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Конструкция атмосферного аэростатного зонда для исследования Венеры

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Аннотация. Венера – вторая по расстоянию от Солнца и ближайшая к Земле планета. Её атмосфера самая плотная, а температура на поверхности Венеры самая высокая среди всех планет Солнечной системы. Из-за конвекции и тепловой инерции плотной атмосферы на Венере температура существенно не изменяется между дневной и ночной сторонами планеты. Температура верхних слоев атмосферы составляет около -45°C . Минимальная температура поверхности не менее 400°C . Давление на поверхности планеты в 90 раз выше, чем на уровне поверхности Земли. В связи со сложностью функционирования космических аппаратов (КА) на поверхности, планета до сих пор остается практически не изученной.

Однако, на высоте чуть выше 50 км расположена тропопауза – граница между тропосферой и мезосферой. Здесь условия наиболее похожи на условия на поверхности Земли. Это оптимальная область для КА, где температура и давление будут подобными земным. В эту область целесообразней всего отправлять аэростатные зонды, для сбора научной информации.

Целью исследования является разработка конструкции аэростатного зонда, в течение длительного времени обеспечивающего передачу информации из тропопаузы атмосферы Венеры.

В работе проведен баллистический расчет траектории снижения космического аппарата в атмосфере Венеры и определены характеристики траектории.

Для определения параметров траектории спуска была написана программа для расчета дифференциальных уравнений движения атмосферного зонда.

В работе разработана конструкция атмосферного зонда и определен порядок его работы.

Ключевые слова: конструкция атмосферного зонда, атмосфера Венеры, дифференциальные уравнения движения в атмосфере, траектория.

Design of an atmospheric aerostatic probe for Venus exploration

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Abstract. Venus is the second planet from the Sun and the closest to Earth. Its atmosphere is the densest, and the temperature on the surface of Venus is the highest of all the planets in the Solar System. Due to convection and thermal inertia of the dense atmosphere, the temperature on Venus does not change significantly between the day and night sides of the planet. The temperature of the upper layers of the atmosphere is about -45°C . The minimum surface temperature is at least 400°C . The pressure on the surface of the planet is 90 times higher than at the surface of the Earth. Due to the complexity of the functioning of spacecraft (SC) on the surface, the planet remains virtually unexplored.

However, at an altitude of just over 50 km there is the tropopause – the boundary between the troposphere and the mesosphere. Here, the conditions are most similar to the conditions on the surface of the Earth. This is the optimal area for SC, where the temperature and pressure will be similar to those on Earth.

It is most advisable to send balloon probes to this area to collect scientific information. The aim of the study is to develop a design for an aerostat probe that will provide long-term transmission of information from the tropopause of the Venusian atmosphere. The work includes a ballistic calculation of the descent trajectory of the spacecraft in the Venusian atmosphere and the trajectory characteristics. To determine the parameters of the descent trajectory, a program was written to calculate the differential equations of motion of the atmospheric probe. The work includes a design for an atmospheric probe and the order of its operation.

Keywords: atmospheric probe design, atmosphere of Venus, differential equations of motion in the atmosphere, trajectory.

Introduction

Visiting extraterrestrial worlds has been a goal pursued by humanity since the dawn of the space age. While humans have only managed to personally visit the Moon, probes and robotic vehicles have made much greater progress in exploring celestial bodies.

Venus is the second planet from the Sun and the closest to Earth. It has been known to humans since ancient times. Its atmosphere is the densest, and its surface temperature is the highest of all the planets in the Solar System [1; 2].

Venus's atmosphere consists primarily of carbon dioxide and a small amount of nitrogen. The pressure at the planet's surface is enormous – 90 times greater than that at Earth's surface, or equivalent to the pressure in Earth's oceans at a depth of about 1 km. The carbon dioxide-rich atmosphere causes a strong greenhouse effect, raising the planet's surface temperature to 500°C .

Due to convection and the thermal inertia of the dense atmosphere, the temperature on Venus does not vary significantly between the day and night sides of the planet. Solar energy at the planet's surface is much lower than in the upper atmosphere, and its dense cloud cover reflects most of the energy back into space. Without the greenhouse effect, Venus's temperature would be very close to Earth's surface temperature. Venus's high clouds consist primarily of droplets of sulfur dioxide and sulfuric acid, making the planet's surface invisible in optical wavelengths. The temperature of the upper atmosphere is approximately -45°C . The average temperature on Venus is 464°C . The minimum surface temperature is at least 400°C .

