Investigation of the possibilities of aerodynamic forms of a lander capable of maneuverable descent in the venus atmosphere

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A. V. Kosenkova

Investigation of the Possibilities of Aerodynamic Forms of a Lander Capable of Maneuverable Descent in the Venus Atmosphere

A.V. Kosenkova

Lavochkin Association, Khimki, Moscow region, Russia, 141402

Kosenkova.AV@yandex.ru

Abstract. This paper considers various types of a lander for the possibility of making maneuverable descent to the Venus surface, conducts a comparative analysis of these landers and determines their design characteristics, namely, maneuverability and mass characteristics. The calculation of the aerodynamic characteristics for the chosen lander type is presented using the numerical method according to the Newton's theory of hypersonic flow and ways of ensuring the lander stability are considered. Proposed lander configurations have certain values of the lift-to-drag ratio for hypersonic flow, are capable of maneuvering and landing in the set areas, which are the most promising for exploration. Besides, they are characterized by improved thermal operation regimes and reduced overloads during the descent in the Venus atmosphere, and they can help to expand a range of solving scientific tasks.

INTRODUCTION

The exploration of Venus as a terrestrial planet is interesting not only from the standpoint of fundamental science, but also from the standpoint of comparative planetology, as the study of the Earth, Mars, and Venus enable better understanding of the early history of the formation and development of the terrestrial planets, the evolution of their atmospheres, and the differences in the history of their tectonic development. In particular, this allows prediction by analogy by revealing possible ways the Earth, its atmosphere, and climate are going to evolve.

After a long break, there are several projects on resuming the exploration of Venus being considered. Scientists and technical specialists are mostly interested in the landing areas, where there are traces of tectonic processes occurred in the past. In this connection the task of creating landers, including consideration of using ones with the alternative configuration, capable of making maneuverable descent to the Venus surface, is becoming important.

SPACECRAFT FOR CONTACT EXPLORATION OF VENUS. PAST EXPERIENCE AND PROSPECTS

Currently, there is a project “Venera-D” being developed to resume the fundamental Venus research. The project is conducted by a group of American and Russian scientists, engineers, and technical specialists. The structure of the lander is similar to the landers “Venera” and “Vega”, which have a spherical form and belong to the ballistic type of a lander that are characterized by zero lift-to-drag ratio at hypersonic velocity and do not provide the possibility of maneuvering during the descent in the Venus atmosphere.

The use of spherical (Soviet ones) and conical (American ones) landers at the initial stages of the Venus exploration was related to the simplicity and reliability of their structure, as the primary task for the lander was to reach the surface with working equipment. To choose the needed landing area, a lander capable of making maneuvers is required, i.e., it must have a certain lift-to-drag ratio.

However, ensuring a required lift-to-drag ratio means that the lander mass increases and its structure becomes more complex. A trade-off solution would be to use landers of the “lifting body” type. The complication of the

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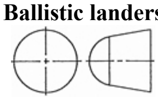
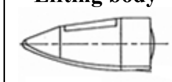
structure of such landers is permissible, but they have a lift-to-drag ratio sufficient for solving the existing maneuvering tasks in the Venus atmosphere.

This paper proposes considering new configurations of landers capable of performing a significant degree of maneuvering and enabling wide outreach to choose the required landing area, including possible areas for safe landing.

Table 1 presents the comparative characteristics of various lander types for this task.

TABLE 1. Comparative design characteristics of various Venus landers.

Comparative parameters and criteria estimates	**Parameters**	**Lander types**		
		I **Ballistic landers** 	**II** **“Gliding descent”** 	**III** **“Lifting body”** 
lift-to-drag ratio for hypersonic velocity (M>6)	$K_{\text{hyp}} = {C_{ya}}/{C_{xa}}$ Range, average value	0 0	0.15...0.5 0.3	0.8...1.5 1.0
Range of the lift-to-drag ratio change during the switch from the hypersonic to the subsonic descent mode	K_{sub} $\overline{K} = {K_{\text{sub}}}/{K_{hyp}}$	0 1	0...0.5 1.5	2...3.5 2.5
Comparative mass characteristics	$K_m = {G_{VL}}/{G_{BVL}}$	1	1.2	1.5
Volume efficiency (fill factor)	$K_{\text{fill}} = 4.836\frac{(V_\Sigma)^{\frac{2}{3}}}{S_\Sigma}$	1...0.85	0.95...0.75	0.75...0.6
Relative mass of thermal protection	$\overline{K}_{tp} = {G_{tp}}/{G_{VL}}$	0.15...0.28	0.12...0.25	0.12...0.2
Overload during descent	n	120..130	100..110	< 85
Lateral maneuver in the atmosphere, km	L_{side}	0	80...100	1000...2000
Note VL – Venus lander; BVL – Venus lander of a ballistic type				

