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AERODYNAMICS AND THERMAL FEATURES OF REENTRY SPACECRAFT WITH BLUNT BODY CAPSULE

By introducing the idea of "Controlled Re-entry of Spacecraft" (CSR), we can avoid the future space debris. Control re-entry is the process of retrieving the Spacecraft safely after its operational life with Spacecraft capsule. The basic idea behind this project is providing the capsule for every Spacecraft carrying nuclear power source onboard and spacecraft performing high speed reentry after the interplanetary missions. In this paper we will discuss the aerodynamic analysis performed analytically and experimentally, in Continuous and Newtonian flow. Analysis of aerodynamic characteristics at wide Knudsen and Mach number range of body is done. Thermal loads and kinematic parameters of vehicle are determined. And results of wind tunnel test of the blunt capsule performed in wind tunnel T-5 are also discussed.

Key words: *space vehicle, reentry trajectory, drag, thermal loads, wind tunnel.*

Introduction

Planetary exploration demands critical technological operation in different phases, this paper is a initial phase of the high speed planetary reentry of spacecraft. Revealing the best reentry trajectory for the spacecraft allows a designer to consider the aerodynamic and thermal loads for the structure designing and also it reveals the spacecraft propulsion system requirements. Hypersonic deceleration design which is dominated by aerodynamic surface heating, where reduction of heat transfer rate plays an important role. The aerodynamic drag coefficient is inversely proportional to the heat load. Therefore, the blunt body configuration which has a detached shock wave experiences less heating than the traditional shape with its attached shock wave the choice of the hypersonic vehicle. Spacecrafts for the Mercury, Gemini, and Apollo programs were designed using this concept. However the maximum temperature that a space vehicle experiences in its hypersonic flight is far above the maximum sustainable temperature of any material. Hence, a proper heat shield should be designed to withstand the heating loads. Consequently nose bluntness increase the aerodynamic drag experienced by the body. Increase in wave drag is useful during reentry of the spacecraft for aero breaking.

Generalities

Three phases of the mission are:

- launch phase;
- mission phase;
- reentry phase.

It starts from launch pad to the end of mission assigned to launch vehicle. From this phase Spacecraft will be attached to the Capsule which allows Spacecrafts linear moment in and out of capsule.

At the end of launch phase begins the mission phase where the spacecraft fulfills its mission. In this phase Spacecraft will extend out of the capsule attached to it and perform its function during its operational life. After its useful life Spacecraft will retract inside the capsule.

Spacecraft capsule will correct its attitude for the de-orbit and reduce its altitude to 160 km with specific inclination and by using the onboard thrusters. Fuel should be reserved for the de-orbit.

With successful controlled de-orbit to desired altitude, Spacecraft will prepare for its reentry. Capsule is designed to resist the extreme environment forces during its orbital life and during the controlled reentry into the earth's atmosphere.

In past many spacecraft's have been deorbited after its operational life which provides a feasibility of the CRS with present technology. The technical feasibility of a controlled targeted deorbit into a remote ocean was found to be possible with Russia's assistance. The Russian Space Agency has experience from de-orbiting the Salyut 4, 5, 6, 7 and Mir space stations, while NASA's first intentional controlled de-orbit of a Spacecraft (the Compton Gamma Ray Observatory) occurred in 2000.

Controlled atmospheric reentry is relatively mature and well understood today it remains true that any earth orbital mission for the payload must be recovered or interplanetary mission targeted for planet with an atmosphere must address the issue of how to get up as well as how to get down.

Atmospheric entry system must provide controlled dissipation of combined kinetic and potential energy associated with the vehicle's speed and altitude at entry interface. By control entry we imply that both dynamic and thermal loads are maintained within acceptable limits during entry. This requires a carefully designed flight trajectory and often a precision guidance to achieve a desired result. Control of vehicle in response to guidance system implies control of lift and drag throughout the flight.