However, the Tropopause is situated at an altitude just above 50 km. The Tropopause is the boundary between the troposphere and the mesosphere. Here, conditions are most similar to those on the Earth's surface. According to measurements by the Soviet probes Venera 4 and 14 and the American Pioneer Venera 2 [1; 2], the region from 52.5 to 54 km has a temperature between 293 K (20°C) and 310 K (37°C), and at an altitude of 49.5 km, the pressure becomes the same as on Earth at sea level. This is the optimal region for research ships or colonies, where the temperature and pressure will be similar to those on Earth. And it is precisely into this region that it is most practical to send balloon probes capable of collecting physical data and scientific information over a long period of time without contact with the planet's surface, while remaining within a given range of altitudes in the atmosphere of Venus [3–7].

The challenge of developing such space probes is unique, as evidenced by the small number of spacecraft that have conducted research near Venus throughout the history of its observations. The specific nature and complexity of such research determine the relevance of such developments.

The aim of the study is to develop a design for an aerostat probe that would transmit information from the tropopause of the Venusian atmosphere.

The design of the probe requires it to remain in the Venusian atmosphere at a certain altitude for a sufficiently long period (approximately 100 days) while maintaining optimal operating conditions. To maintain the apparatus's viability, it is necessary to develop a helium refueling system for the balloon, which leaks at a rate of approximately 2.5 % per day.

Features of the atmosphere of Venus

The atmosphere of Venus is the gaseous envelope surrounding Venus. It consists primarily of carbon dioxide and nitrogen; other compounds are present only in trace amounts (Fig. 1). Venus's atmosphere contains clouds of sulfuric acid, which make visible-light observation of the surface impossible, and is transparent only in the radio and microwave ranges, as well as in certain regions of the near-infrared region (Fig. 2). Venus's atmosphere is much denser and hotter than Earth's atmosphere: its average surface temperature is approximately 740 K (467 °C), and its pressure is approximately 93 bar [2].

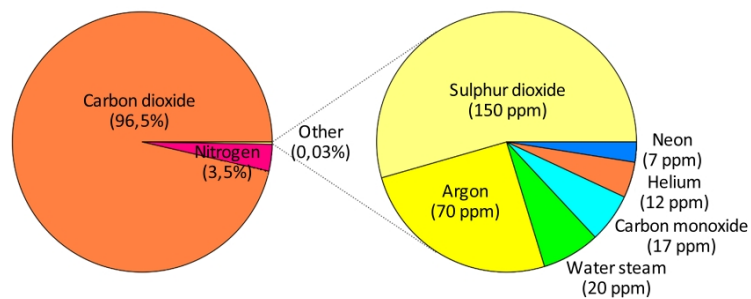


Рис. 1. Состав атмосферы Венеры

Fig. 1. Composition of the atmosphere of Venus

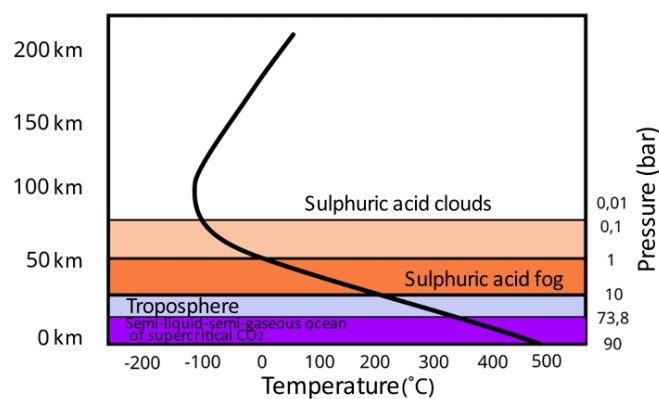


Рис. 2. График зависимости температуры и давления от высоты над поверхностью Венеры

Fig. 2. Graph of temperature and pressure versus altitude above the surface of Venus

Unlike Earth, Venus has no magnetic field, and its ionosphere separates its atmosphere from outer space and the solar wind. The ionized layer blocks the solar magnetic field, giving Venus a unique magnetic environment.

Despite the extreme conditions on the planet's surface, at an altitude of 50–65 km, the atmospheric pressure and temperature are virtually identical to those on Earth's surface. This makes the upper atmosphere of Venus the most Earth-like in the Solar System (even more so than the surface of Mars). Because of these similarities in pressure and temperature, the upper atmosphere has been proposed by scientists as a suitable location for exploration and colonization [3–7]. This region of the atmosphere is particularly suitable for study using balloon probes. Long-term exploration below 50 km is currently unfeasible due to the extreme conditions in the atmosphere and on the planet's surface.

