Influence of gas-dynamic characteristics of a wide-range engine on energy-information exchange during flights at high supersonic speed

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Abstract. Using a conical nozzle as an example, the gas-dynamic and thrust characteristics of high-altitude nozzles are studied in a wide range of atmospheric pressures. A geometric model of the nozzle block and the computational domain is developed in a two-dimensional axisymmetric formulation. A calculation was carried out with setting the parameters of the standard atmosphere in the altitude range from 0 to 80 km. In one of the parts of this work, the most common shock-wave structures (triple configurations of shock waves) that arise during flights at supersonic and high supersonic speeds are considered, during jet outflows from propulsion systems. We also studied the influence of the extreme values of the discontinuities of the flow field parameters on the transmitted electromagnetic signals.

1. Introduction

In modern reality, an open question remains – the possibility of using an optical communication line for energy-information exchange with supersonic aircraft (AC), as well as between spacecraft and their control centers.

In the 2.4 GHz frequency range, communication has a higher penetration capacity than, for example, in the 5 GHz range. However, in today's environment, 2.4 GHz frequencies are becoming more congested. In most countries, unmanned aerial vehicles (UAVs), small spacecraft (SSCs) and robotic systems are operated at 2.4 GHz and 5.8 GHz. The frequency ranges of satellite communications are from 1.5 GHz to 30 GHz, and the transmission of information at frequencies of 40-50 GHz is a promising development [1].

The optical (infrared) range with wavelengths from 2 mcm to 10 nm remains promising for the development of information transmission. This mode of information transmission is called atmospheric optical communication line.

In the implementation of wireless optical communication, technical difficulties arise, since a high accuracy of guidance and mutual tracking is required. The factors that attenuate the signal are atmospheric phenomena, suspended matter, air humidity, absorption and scattering of waves by particles and molecules contained in the air, as well as pressure and temperature gaps, especially on shock waves. In this part of the work, the influence of the propagation of shock-wave structures arising from jet outflows from a propulsion system is considered on the example of a single-stage wide-range engine. Taking into account the effect of shock waves, it is necessary to determine the geometric location of the receiver / transmitter in the implementation of uninterrupted communication with the aircraft.
According to the Aeronet roadmap of the National Technology Initiative [2], as well as the speeches of the heads of the Roscosmos State Corporation, at present, great attention is paid to the development of single-stage ultralight launch vehicles.

One of the promising solutions to the problem of altitude control (the dependence of thrust and specific impulse on the flight altitude at a constant value of the mass flow rate per second and a constant ratio of fuel components) is the use of a slotted nozzle with a large expansion ratio. For such a nozzle, due to the sequential activation of its individual sections, the altitude is close to the characteristic of a nozzle with a continuously adjustable altitude. However, its design is not too complicated.

Owing to the transfer of atmospheric pressure through the annular slot into the nozzle, the gas is forced to detach from its walls, as a result of which the nozzle section behind the slot is, as it were, "turned off", and the nozzle operates in a mode close to ideal. As they rise to the height, the shock waves reach the nozzle exit, and in this case, the high-altitude nozzle also operates in a self-similar mode, in which the averaged characteristics of the turbulent flow do not depend on the viscosity.

Such nozzles have been studied since the 1980s at the Center named after M.V. Keldysh and Moscow Aviation Institute [3].

However, the results of experiments with nozzles using an annular slotted hole are clearly insufficient.

Therefore, it seems expedient to conduct a study of a slotted nozzle with a large expansion ratio, and more accurate simulation of the medium for determining the field of density fluctuations and the phase of the wave front, especially under conditions of extreme drops in the parameters of the flow field and their derivatives on gas-dynamic discontinuities. Obtaining sufficient information about the possibility of practical use of energy-information exchange during flights of a wide-range engine is also necessary [4].

2. The principle of operation of the atmospheric optical communication line

The information enters the transceiver module, encoded, modulated by an optical emitter, focused into a narrow collimated laser beam and transmitted into the atmosphere. A powerful semiconductor laser diode is used as a transmitter. At the receiver, the optical system focuses the signal onto the photodiode. The beam is converted to an electronic signal, which is demodulated and converted to output interface signals [5].

The advantages of optical wireless communication for interaction with aircraft, UAVs and spacecraft are:

- closed communication channel (reading or intercepting a signal is impossible);
- immunity to radio interference (airports, proximity of radars, power lines) and the lack of their generation;
- no need for licensing and frequency allocation;
- broadband transmission (providing a large volume of traffic);
- significant reduction in the size and power of the transmitter and antenna;
- quick installation.