Initial parameters

For the velocity of the capsule, we consider the Soyuz TMA velocity throughout its reentry phase from 160 to 10 km of range (fig. 1) Diameter and length of the capsule is 2.2 meters with 1000 kg mass. In figure 10, is scaled model of the capsule with 0° reentry angle.

During reentry of capsule blunt face is in the forward direction so our interest to find the maximum aerodynamic and thermal distribution over the blunt shape of the capsule.

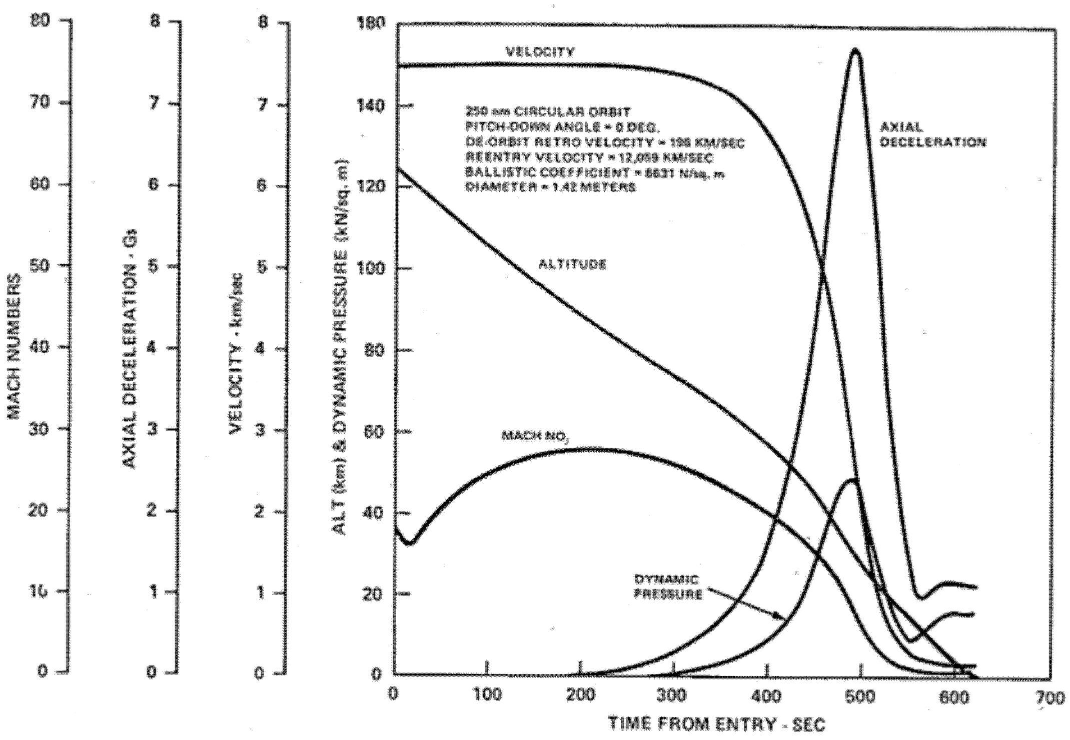

Fig. 1. Soyuz TMA reentry data

Extraction of the velocity vs. altitude data of capsule from Fig 1 is shown in the fig 2.

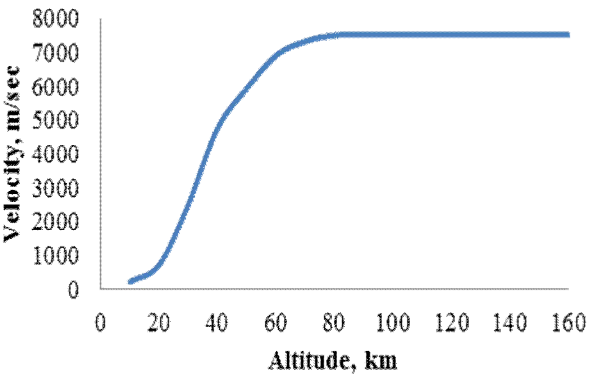

Fig. 2. Velocity of the capsule taken from the Soyuz TMA reentry data

Aerodynamic calculations

The dynamic characteristics of the capsule during its operational life and while reentry is calculated theoretically and experimentally.