Ballistic calculation of the spacecraft's descent trajectory in the atmosphere of Venus

The mission to deliver a balloon probe to the atmosphere of Venus consists of two stages:

- the interplanetary flight of the spacecraft carrying the probe from Earth to Venus and its entry into a circular orbit;
- the undocking of the orbital module and the ballistic reentry of the probe itself into the atmosphere.

The spacecraft itself remains in orbit and is used as a relay satellite to transmit the data collected by the probe to Earth.

We consider only the second stage of the mission, without taking into account the spacecraft's flight to Venus.

The goal of the ballistic calculation is to deliver the payload from a given circular orbit not to the surface of Venus, but to the operational altitude range in the atmosphere ($H = 50\text{--}55$ km). To achieve this, it is necessary to dampen the radial velocity component to values close to zero before reaching the specified altitude.

The study examines a computational model of the ballistic descent trajectory [1,8–10] of an atmospheric probe from a circular orbit at an altitude of 300 km to a specified altitude of 50–55 km above the planet's surface, consisting of an exoatmospheric elliptical section and an atmospheric entry section with subsequent aerodynamic braking, including with the help of a parachute. In this case, the exoatmospheric section is considered in the central gravitational field, and the motion in the atmosphere is in a plane-parallel.

Calculation of motion parameters on an elliptical section of a trajectory

The motion diagram on the elliptical section of the trajectory is shown in Fig. 3.

For the impulse transition from a circular orbit around Venus to an elliptical descent section (Fig. 3), we will select a solid propellant rocket engine (SPRE) with the following characteristics:

- engine thrust $P = 4.5$ kN ;
- specific impulse $J_{sp} = 2700$ m/s.

To study motion on an elliptical section of a trajectory, we use a model problem known in celestial mechanics as the two-body problem. This problem examines the motion of two material points with specific masses under the force of their mutual attraction.

We make the following assumptions:

- 1) we consider the passive motion of the descent module;
- 2) the gravitational force with which Venus attracts the descent module is calculated as the Newtonian force of interaction between two material points with specific masses located at the centers of mass of Venus and the descent module (balloon probe);
- 3) we neglect the gravitational pull of other celestial bodies in the Universe;
- 4) we ignore the aerodynamic effect of the environment on the descent module;
- 5) we assume that no other physical forces (electromagnetic forces, radiation pressure, etc.) act on the descent module.

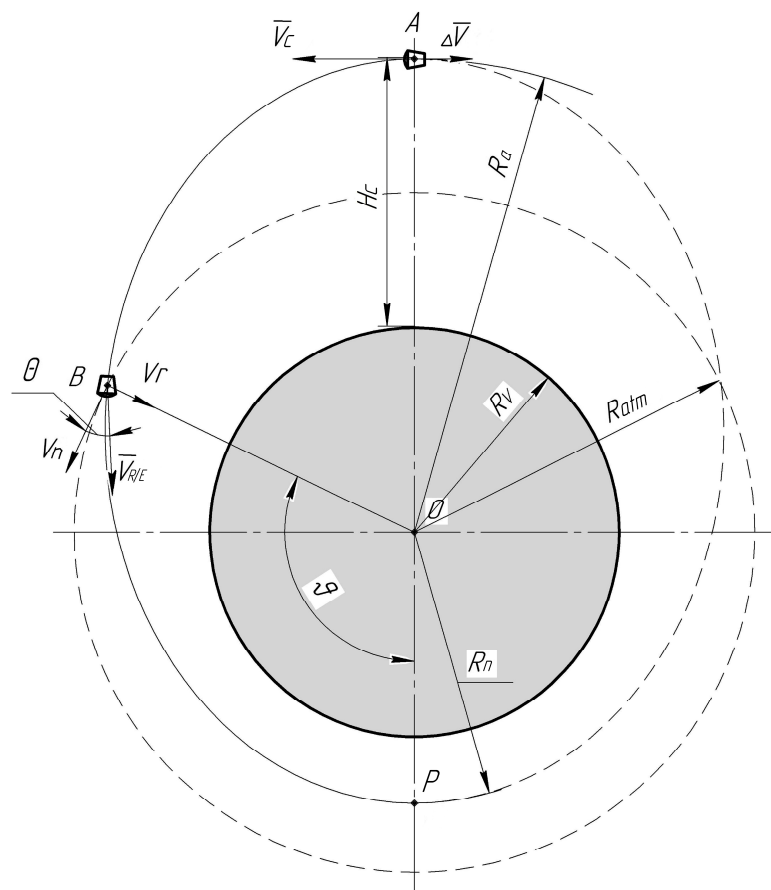


Рис. 3. Схема движения на эллиптическом участке траектории

Fig. 3. Scheme of motion on an elliptical section of the trajectory

For the point of the trajectory A (Fig. 3), corresponding to the moment of the beginning of the descent (initial conditions of movement), we can write :