The proposed lander types equipped with the instruments for Venus research must first be tested for the entry in the Earth atmosphere. During this testing, the control tasks during the entry stage are deal with, the thermal modes of operation are elaborated, and the landing regime is studied. At the initial stage of investigation of the landers, the parachute and the rocket-assisted parachute systems are used to enable multiple tests.

For analysis, we choose the “lifting body” lander type, as it has the greatest lift-to-drag ratio and it is capable of greater maneuvering compared to the “gliding descent” type while maintaining a permissible degree of structural complexity and increase of mass.

CALCULATION MODEL OF THE VENUS ATMOSPHERE

Currently, the COSPAR VIRA-30 (Venus International Reference Atmosphere) model of the Venus atmosphere is used for calculations. Figure 1 presents a comparison of the vertical profiles of the density ρ_0, pressure p and temperature T of the Earth and Venus atmospheres (the parameters of the Earth atmosphere have the index ‘E’).

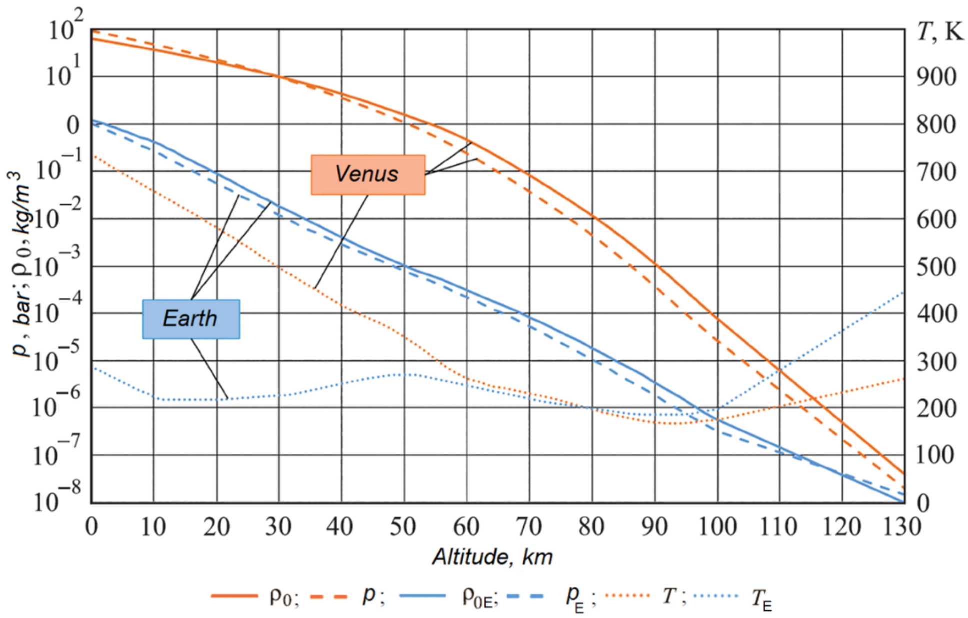


FIGURE 1. Parameters of the Earth and Venus atmospheres

The plots show that the atmospheres are somewhat similar at their boundaries, but the difference becomes quite significant near the surface.

Such characteristics of the near-surface Venus atmosphere make the task of creating a lander capable of landing in this atmosphere complicated.

ANALYSIS OF AERODYNAMIC CHARACTERISTICS OF THE LANDER

The calculation of the lander aerodynamic characteristics was done by a numerical method using the Newton flow theory, which allows acquiring reliable estimates of the aerodynamic characteristics for velocities in the range $M \geq 4 \div 6$. According to Newton's theory, the medium flowing around a body consists of equidistant identical particles, which do not interact with each other. When the particles impact the body surface (inelastic impact), they lose the motion normal to the body surface, which creates the pressure flow on the body. The tangent component of the velocity does not change. Thus, the impact wave is assumed to lie on the body surface, and the pressure coefficient on the body surface is given by:

$$C_p = \frac{p - p_\infty}{q_\infty} = 2 \cdot \sin^2 \eta \,, \tag{1}$$

where p – pressure on the body surface; p_∞, q_∞ – static pressure and static head of the impinging flow; η – the angle between the velocity vector of the unperturbed flow and the elementary area of the body surface.