We consider the drag, thermal and pressure force distribution over the surface of the spacecraft capsule. The maximum aerodynamic force acting over the capsule surface at the altitude of continuous region and Newtonian region is discussed.

Experimental approach for calculating the maximum drag over the surface of the Spacecraft capsule with Venera at different angle of attack in the T5 study wind tunnel is also carried out for proper understanding of the angle of reentry.

Dimensional analysis of the theoretical flow equations shows the number of parameters can be considerably reduced by the use of dimensionless “similarity parameters.” In our case, the hypersonic aerodynamics coefficient most commonly used parameters is Knudsen number average free path of gas molecules.

For better understanding of the flow at different altitudes, Knudsen number is calculated. As the air molecules behavior at different altitudes are not uniform (fig. 3).

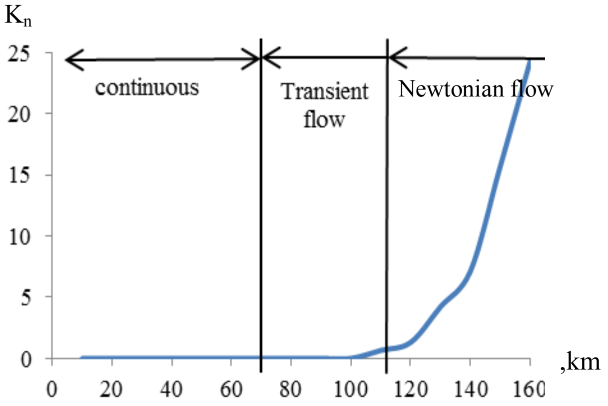

Fig. 3. Knudsen number at different altitudes

By the fig. 2, it is clear that the air flows from the 0 km to 75 km range are in continuous flow and from 75 km to 110 km are in Transient flow and above 120 km it is in Newtonian flow. By analytical and experimental method aerodynamic characteristics can be determined for continuous and Newtonian flow. Theories are inappropriate to determine accurately the aerodynamic characteristics in transient flow, so experimental approach is more preferable than analytical calculations. We ignore the transient regime flow and our interest is in analysis of Continuous and Newtonian flow regime.

Aerodynamic and thermodynamic parameters of capsule in continuous flow

In continuous mode we must examine the model of aerodynamic coefficient, coefficient of pressure and thermal distribution over the capsule. The atmospheric density in the continuous flow is more as compared to the Newtonian flow so the loads acting are high in this region. It is important to understand the maximum load acting over a capsule for further structure designing of the capsule.

Mach number.

Below the 10 km altitude, velocity and Mach number decrease sharply under drag effect, we observe the behavior at Mach lower than 2 by the evolution of base drag with Mach number [6].

Pressure distribution.

The compression ratio of air in front of the capsule may cause structural deformation which will be considered while designing the aerodynamic profile of the capsule. Blunt shape will increase the compression ratio whereas the sharp profile increases temperature gradient. So achieving the equilibrium is necessary.

Formula for pressure coefficient in continuous flow (inversed motion):

$$C_p = \frac{p - p_\infty}{\rho \cdot \frac{v^2}{2}}, \tag{1}$$

where p – local pressure on the capsule;

ρ – atmospheric density;

v – velocity of the capsule at different altitude;

p_∞ – atmospheric pressure.