– $\theta = 0$, the angle of inclination of the trajectory will be equal to 0, since we are considering the beginning of the motion at the apocenter of the elliptical branch ;

– $H_{кр} = 300$ km is altitude of a circular orbit ;

– $V_{кр} = 7151,53$ m/s is speed in a given circular orbit ;

– $d_m = 2,5$ m is midsection diameter of the descent module.

Parameters of the exoatmospheric portion of the elliptical orbit :

1) focal parameter :

$$p = Ra * (1 - e) ; \quad (1)$$

2) orbital eccentricity :

$$e = \frac{Ra - Rn}{Ra + Rn} ; \quad (2)$$

3) true anomaly angle at the atmospheric entry point:

$$\vartheta = \arccos \left(\frac{p - R_{atm}}{e * R_{atm}} \right). \quad (3)$$

The equation of the trajectory is determined by the formula

$$r = \frac{p}{1 + e \cos \vartheta} \quad (4)$$

The speed at any point of the elliptical trajectory can be calculated using the formula

$$V = \sqrt{\frac{\mu_V}{p}} \sqrt{1 + e^2 + 2e \cos \vartheta}, \quad (5)$$

where μ_V is a gravitational parameter of Venus ($\mu_V = 324.859 \cdot 10^{12} \text{ m}^3/\text{s}^2$).

The result of the calculation at this stage is the speed and angle of inclination of the trajectory at the point of entry into the atmosphere.

Calculation of motion parameters at the entry point into the dense layers of the atmosphere

The section of entry into the dense layers of the atmosphere begins with a conditional boundary, which is located at an altitude of 120 km from the surface of Venus (Fig. 3).

We make the following assumptions:

- 1) we consider motion in a plane-parallel gravitational field;
- 2) we assume the angles of attack and sideslip to be zero;
- 3) we neglect lift.

The initial motion conditions are taken from the calculation results for the exoatmospheric segment.

The force of frontal aerodynamic drag is determined by the formula

$$X_a = c_x \frac{\rho V^2}{2} S_M, \quad (6)$$

where c_x is a drag coefficient ; ρ is density of the medium ; S_M is midship cross-section area.

The atmospheric parameters are determined using the standard atmosphere table of Venus (Table 1).

The differential equations of motion at the entry section (Fig. 4) will have the following form (7), (8):

$$m \frac{dV}{dt} = -\frac{1}{2} c_x \rho S_M V^2 - G \sin \theta, \quad (7)$$

$$mV \frac{d\theta}{dt} = -G \cos \theta, \quad (8)$$

where θ is the angle of inclination of the trajectory relative to the plane of the local horizon; $G = m \cdot g_V$ is gravity acting on the descent module; g_V is acceleration of gravity on Venus, m is a mass of the descent module.

Table 1

A working model of the atmosphere of Venus up to an altitude of 120 km [2]

z , km	T , °K	p , atm	ρ , g/sm ³	Note
0	750	93.0	$6.3 \cdot 10^{-2}$	The surface of the planet
5	713	69.0	5.0	
10	675	50.3	3.8	
15	636	35.0	2.8	
20	596	25.2	2.18	
25	556	17.3	1.58	

End of table 1

z , km	T , °K	p , atm	ρ , g/sm ³	Note
30	515	11.5	1.15	
35	472	7.4	$8.1 \cdot 10^{-3}$	
40	428	4.5	5.5	
45	382	2.6	3.58	
50	340	1.43	2.16	
55	304	0.71	1.25	
60	274	0.24	$6.6 \cdot 10^{-4}$	
65	250	0.14	2.7	Cloud top
70	240	$5.5 \cdot 10^{-2}$	1.2	
80	220	$7.0 \cdot 10^{-3}$	$1.7 \cdot 10^{-5}$	
90	200	$7.4 \cdot 10^{-4}$	$1.9 \cdot 10^{-6}$	
100	180	$6.2 \cdot 10^{-5}$	$1.8 \cdot 10^{-7}$	
110	160	$4.9 \cdot 10^{-6}$	$1.6 \cdot 10^{-8}$	Mesopause
120	205	$3.9 \cdot 10^{-7}$	$1.0 \cdot 10^{-9}$	Eclipse of Regulus

The kinematic relations are of the form (9), (10):

$$\frac{dx_0}{dt} = V \cos \theta, \quad (9)$$

$$\frac{dy_0}{dt} = V \sin \theta, \quad (10)$$

where x_0 is a linear coordinate x , relative to the Venusian coordinate system; y_0 is a linear coordinate y , relative to the Venusian coordinate system.

