the satellite; 3—4 — the surface of a special «sensitivity» on the horizontal side of the satellite

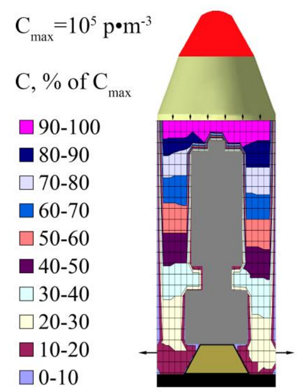

Fig. 9. The field of dust concentration in the main fairing when the satellite is located according to the «scheme number 2»

Fig. 10, 11 show how many dust particles will «settle» on the vertical «sensitive» surface of the satellite (region 1–2, Fig. 4) and on the horizontal «sensitive» surface of the satellite per day. Note that the value of «x=0» in Fig. 11 corresponds to point 3 in Fig. 8.

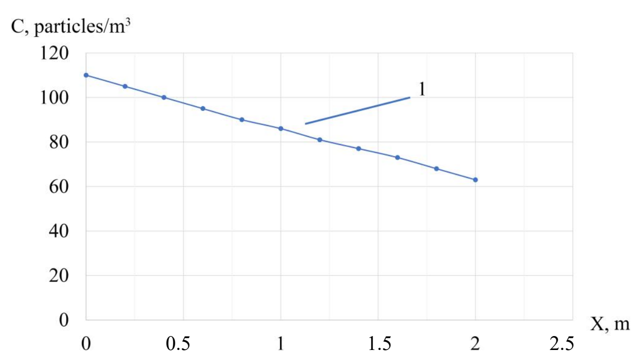

Fig. 10. The number of settled dust particles on the vertical «sensitive» surface 1—2 per day

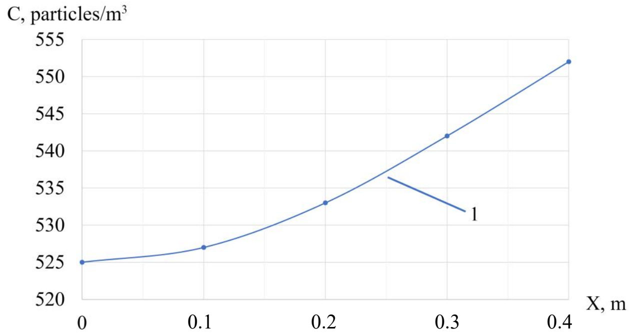

Fig. 11. The number of settled dust particles on the vertical «sensitive» surface 3–4 per day

It should be noted that the calculation time of each problem lasted 4 s.

6. Discussion of results of the study to devise a method for assessing the level of dust in the main fairing of the launch vehicle

The constructed numerical model, based on equations (11), (12), makes it possible to determine the field of dust pollution in the main fairing of the launch vehicle under different modes of its thermostating. The constructed model takes into consideration the process of convective and diffusion propagation of dust particles, as well as the geometric shape of the satellite. This makes it possible to simulate the process of dust pollution in the main fairing with a greater approximation to reality. Based on the numerical model built, a study was conducted to determine the concentration fields of dust in the main fairing during its thermostating.

The results of the computational experiment show that the formation of the concentration field of dust in the main fairing is influenced by the mode of organization of air exchange in the middle of the fairing. Fig. 5, 6 show that for the estimated «scheme No. 1», the value of the dust concentration along the surface of «special sensitivity» varies in the range from 85 % (upper part of the satellite) to 55 % (middle of the satellite). For the second scenario, the concentration of dust along this surface varies in the range from 65 % (upper part of the satellite) to 39 % (middle of the satellite).

Studies have shown the influence of the shape of the satellite on the formation of a dust pollution zone inside the main fairing. Thus, when the satellite is located in a «rectangular» shape (in the absence of a blowout), the dust concentration at the place of the adapter varies in the range of 22–23 % of the maximum dust concentration in the main fairing. When a satellite of complex shape is located, the concentration of dust varies in the range of 18–21 %. It is important to emphasize that due to the increased requirements for dust pollution of satellite surfaces, reducing the concentration of dust by several percent can be very important.

Computer experiments have confirmed the possibility of using the constructed numerical model to predict the level of dust pollution in the entire volume of the main fairing when it is thermostated. This complete picture of the distribution of dust concentration in the main fairing was obtained due to the fact that a compatible solution to two problems was used to analyze the pollution areas: aerodynamics and mass transfer in the entire volume of the main fairing, and not in some part of it. This approach makes it possible to determine how air pollution in the main fairing and surfaces of the satellite changes when the aerodynamics of ventilation change. This is a significant advantage of the constructed numerical models, in contrast, for example, from the methodology for assessing dust pollution of satellite surfaces proposed in [8] where only part of the volume of the main fairing is considered, and not its entire volume.

A feature of the constructed numerical model is the speed of calculation on computers of low and medium power. The disadvantages of the proposed numerical model include the fact that the aerodynamic model (1) does not take into consideration turbulent viscosity. In addition, when determining the amount of dust falling on the surface of the satellite, empirical constants are used, the values of which need to be clarified in some cases. The obtained solutions make it possible at a qualitatively new level to assess the level of purity of the surfaces of the satellite at the stage of thermostating. The limitations of the proposed numerical model include the impossibility of taking into consideration the effect of heating the outer walls of the main fairing on the aerodynamics of the flow in it.

Further development of this model involves the design of a computational unit that will make it possible to calculate the aerodynamics of the flow based on the Navier-Stokes equations to take into consideration the effect of viscosity on the air flow velocity field.

7. Conclusions

1. A numerical model has been built for calculating the uneven field of air flow velocity supplied to the main fairing at the stage of its thermostating. The calculation of the velocity field based on this model creates a platform used in the second stage of the computational experiment in calculating the concentration of dust in the entire volume of the main fairing. In addition, the constructed numerical model makes it possible to take into consideration different places of air supply to the main fairing when it is thermostated and the different geometric shape of the satellite.

2. A multivariate numerical model has been built to identify patterns of formation of areas of dust air pollution inside the main fairing and assess the level of pollution of the «sensitive» surfaces of the satellite (locations of optics, apertures, detectors). When performing the calculation, the model makes it possible to take into consideration a set of important physical factors affecting the intensity of dust pollution of these satellite surfaces. It was established that due to additional air blowing from the side into the main fairing, it is possible to reduce the level of dust pollution of the «sensitive» surfaces of the satellite by 20 %.

3. The results of our computational experiments, which were carried out based on the constructed numerical model, allow us to assert that the numerical model built has a wide working range and makes it possible to get predictive data in real time. This can be useful in assessing the effectiveness of the selected thermostating scheme in order to provide the necessary conditions for storing the satellite before launching the launch vehicle.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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