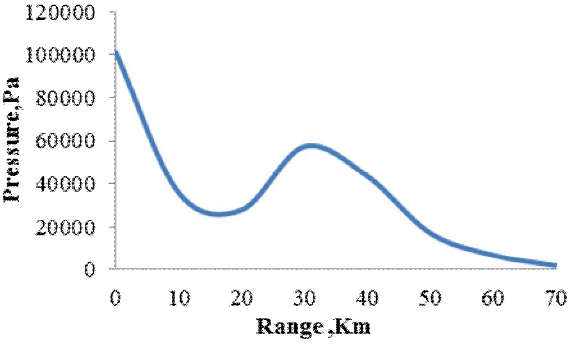

Fig. 4. pressure distribution over surface of capsule at altitudes

Instead of coefficient of pressure we have plotted pressure graph as maximum (see fig. 4).

C_p value in continuous flow equals to 1. Compared to atmospheric pressure air around the capsule is nearly 500 times compressed at the altitude of 70 km and as the altitude drops gradually the compression ratio decreases.

Maximum coefficient of drag (Cd).

Considerable amount of energy is dissipated during reentry so at lower altitude coefficient of drag is less.

Coefficient of drag (fig. 5) is maximum at 80 km, sufficient drag force is required to reduce the velocity of the capsule during reentry as it poses more kinetic energy which should be dissipated in acceptable limit and if it dissipates fast it can burnout the vehicle before reaching the surface of earth. We have to choose the blunt profile because it induces required drag to slow down the velocity of the capsule and it forms the bow shock wave which prevents the high temperature atmospheric air to come in contact with the blunt profile of the vehicle.

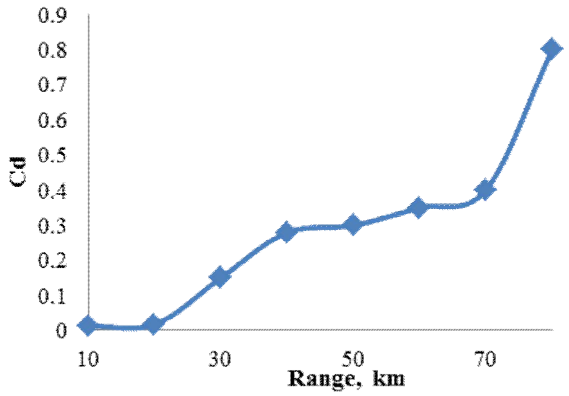

Fig. 5. Coefficient of drag over the surface of the capsule

While considering the coefficient of drag of the Capsule in continuous flow for initial phase of the research, we considered the coefficient of drag of the Soyuz TMA because the geometry is similar to it. Work is in progress to find the coefficient of drag more precisely with Navier stokes equation in continuous regime and verification with CFD package.

Maximum thermal distribution.

The flow field around hypersonic vehicle is characterized by strong shock and very high temperature as a consequence of large thermal fluxes requiring a proper designed thermal protection system. For these reason estimation of reentry environment and correct design of thermal protection system is essential. Formula for thermal distribution in continuous flow.

$$\sigma \cdot \frac{\varepsilon}{h} \cdot T_s^4 + T_s - T_r = 0, \qquad (2)$$

where T_s – surface temperature. (k);

h – coefficient of heat transfer

$$h = 2700 \cdot \rho_\infty \cdot M_\infty, \left(\frac{k_{CAL}}{m^2 \cdot h \cdot \deg ree}\right) \quad ;$$

M_∞ – mach number;

$\frac{\rho.\infty}{10}$ –Atmospheric–density · $(Kgf \cdot sec^2)/m^4$;

T_∞ – atmospheric temperature (k);

ε – emissivity;

T_r – reduction temperature

$$T_r = T_\infty \cdot (1 + 0.18 * M_\infty^2);$$

σ – Stefan Boltzmann constant ($\sigma = 4.9 \cdot e - 18$).

In the continuous flow, thermal distribution gradually increases from 70km to 40 km (fig. 6).