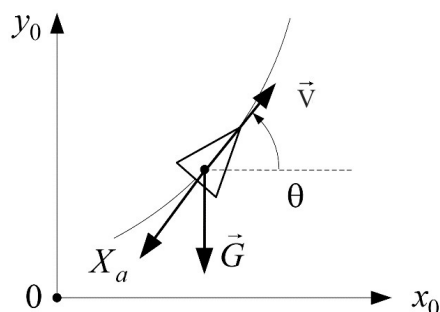


Рис. 4. К выводу уравнения движения на участке входа в плотные слои атмосферы

Fig. 4. To the derivation of the equation of motion at the entry section into the dense layers of the atmosphere

We will integrate the equations of motion (7–10) using the Euler method, having previously set the integration step over time.

The calculation takes into account the parachute's effect on propulsion parameters. The parachute begins to deploy when the speed drops to 245 m/s and is released along with the top cover of the Venusian atmospheric probe at 3103 seconds into the flight.

The calculation of the trajectory and its parameters was performed in a specially created software product, Mapple 17. Table 2 shows four variants of the probe descent trajectories for ellipses with different focal parameters.

The result of the calculation is the values of speed, maximum overload, descent time and trajectory of movement in a plane-parallel gravitational field.

Table 2

Results of calculation of the descent trajectory options for the spacecraft

N ₀	H _{pericenter} , km	ΔV, m/s	m _r , kg	T _{turn on remote control} , c	Θ _{in} , °	V _{in} , m/s	n _{max}
1	0	87.01	16.4	2.46	−1.36	7272.6	26.01 g
2	50	72.15	13.5	2.03	−1.03	7287.04	25.74 g
3	100	57.42	10.8	1.61	−0.55	7301.34	25.43 g
4	119	51.87	9.7	1.46	−0.12	7306.74	25.3 g

Calculation of balloon characteristics that provide buoyancy in a given range of altitudes in the atmosphere of Venus

After a ballistic descent to a predetermined altitude (approximately 50 km), the aerostat balloon inflates and the probe enters operational mode. To maintain the apparatus at operational altitude, it is necessary to calculate the buoyant force acting on it (the Archimedes force).

The buoyant or lifting force is opposite in direction to the force of gravity and is applied to the center of gravity of the volume displaced by the body from the liquid or gas.

The designed aerostat must remain at a constant altitude for a long time. This requires the condition of floating bodies to be met. A body floats in a liquid or gas if the buoyant force is equal in magnitude to the force of gravity (Fig. 5).

Based on the condition of floating bodies:

$$F_A = m_{He}g_V + m_{об}g_V + m_{пр}g_V, \quad (11)$$

$$\rho_{atm}V_{III}g_V = m_{пр}g_V + m_{об}g_V + \rho_{He}V_{III}g_V, \quad (12)$$

$$V_{III} = \frac{m_{об} + m_{пр}}{\rho_{atm} - \rho_{He}}, \quad (13),$$

where $m_{пр}$, $m_{об}$, m_{He} are the masses of the balloon probe's payload, the probe's shell, and the filled helium, respectively; ρ_{atm} is the density of Venus's atmosphere at a certain altitude (Table 1); ρ_{He} is density of helium; V_{III} is volume of the helium balloon of the aerostat probe.

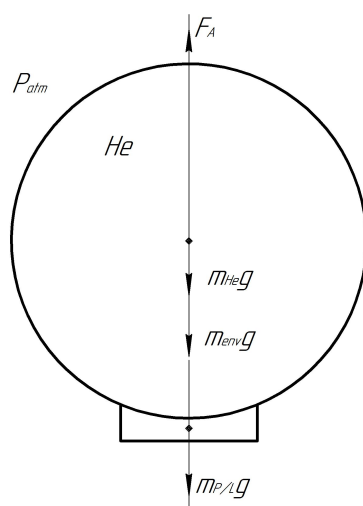


Рис. 5. К расчёту выталкивающей силы

Fig. 5. To the calculation of the buoyant force

The calculation was performed for altitudes in the range of 50–55 km above the surface (Fig. 5). The results are presented in Table 3.