The real mechanism of the interaction between the gas molecules and the solid body boundaries differs from Newton's theory. However, the flow pattern for extremely large and hypersonic velocities is similar to the one proposed by Newton for the inelastic collision between the gas particles and the body.

For numerical calculation of the aerodynamic characteristics, the surface of the lander is subdivided into small elements. For each element, the pressure coefficients are calculated according to Newton's formula taking into account the 'aerodynamic shadow' of the lander, where the pressure is assumed to be equal to the static pressure in the free flow $p_e = p_\infty$, i.e. $C_{pe} = 0$. Then the calculated vectors of the coefficients of the forces acting on elementary elements are summed and transformed in the total aerodynamic coefficients C_x and C_y for all values of the angle of attack ranging from 0 to 180°. The forces of friction are neglected.

This can be formulated as follows:

$$C_p = \frac{\vec{P}}{\rho_\infty \left|\vec{v}_\infty\right|^2 S} = -\frac{1}{S} \int\limits_{\substack{S \in S_p \\ S \notin S_t}} \vec{n} \cdot \sin^2 \eta \cdot dS \, , \tag{2}$$

where $\vec{P}$ – vector of the total aerodynamic force acting on the body, N; ρ_∞ – density of the unperturbed flow, kg/m^3; $\vec{v}_\infty$ – unperturbed velocity vector, m/s; $\vec{n}$ – normal of the surface (normalized vector); dS – elementary area, m^2; S – lander surface area, m^2; S_p, S_t – areas of the surface and the shadow, m^2.

The analysis considers the "lifting body" lander type shown in Figure 2. Based on the analysis of the volume and mass of the target equipment, the diameter is set to $D = 1.1\ м$, the lander length for this diameter is $L = 2.75\ м$. The center of mass of the lander is assumed to be the average value of the centers of mass of the volume and center of mass of the surface: X_C=1803 mm, $Y_C = -62\ mm$.

Figures 3, 4 present the aerodynamic characteristics of the "lifting body" lander with the following notation: C_x, C_y – longitudinal and normal force coefficients in the body-fixed coordinate systems (See Figure 6); C_{xa}, C_{ya} – drag and lift coefficients in the velocity coordinate system (See Figure 6), K_{hyp} - lift-to-drag ratio for hypersonic velocities (M>6), α - angle of attack, º.

The aerodynamic characteristics of the lander determine the lander control action at the descent stage and also determine the parameters of the actuating mechanisms of the control system (engines, aerodynamic rudders, and trim panels).