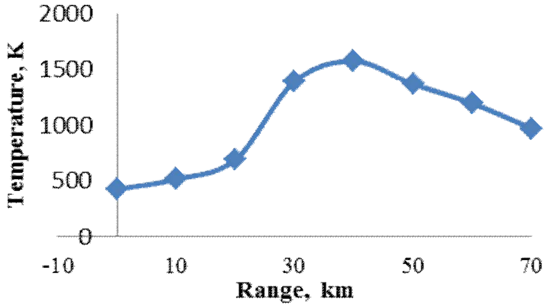

Fig. 6. Maximum Thermal distribution over the surface of the capsule with altitude variation.

The maximum temperature is experienced at 40 km because of relatively high ratio of velocity and the density at this altitude. Energy is dissipated with the thermal heating of the blunt profile and below 40km thermal distribution falls relatively.

Aerodynamic and thermodynamic parameters of capsule in Newtonian flow

From the Knudsen number analysis (see fig. 2) it is clearly mentioned that with the design specifications of the capsule, from the altitude 110 to 160 km is under Newtonian flow. So for this flow, continuous flow analytical theory is not applicable. Different analytical formulas are used as mentioned below.

Coefficient of drag.

Coefficient of drag (Cd) distribution over the surface of capsule blunt face is calculated at different altitudes in Newtonian region (fig. 7).

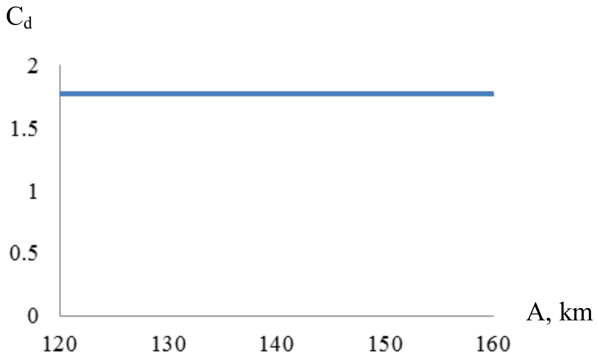

Fig. 7. Maximum coefficient of drag over the surface of the capsule in Newtonian flow

Formula for coefficient of drag in Newtonian flow

$$C_d = 2 \cdot \frac{dA}{s} \cdot \sin^2 \gamma, \qquad (3)$$

where $s - \text{Area} = \frac{\pi D^2}{4}$;

C_d – coefficient of drag;

dA – differential area;

γ – angle of orientation for differential area;

s – cross section area.

Drag force acting in this flow with low density remains nearly constant as long as the high velocity is sustained.

Maximum coefficient of Pressure.

Maximum coefficient of pressure (Cp) distribution over the surface of the blunt face of capsule is calculated at different altitudes in Newtonian region. Formula for coefficient of pressure in Newtonian flow

$$C_p = 2 \cdot \sin^2 \gamma\ ; \tag{4}$$

where C_p – coefficient of pressure;

q_∞ – dynamic pressure;

γ – angle of orientation for differential area;

v – velocity of the capsule;

ρ – density of the air.

Formula for pressure definition

$$p = C_p \cdot q_\infty , \tag{5}$$

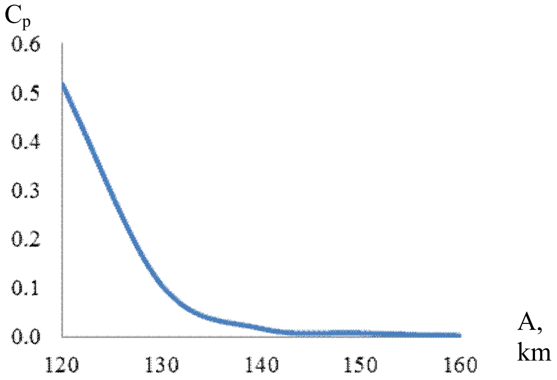

Fig. 8. Pressure coefficient over the surface of the capsule

With decreasing altitude pressure increases due to dense atmosphere with the altitude drop. Pressure coefficient results from linear momentum normal and parallel to wall by unit of area per unit of time. In Newtonian flow maximum pressure distribution over capsule occurs at 120 km altitude (see fig. 8).