Table 3

Results of calculation of the parameters of the ball to create the required buoyant force

Height from the surface of Venus H, km	Temperature in atm T, K	Pressure in atm P, atm	Density atm $\rho, \text{kg/m}^3$	Volume of a sphere V_{sp}, m^3	Radius of a sphere R_{sh}, m	Helium losses (in 2 days) $m_{\text{He los}}, \text{kg}$	Mass of helium m_{He}, kg	Volume of helium $V_{\text{He}}, \text{m}^3$
50	340	1.43	2.16	129.3	3.14	1.47	73.3	0.59
53	322	1.07	1.71	161.3	3.38	1.29	64.6	0.5
55	304	0.71	1.25	219.8	3.74	1.24	61.8	0.48

The procedure for entering the operating mode of the descent vehicle with the aerostat probe

Based on the characteristics obtained during the preliminary design, a descent module [11–18] was constructed, including an aerostat probe placed in a special container. A general view of the descent module is shown in Fig. 6.

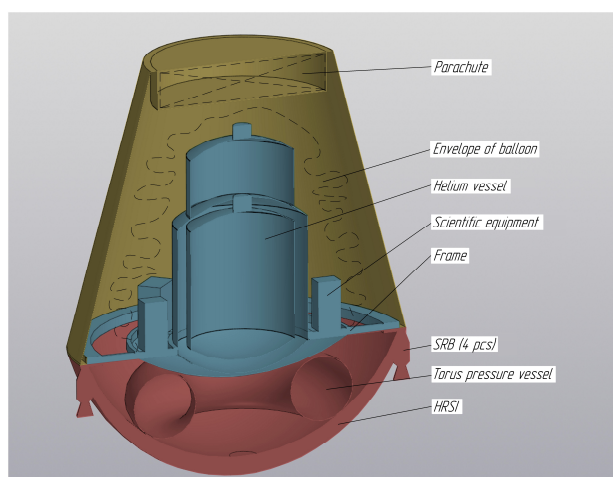


Рис. 6. Общий вид спускаемого аппарата

Fig. 6. General view of the descent vehicle

During the initial phase, the orbital space module (OSM), coupled with the descent module (DM), moves in a circular orbit around Venus at an altitude of 300 km above the surface. After the descent module separates from the OSM, the descent module, driven by the thrust of the solid-propellant rocket engines (SPREs) located in the lower cover of the OSM (Fig. 6) at $t_{\text{imp}} = 1.46 \text{ s}$, enters an elliptical descent trajectory through the Venusian atmosphere (Fig. 3), freely descending along a ballistic trajectory until reaching the upper atmosphere.

When the craft reaches a speed of 245 m/s, the parachute compartment hatch is released and the parachute is deployed. Aerodynamic braking occurs using the parachute (Fig. 7).

At 3103 seconds after undocking from the OSM (500 seconds of atmospheric descent), when the vehicle reaches an altitude of 58 km, the upper cover and parachute are jettisoned (Fig. 8). At the same time, the process of inflating the aerostat balloon with helium gas begins from a torium cylinder attached to the lower cover of the descent module (Fig. 6). Inflation occurs in 96 seconds.

By the time the balloon is fully inflated, the descent module reaches an altitude of 50 km. At this point, the lower cover, containing the spent engine and the empty helium cylinder, is jettisoned to release ballast (Fig. 8).

The balloon reaches a drift altitude of 53 km and switches to operating mode as an atmospheric probe.