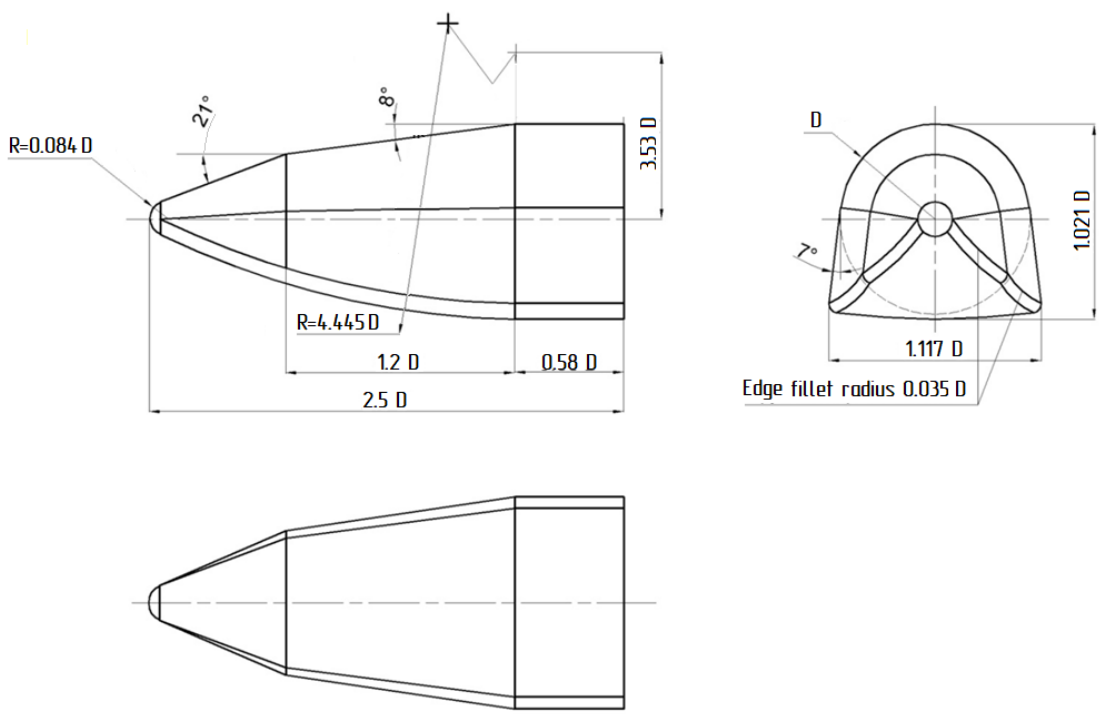


FIGURE 2. Layout and general dimension of the "lifting body" type of a lander

The center of mass and center of pressure of the lander have to be determined to evaluate its stability (See the scheme in Figure 6).

The calculations indicate that the lander of the chosen configuration (without additional surfaces) is unstable for the lift-to-drag ratio $K_{\text{hyp}} \cong 1.4$ - See Table 2 and Figure 5. Installing a balancing weight or rearranging the systems and equipment to make the rear part of the lander free can shift the center of mass to the left along the X-axis of the body-fixed coordinate system. Such rearrangement can make the lander stable. In this design, the lander is balanced by adding an aft shield with the opening angle $\gamma = 17°$ (See Figure 6). The trimmed angle of attack can be chosen in the range of 16 º…24º. In this range, the aft shield ensures lander stability.

We set the following parameters

$$K_{hyp} \cong 1.4 : \alpha = 18°; C_x = 0.42; C_y = 1.34; C_{xa} = 0.81; C_{ya} = 1.15 \tag{3}$$

TABLE 2. Coordinates of the center of mass and the center of pressure of the "lifting body" type of a lander

Name	Lander without aft shield	Lander with an aft shield
Coordinates of the center of mass *, mm	X_c = 1803 *mm*, Y_c = -62 *mm*	
Coordinates of the center of pressure, mm	X_{cop} = 1669 *mm*, Y_{cop} = 1051 *mm*	X_{cop} = 1916 *mm*, Y_{cop} = 330 *mm*
Note *The change of center of mass caused by the trim panel is assumed to be negligible The opening angle of the aft shield - 17 º The trimmed angle of attack - 18 º		

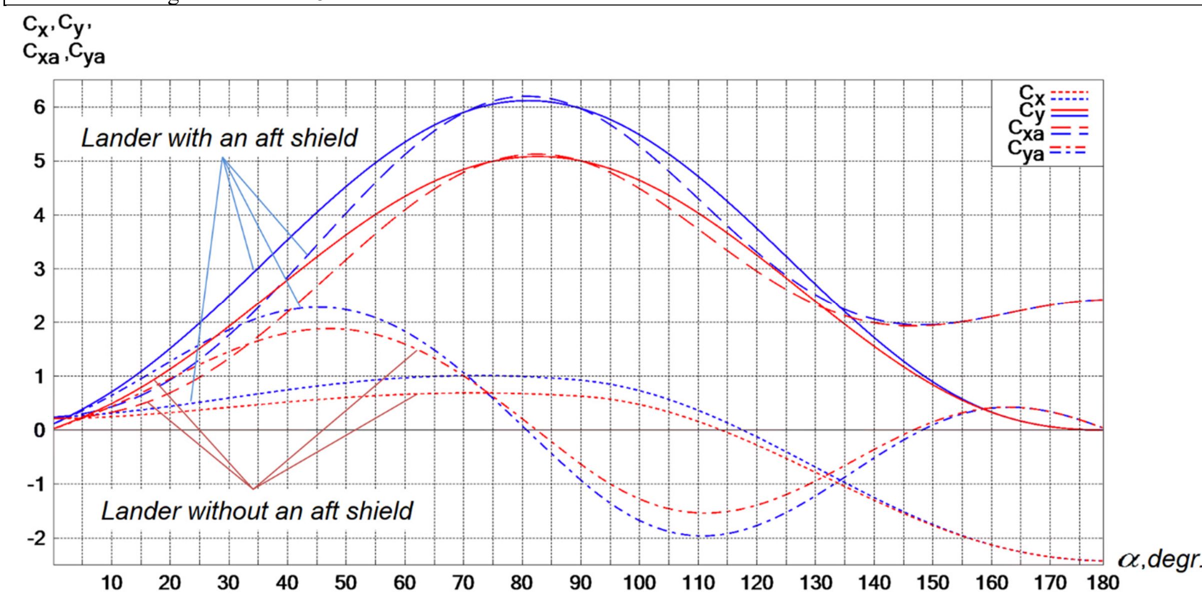


FIGURE 3. Coefficients of the aerodynamic forces in the body-fixed and velocity coordinate systems for the "lifting body" type of a lander with the aft shield and without it.