When electromagnetic radiation of the optical range passes through the atmosphere, it is necessary to take into account the inhomogeneity of the medium (turbulent vortices, shock waves, shear and compressed layers). Since the characteristic size of such irregularities is larger than the beam diameter, passage through them can lead to optical aberrations. Aero-optics is studying these issues.

Vortex formations and other inhomogeneities of the medium cause a change in the amplitude and phase of the wave, as a result of which the beam can expand. The larger its expansion, the smaller the distance at which it can be focused and receive undistorted information. In addition, inhomogeneity of the supersonic flow field can cause fluctuations in the propagation direction (the geometric center of the beam is displaced), beam splitting, which at small distances manifests itself in a complex spot
structure (and as the distance increases, the optical beam turns out to be split into filaments and the power is redistributed in the cross section); the scattering of the beam leads to fluctuations in the radiation intensity [6, 7].

Aero-optical aberrations depend on the geometric ratio of wavelength, beam diameter, turbulence scale, and propagation distance. The passage of electromagnetic radiation through a vortex smaller than the beam diameter causes scattering, beam divergence and, subsequently, attenuation of its intensity. When the vortex size is larger than the aperture, the beam as a whole is deflected (direction fluctuation). In the case of approximately equal dimensions of the vortex and the beam aperture, the effect of a lens arises, which re-shapes the electromagnetic wave [7, 8].

Gladstone-Dale's law shows that the refractive index depends on the density of the medium through which electromagnetic radiation passes. It is also known that the distortion of the amplitude characteristics of radiation is relatively small compared to phase fluctuations [9]. It follows from this that the main task is to simulate the medium as accurately as possible to determine the density fluctuation field and the wavefront phase, under conditions of extreme drops in the flow field parameters and their derivatives on gas-dynamic discontinuities.

3. Basic equations of aero-optics

The Bouguer-Lambert-Beer law is used to measure the transparency of the atmosphere and find transparency windows. It determines the attenuation of a parallel monochromatic light beam during its propagation in an absorbing medium and is expressed by the following formula:

\[ I(l) = I_0 e^{-k \lambda l} \]  

(1)

where \( I_0 \) is the intensity of the incoming beam; \( l \) is the thickness of the working medium layer; \( k \) is absorption index (absorption spectrum of a substance).

\[ k = 4\pi k / \lambda, \]  

(2)

where \( \lambda \) – wavelength; \( k \) – dimensionless absorption coefficient.

Gladstone-Dale law establishes the relationship between the refractive index and the density of the medium [6, 7]

\[ n(x,t) = 1 + G(\lambda) \frac{\rho(x,t)}{\rho_0} \]  

(3)

where \( \rho_0 \) is characteristic density; constant \( G \) depends on the wavelength of the transmitted light and the working medium:

\[ G(\lambda) = 0.223 \times 10^{-3} \left(1 + \frac{7.52 \times 10^{-15}}{\lambda^2} \right), \text{ m}^2/\text{kg}. \]  

(4)

Dispersion of density fluctuations \( \sigma_\rho^2 \) and the corresponding correlation scale \( l_\rho \) related to the phase dispersion of the wave \( \sigma_\phi^2 \) ratio [7]

\[ \sigma_\rho^2 = \alpha \beta^2 \int_0^L \sigma_\phi^2 dy, \quad \beta = \frac{2x \frac{dn}{d\phi}}{\lambda} = kG(\lambda) \]  

(5)

where \( L \) is the path traveled by the optical beam (integration is performed across the boundary layer). The value of the constant factor \( \alpha \) depends on the adopted form of the density fluctuation correlation function.

Linear scale \( l_\rho \) is found by integrating the corresponding correlation function:

\[ l_\rho = \int_{-\infty}^{+\infty} R_\rho(y) dy \]  

(6)

Under local equilibrium conditions, the correlation scale \( l_\rho \) coincides with the correlation scale of the velocity fluctuations \( l_u \sim k^{3/2}/\varepsilon \).

The propagation of electromagnetic radiation is described by Maxwell's equations:
where \( E \) – electric field strength. The refractive index is found from the relationship

\[
n = \frac{c_0}{c},
\]

where \( c \) — speed of light in a medium, \( c_0 \) — speed of light in vacuum.

The phase function of the wavefront is determined by the dependence

\[
\varphi = \int k(x, t) \, dx
\]

where \( k = 2\pi \mathbf{n}/\lambda \) is wave vector, and vector \( \mathbf{l} \) characterizes the direction of wave propagation.