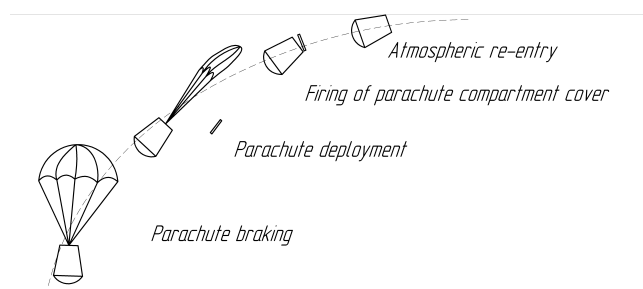


Рис. 7. Раскрытие парашюта

Fig. 7. Opening the parachute

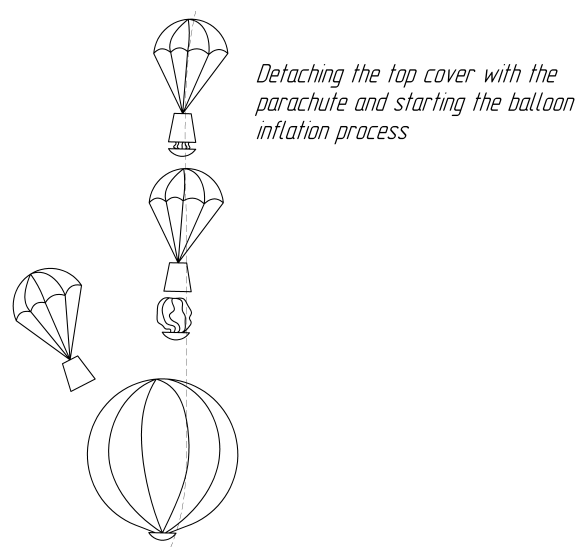


Рис. 8. Заполнение шара аэростата гелием

Fig. 8. Filling a balloon with helium

The detachable lower cover of the spacecraft withstands the high temperatures generated during aerodynamic braking in the Venusian atmosphere (Fig. 9). To provide the required thermal protection, it is covered with a layer of heat-protective coating. A pulsed solid-propellant rocket motor is attached to the load-bearing frame of the lower cover of the spacecraft to detach the spacecraft from a circular orbit around Venus to an elliptical descent orbit.

Additionally, a high-pressure toroidal cylinder filled with compressed helium (He) is attached to the lid. This is necessary for the initial inflation of the balloon. This solution allows for a reduction in the balloon's operating weight by separating the empty cylinder and lower lid, which together weigh 160 kg.

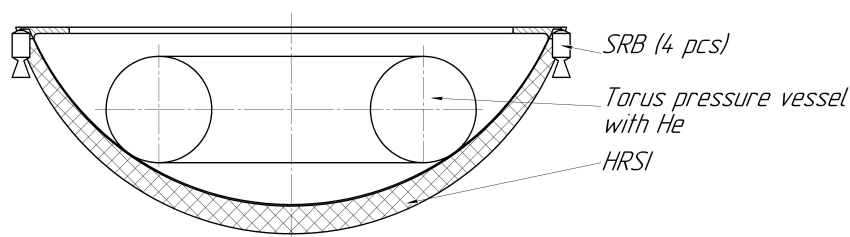


Рис. 9. Нижняя крышка спускаемого аппарата

Fig. 9. Lower cover of the descent module

The design and operating principle of a balloon probe

The design of the balloon probe is shown in Fig. 6.

All of the probe's working components and assemblies are attached to the load frame. The helium-filled balloon shell and the scientific equipment sensors are hermetically secured to it. Inside the structure, beneath the shell, the load frame houses scientific instruments and a dual vessel containing liquid and gaseous helium, which make up a significant portion of the balloon's mass.

According to the technical specifications, the probe is to drift at an altitude of approximately 50 km above the surface of Venus and collect scientific data for 100 days. Until now, spacecraft operating near the surface of Venus have operated for no more than two days due to extremely harsh environmental conditions (Table 1). Existing projects (Venera-D, Venera GLOBE, DAVINCI) are also limited to a lifespan of approximately 30 days.

Thanks to the Vega mission, it is known that helium leakage from the balloon during the probe's estimated operational period (approximately two days) did not exceed 5%, corresponding to an altitude loss of approximately 0.5 km. Therefore, by providing a constant supply of additional helium (up to 5% over two days), the spacecraft's active operational period can be extended without the risk of descending to an altitude with unfavorable atmospheric conditions. For this purpose, a cryogenic helium vessel is located onboard the balloon (Fig. 6). Gradually evaporating, the helium accumulates in the upper compartment of the vessel, from where it is released directly into the balloon through an electric valve. Sensors inside the balloon determine when the pressure has dropped sufficiently for a new supply of gas. This way, the probe's drift altitude can be maintained for at least 100 days.

The helium vessel (Fig. 6) consists of two parts: a Dewar flask for storing the liquefied helium and a cylinder connected to it, which accumulates the gaseous helium. In its liquid state, helium exists only at a temperature of 4.2 K and is a cryogenic liquid. Therefore, to maintain it in a liquid state, we will use a vessel with screen-vacuum insulation [17; 18].

The masses of the structural elements of the descent vehicle and the balloon probe after the necessary calculations (taking into account helium refueling) are presented in Tables 4 and 5.