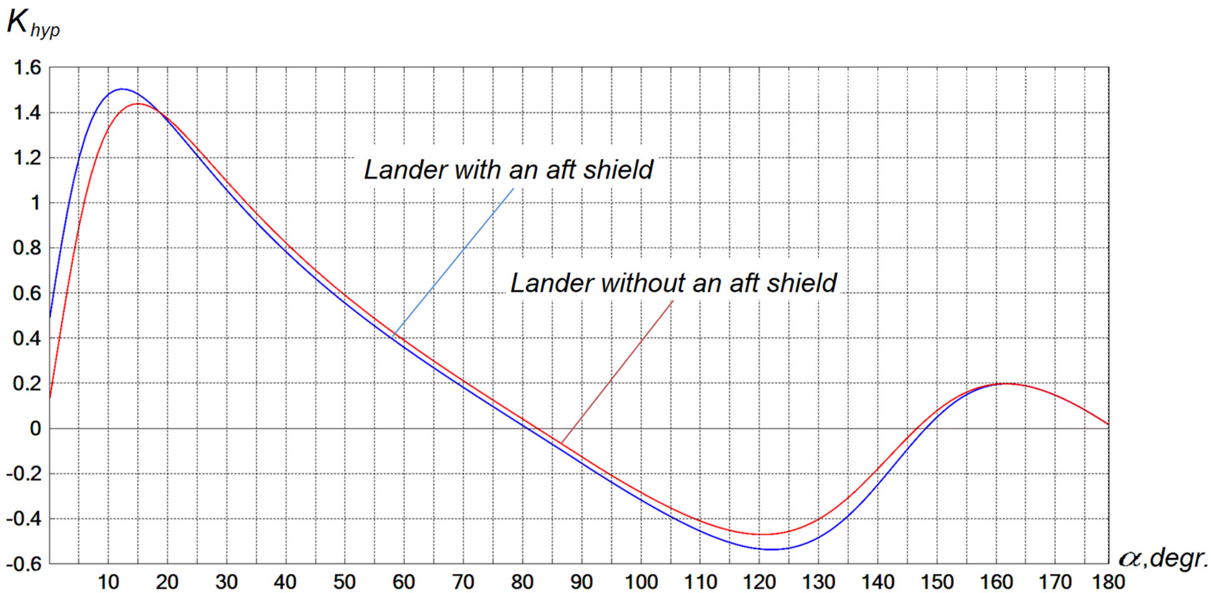


FIGURE 4. Lift-to-drag ratio for hypersonic velocity for the "lifting body" type lander with the aft shield and without it.