To solve the system of equations (1-8), it is necessary to specify the field of parameters of the medium through which the electromagnetic radiation passes, and the type of wave (most often - monochromatic sinusoidal). To calculate the flow field, the system of Navier-Stokes equations is solved with the introduction of a certain turbulence model and a method for calculating turbulent flows. The system is supplemented by the equation of state of the medium if it is necessary to take into account the influence of temperature fluctuations. It was determined in [8] that a change in temperature does not significantly affect the propagation of optical waves.

The experimental study of optical aberrations is devoted, in particular, to works [8, 9]. Simulation was also carried out for the field of a randomly inhomogeneous medium when an optical beam passes through a turbulent flow, a boundary layer, and a free mixing layer. In [10-12], the passage of radiation through a shock wave in a turbulent atmosphere at various altitudes and flight modes of an aircraft was considered. As the research results in these works, a comparison with experimental data, expressions of density pulsations, conclusions on the intensity of the influence (strengthening and weakening) of atmospheric phenomena on aero-optical effects are given.

### 4. Setting up a numerical experiment

A conical nozzle was chosen as the primary object of research for modeling gas-dynamic methods of adjusting the nozzle height in a wide range of atmospheric pressure.

To achieve the set goals, the following tasks were formulated:

- to calculate the nozzle with the parameters of the atmosphere on the Earth surface;
- to determine the position of the separation section;
- based on the above points, to change the computational domain by adding a slit in the nozzle in this section;
- to calculate the above-described points with atmospheric parameters at other heights (0, 10, 20, 40, 80 km);
- to plot the density distribution when passing through shock-wave structures;
- to discuss the practical applications of the aero-optics equation in numerical modeling.

The scientific novelty of the work is the experimental study of methods for regulating the height of the nozzle, based on the prevention of gas overexpansion inside the nozzle by bypassing gas through annular slots organized in the expanding part. In addition, it is necessary to identify the influence of various design parameters of the slot on the increase in thrust and develop recommendations for the design of the slotted nozzle. As well as accurate modeling of the environment under conditions of extreme drops in the parameters of the flow field and their derivatives on gas-dynamic discontinuities.

This part of the work presents the results of numerical simulation of the flow from the RD-120 nozzle (the engine is made in a closed circuit with the afterburning of the generator gas after the turbine). It is a liquid propellant rocket engine that uses liquid hydrogen and liquid oxygen.

The geometric characteristics of the nozzle block of the selected engine are as follows: the diameter of the inlet and outlet sections \( d_1 = 0.18 \, m \), \( d_2 = 1.9 \, m \), length of the curved section of the nozzle \( L = 2.49 \, m \), nozzle wall thickness \( \Delta = 0.005 \, m \), computational area \( S = 34.5 \, sq.m \).
atmosphere parameters for different heights were determined in accordance with the Russian standard GOST 4401-81 "Standard atmosphere". The geometric Mach number of the nozzle \((M = 4.5)\) was calculated using the one-dimensional theory [13], according to the formula:

\[
q(M) = \frac{F_1}{F} = \frac{M^{(\gamma + 1)/2}}{(1 + (\gamma - 1)/2M^2)^{(\gamma + 1)/2(\gamma - 1)}} (9)
\]

The supersonic nozzle operates at zero altitude in the strong overexpansion mode.

For numerical simulation, the Navier-Stokes Reynolds-averaged equations were solved. The numerical model was supplemented with a two-parameter turbulence model. A perfect gas model with a temperature-dependent viscosity was used.

The described flow conditions correspond to the off-design regime of strong overexpansion, i.e. the pressure in the jet at the nozzle exit is significantly less than atmospheric one. Such a pressure difference leads to the fact that the normal shock that usually appears in the jet (central Mach disk) moves into the nozzle; in addition, there is a separation of the jet from its wall.

The thrust force is generated only by that part of the nozzle with attached flow, while the rest of the nozzle will create an opposite force opposite due to the suction of the flow from the atmosphere into the nozzle. Prevention of the action of this force is possible by making a gap in the flow separation section. It prevents backflow into the nozzle.

When increasing the flight altitude, i.e. as the atmospheric pressure decreases, the jet will expand significantly and must adhere back to the surface of the rest of the nozzle. Moreover, the flow rate through the nozzle (and the thrust together with it) will also increase, because a part of the working substance is sucked in from the atmosphere through the slit and is accelerated by a jet stream, as in an ejector.

As a separation is formed inside the nozzle at an altitude of 10 km, it is advisable to create another slotted hole and perform further calculations with modified geometric parameters. This method of solving the emerging separation problem makes sense, since air injection gives an additional increase in thrust, but only in dense layers of the atmosphere. At an altitude of about 80 km, the increase in thrust will be insignificant due to the possible flow reversal and the occurrence of the so-called thrust reverse.