Thermal distribution over the capsule.

Maximum thermal distribution over the surface of the blunt face of the capsule is calculated at different altitudes in Newtonian region.

$$T_w = \frac{\rho \cdot V_\infty^3}{2 \cdot \sigma \cdot \varepsilon}, \tag{6}$$

where T_w – maximum thermal distribution over the surface of the blunt face of capsule;

V_∞ – velocity of the capsule;

ε – emissivity;

σ -Steffen Boltzmann constant.

Thermal distribution gradually increases with decreasing altitude because of the increasing density of atmosphere (fig. 9).

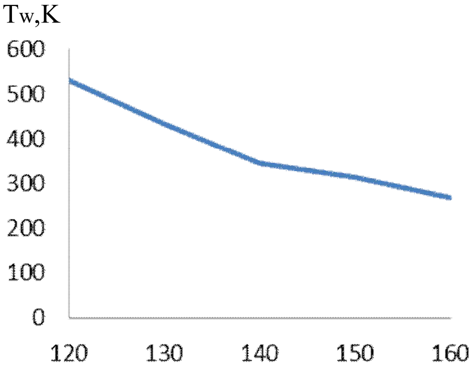

Fig. 9. Maximum thermal distribution over the surface of the capsule

At the point of atmospheric impact of the capsule surface thermal shocks reaches its peak, as in Newtonian flow the maximum thermal distribution occurs at the 120 km altitude.

Test of the Damru capsule in study wind tunnel T-5

This primarily consists in measuring aerodynamic characteristics of the model in a wind tunnel. Wind tunnel test is performed to understand the flight path angle of the capsule with the change in angle of attack under acceptable loading. Test was performed with the 10% of full scale wind tunnel models for entry of capsule with angle of attack from -10 to +40 for low Reynolds number. Figure 10 is the scaled model of the Venera capsule used for the flow analysis in the wind tunnel (fig. 10).

Coefficient of drag.

The coefficient of drag is the key parameter for determining the deceleration load, trajectory of the flight and the total heat load for an entry vehicle.

Coefficient of drag is maximum at the 0° AOA (fig. 11), it is 1.03 and it is minimum around 0.8 at 40° AOA. To avoid the hypervelocity impact appropriate AOA is important during reentry as the drag force decelerates the vehicle with altitude drop. A more rapid high drag entry usually reduces the total energy input at the expense incurring at very high local heating rate and may in addition result in unacceptable dynamic loads.