Table 4

Masses of the landing vehicle structural elements, kg

Balloon sonde	Top cover with parachute	Bottom cover				
250.0	71.0	Compressed helium	Torus cylinder	SPREs (4 pcs)	Housing with FSP (fuel supply point)	Total weight
		25.8	64.5	10.0	68.7	169.0

Table 5

Masses of the structural elements of the balloon probe, kg

Helium for refueling	Helium balloon shell	Scientific equipment	Power frame with body	Gel container (refill)	Total weight
64.6	30.4	20	41.9	93.1	250.0

Strength calculation of the frame of a balloon probe

The balloon probe's load-bearing frame is the primary load-bearing element of the descent module's design. Attached to it are the top and bottom covers of the apparatus, as well as all of the balloon probe's components: the helium refueling vessel, the probe body, the balloon shell, and the scientific equipment.

Ballistic calculations (Table 2) indicate that the maximum g-force acting on the descent module during reentry is $n = 25.3g$. Accordingly, the load frame must be strong enough to withstand high g-forces, while having a minimal mass to reduce the required amount of helium.

Table 6

Results of strength calculations for various titanium alloys

№	Material	Weight of frame structure, kg	Safety factor
1	Технически чистый CP-Ti	46.7	0.71
2	Ti-10V-2Fe-3Al	48.1	1.6
3	Ti-3Al-8V-6Cr-4Mo-2Zr	49.9	2
4	Ti-5Al-2,5Sn	46.4	1.4
5	Ti-6Al-2Sn-2Zr-2Mo-2Cr-0,25Si	48.1	2
6	Ti-13V-11Cr-3Al	49.9	1.6
7	Ti-5Al-2,5Sn	46.3	1.6
8	Ti-8Al-1Mo-1V	45.2	1.7
9	Ti-8Mn	48.9	1.5

The strength calculation of the balloon probe frame was performed using SolidWorks Simulation software.

The calculation results for various materials of the power frame are presented in Table 6.

Based on the calculation results, three alloys were identified: Ti-3Al-8V-6Cr-4Mo-2Zr and Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si, which provide the highest safety factor, and Ti-8Al-1Mo-1V, which provides the lowest structural weight.

The geometric dimensions of the load-bearing frame structure were optimized for the selected materials. The calculation results for the selected materials are presented in Table 7.

Table 7

Results of strength calculation for lightweight frame design

№	Material	Weight of frame structure, kg	Safety factor
1	Ti-3Al-8V-6Cr-4Mo-2Zr	36.7	1.6
2	Ti-6Al-2Sn-2Zr-2Mo-2Cr-0,25Si	35.4	1.6
3	Ti-8Al-1Mo-1V	33.3	1.4

Thus, following strength calculations, the Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si alloy was selected for the balloon probe frame structure. The safety factor diagram for this alloy is shown in Figure 10. This alloy provides a sufficient safety factor with the lowest weight. The final weight of the load-bearing frame was 35.4 kg.

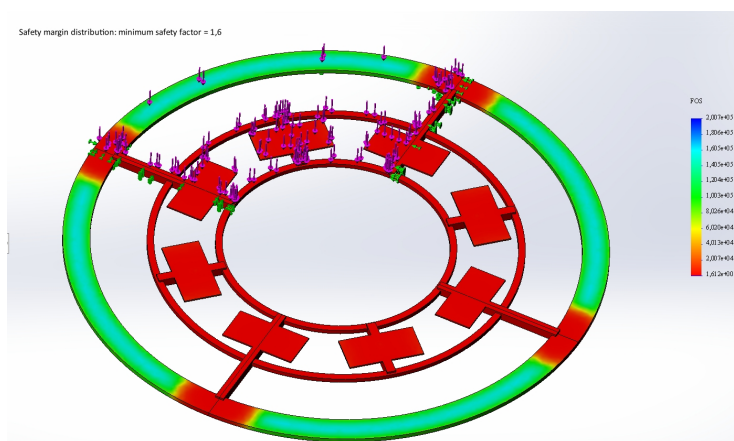


Рис. 10. Эпюра запаса прочности силовой рамы аэростатного зонда

Fig. 10. Safety factor diagram of the power frame of the balloon probe

Conclusion

This paper examines the design of a Venusian surface lander and a balloon probe for atmospheric characterization. A ballistic trajectory for the descent of the probe into the Venusian atmosphere to a specified altitude is calculated. A principle for securing the balloon probe at a specified altitude in the Venusian atmosphere is discussed and a system for securing the balloon probe at a specified altitude is developed. Mass calculations are performed for the structures of the descent module, the balloon probe, and their main components. A strength analysis of the atmospheric probe's load-bearing frame is conducted for the case of maximum G-forces during descent.

A solution to differential equations for descent through the Venusian atmosphere was implemented in the Maple computer algebra environment using the Euler method. This solution yields ballistic characteristics of descent trajectories for various ellipse parameters.

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