5. Results of a numerical experiment
In the course of the numerical experiment, the flow inside the nozzle block and in the surrounding space was simulated in a two-dimensional axisymmetric formulation.

A calculation was performed with setting the parameters of the standard atmosphere at zero altitude. At this stage, the main task was to determine the place of separation in the supersonic part of the nozzle duct and to make a slot hole there. Fig. 1 shows that the Mach number fields of the flow field inside the nozzle of the RD-120 engine at low flight altitudes.

It is obvious that the nozzle operates in the mode of strong overexpansion, which is why the separation of combustion products from the inner wall of the nozzle occurs. The degree of off-design for a given nozzle operation mode
Figure 1. The flow field in the computational domain at a height: a) 0 km; b) 10 km; c) 20 km; d) 30 km; e) 40 km; f) 60 km; g) 80 km.

In the next calculation example (Fig. 2), the outflow of an overexpanded gas jet at an altitude of 10 km was simulated.

With an increase in the flight altitude (Fig. 1, a-c), the outflow of the jet stream goes into underexpansion mode, the pressure in the environment becomes much less than the pressure at the nozzle exit, and the degree of off-design increases.

When flying at high altitudes, the flow turns in the direction of the outer walls of the nozzle (Fig. 1, d-g). This effect is also traced during the outflow of a supersonic jet into vacuum. A detailed analysis of the outflow field with overexpansion in the vicinity of the edge of the conical nozzle was carried out in [14, 15].

The calculation was carried out with the setting of the following boundary conditions. The temperature and pressure at the outlet from the proposed combustion chamber were set as input parameters. The pressure was indicated, which was set in the range from 20 to 160 atmospheres and then increased to real values in order to achieve a stable solution. The gas temperature was set in a similar way in the range from 300 to 2200 K.

In the formulation of the problem, it was also necessary to add a wake flow, using the parameters of the standard atmosphere, characteristic of a particular required flight altitude above sea level. Similar boundary conditions were set through the pressure-far-field option. The static pressure was calculated by the formula (5) at a known total pressure was given as

\[ p_0 = p_\infty \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\gamma/(\gamma - 1)} \]

A stable solution was achieved by smoothly increasing the input parameters in the critical one (with the achievement of settling at each increase).
In addition, a numerical simulation of a turbulent flow inside a similar nozzle with a slotted hole was carried out.

A nozzle with a geometric expansion ratio of 10.56 is considered. The slotted section is located in the supersonic part at a distance of 659.54 mm from the critical section.

The calculations were carried out at different flight altitudes, the parameters at the exit from the combustion chamber remained the same. The resulting flow patterns in a nozzle with a slotted hole are shown in Fig. 2.

At high altitudes, flow reversal occurs, since the pressure in the environment is low (Fig. 2,d-g).

According to formula (10), the traction force was calculated at different heights and for different design modes (Fig. 3). Thrust force at a certain height is calculated as it follows:

\[
R_H = \dot{m} w_a + \int_{F} (p_a - p_u) dF,
\]

where the integration is provided over the outlet section of the nozzle, as well as the determination of the amount of motion of the gas leaving the nozzle volume \( \dot{m} w_a \), where \( \dot{m} = \frac{dM}{dt} \) – flow rate of exhaust gases per one second, \( w_a \) is gas flow rate from the nozzle, is performed numerically. As the nozzle operates in a correctly expanded mode, when \( p_a = p_u \), combustion chamber jet thrust in this case \( R_H = \dot{m} w_a \).
The results of calculating the flow of a gas in a nozzle with a slotted hole, taking into account the effect of an external flow on its operation, show that the organization of an annular slot improves the thrust characteristics due to the use of an early separation of the flow inside the nozzle. However, from Fig. 3, it can be seen that the nozzle with a slotted hole at low heights has significant thrust losses in comparison with the characteristic of a smooth Laval nozzle. To eliminate this drawback, it is advisable to create another slotted hole and perform further calculations with modified geometric parameters. This method of solving the emerging separation problem makes sense, since air injection gives an additional increase in thrust, but only in dense layers of the atmosphere.

6. Conclusion.
A nozzle operating in a mode in which the static pressure at the exitnozzles more pressure in the surrounding space, creates less thrust. In the opposite case, a negative component of the thrust force is created, the value of which is subtracted from the thrust generated by the design nozzle. To obtain the highest thrust value, it is necessary to design a nozzle operating under the condition when $P_a = P_e$. To achieve this goal, it is proposed to vary the geometric parameters of the nozzle and its design.

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