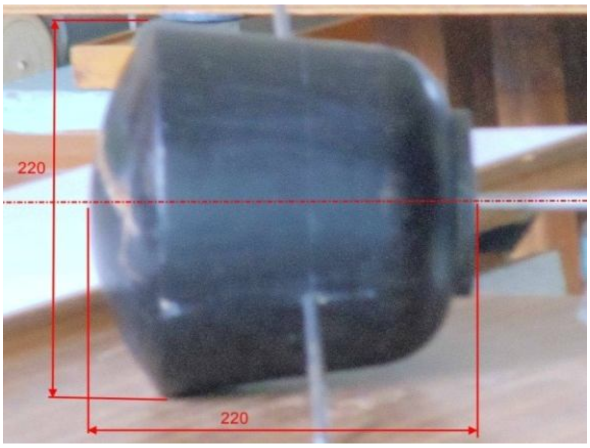

Fig. 10. Venera 4 Scale model used for flow analysis

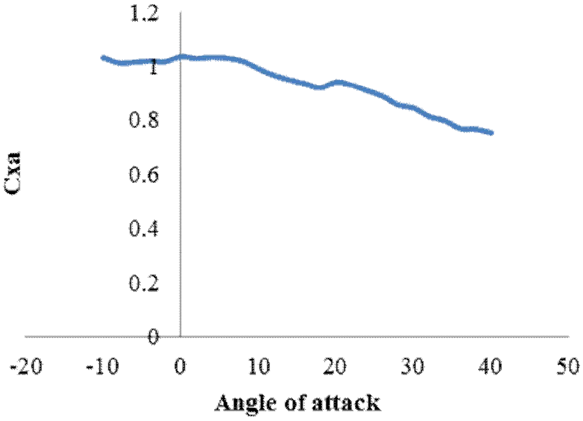

Fig. 11. Coefficient of drag of Damru capsule

With the above result of the T-5 windtunnel it is understoood that the small variation of the AOA during reentry is on symmetrical body with the coefficient of drag for AOA between -10° to 10°. The above result of varying drag with the wide AOA will be considered for the trajectory deisgning while considering the heat transfer within limits.

Conclusions

For understanding the dynamics of capsule in Low earth Orbit (LEO) and forces experienced by spacecraft during reentry are found and the experimental data in low Reynolds number is found reasonable. Aerodynamic analysis of the capsule will be considered for trajectory designing with minimum thermal distribution for different masses after verification of the result in the CFD package.

Maximum temperature within the blunt end was found to be 1593 K in continuous region if compared with the orbital temperature during reentry is 530 K at 120 km in Newtonian region.

It is interested to find the value of the spacecraft capsule average heating rate as well as altitude and velocity at which this rate occurs. This maximum heating rate often constrains the entry trajectory. Future research will be focused on designing minimum energy trajectory with active and passive propulsion along with the reentry forces which will be further considered for structural analysis of the capsule.

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АЕРОДИНАМІЧНІ ТА ТЕРМІЧНІ ВЛАСТИВОСТІ КАПСУЛИ КОСМІЧНОГО АПАРАТУ ПОГАНООБТІЧНОЇ ФОРМИ, ЩО ПОВЕРТАЄТЬСЯ

Р. Раджедрасінг, Ю. Гірька, В. Захаренко, В. Маллікарджуна, А. Бупатіраджа

У роботі розглянуто основні стадії процесу керованого повернення з орбіти супутників після закінчення терміну їх експлуатації, надано основні характеристики атмосфери в залежності від висоти траєкторії. Надано результати аеродинамічних досліджень виконаних аналітичним та експериментальним методом у неперервному та ньютоновому середовищах. Визначено термічні та аеродинамічні параметри літального апарату у широкому діапазоні чисел Маха та Кнудсена. Надано результати експериментальних досліджень аеродинамічних характеристик моделі капсули, що повертається в аеродинамічній трубі Т-5 ХАІ.

Ключові слова: літальний апарат, траєкторія, лобовий опір, термічні навантаження, аеродинамічна труба.

АЭРОДИНАМИЧЕСКИЕ И ТЕРМИЧЕСКИЕ ХАРАКТЕРИСТИКИ КАПСУЛЫ ВОЗВРАЩАЕМОГО КОСМИЧЕСКОГО АППАРАТА ПЛОХООБТЕКАЕМОЙ ФОРМЫ

Р. Раджедрасинг, Ю. Гирька, В. Захаренко, В. Малликарджуна, А. Бупатираджа

В работе рассмотрены основные стадии процесса управляемого возвращения с орбиты спутников после окончания срока их эксплуатации, приведены основные характеристики атмосферы в зависимости от высоты траектории полета. Приведены результаты аэродинамических исследований выполненных аналитическими и экспериментальными методами в непрерывной и Ньютоновой средах. Определены термические и аэродинамические характеристики летательного апарата в широком диапазоне чисел Маха и Кнудсена. Приведены результаты экспериментальных исследований аэродинамических характеристик модели капсулы в аэродинамической трубе Т-5 ХАИ.

Ключевые слова: летательный апарат, траектория, лобовое сопротивление, термические нагрузки, аэродинамическая труба.

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