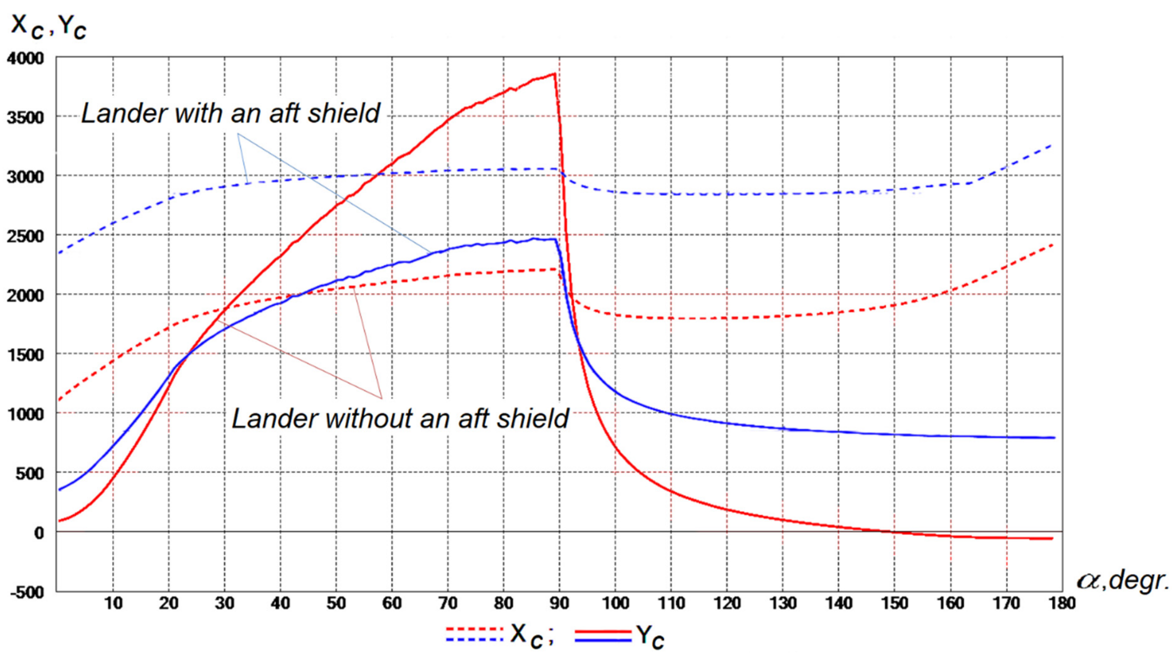


FIGURE 5. Coordinates of the center of aerodynamic pressure for the "lifting body" type of a lander with the aft shield and without it.

The diagram of the aerodynamic forces acting on the "lifting body" type of a lander is presented in Figure 6.

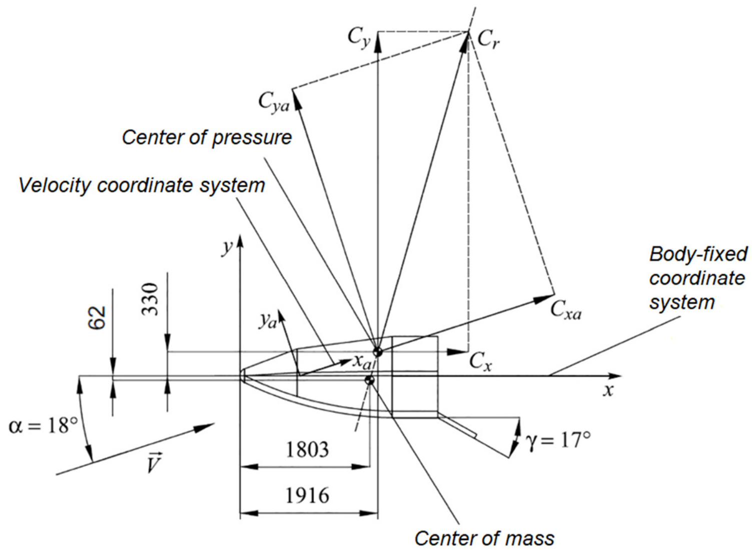


FIGURE 6. Diagram of aerodynamic forces

As seen from Figure 6, the position of the lander with the aft shield is stable.

The lander shape investigated can be easily balanced for the given $K_{hyp} \geq 1$ by simply adding the aft shield. Besides, rearrangement of the systems inside the lander can achieve even greater lift-to-drag ratio.

CONCLUSION

This paper considered various lander types capable of maneuverable landing on the Venus surface, conducted a comparative analysis of the landers' characteristics, and estimated their design capabilities, namely maneuverability and mass characteristics. We conducted the calculation of the aerodynamic characteristics of the "lifting body" type of a lander using numerical procedure according to Newton's hypersonic flow theory. The lander stability can be ensured in various ways. The most simple and beneficial method is to add the aft shield, which can potentially improve the lift-to-drag ratio.

The main technical characteristics of the proposed lander configurations are high maneuverability, the capability to land in the required area, which are deemed most promising for exploration, as well as the capability of entering the Venus atmosphere while maintaining better thermal operation modes and reduced overloads compared to landers of the ballistic type. Besides, the use of these landers will broaden the range of tasks and number of scientific investigations that can be conducted not only on the Venus surface but also during the descent in the atmosphere before reaching the surface.

However, it should be noted that the development of the new lander configuration requires both designing the lander shape and solving the issues related to the control system, organizing the communication and navigation system for maneuvering the lander, creating a complex of subsystems for landing, and so on.

In conclusion, this lander can be created at present based on the existing hardware and software by utilizing the current level of aerospace development and adopting new promising aerospace technologies.

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