PECULIARITIES OF GASDYNAMICS OF DESCENT AND LANDING ON PLANETS WITH RAREFIED ATMOSPHERE

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Introduction

One of the ways to provide soft landing on a planet surface is the usage of a brake-engine with thrust opposite to space vehicle movement. In this connection it is necessary to investigate interference between the brake-engine jet and oncoming flow in the planet atmosphere, and also between the jets and surface. Shapes of examined models (lunar module and Martian probe) are illustrated in Fig. 1.

TSNIIMash was one of the first scientific centers where such investigations had been started dealing with force and heat loads from the engine jets acted on the space vehicle structure during soft landing on the lunar and Martian surfaces.

Interaction of single/multiple jet with oncoming flow or surface is characterized by appearance of a large number of shock waves, contact surfaces, separated zones and other peculiarities and this defined the necessity of fulfillment of extensive experimental studies. For these aims U-22 and U-22M vacuum chambers were created in TSNIIMash in 1970-ies and 1980-ies.

Some results regarding drag coefficient of the space vehicle with working jets are presented below.

1. Interaction of the jets with oncoming flow

Gasdynamic pattern of interaction between one or several jets and oncoming flow is studied in detail [1-7]. Jet flow, interacting with oncoming flow, generates a contact surface, and a stagnation zone appears behind the latter. This zone may be closed on the body surface or stay open. Pressure in the zone defines a local jet pressure ratio $n_a = P_a / P_\infty$ for working jets (P_a – pressure at a nozzle exit, and P_∞ – ambient pressure). At supersonic flow velocity, a shock is generated in front of the contact surface and unstable flow regimes may appear.

Injection of one or several jets from the drag screen causes always pressure fall at the screen and drag decreases. The influence of one central jet in case when the drag screen is a blunted cone with half-cone angle $\theta = 70°$ at angle attack $\alpha = 0$ is shown in Fig. 2. Here M_a, M_∞ – Mach numbers at the nozzle exit and in outside flow, correspondingly; Re_a – Reynolds number at the nozzle exit; P – pressure at the screen surface; $P'_{0\infty}$ -pressure past normal shock in the outside flow; L_k – a distance along the jet axis from the nozzle exit to the contact surface [3]; r_a – the nozzle exit radius; r – a coordinate of a point on the screen surface with origin on its center.

Increase of the jet injection intensity, defined by the value L_k, when the latter is small, causes reduction of pressure level mainly in the central part of the screen surface. If L_k value is large, the drag screen wholly is located in the stagnation zone, and pressure reduces on the whole screen surface.

The influence of 4 injected jets placed over the drag screen periphery is illustrated in Fig. 3 (the nozzle position is $r/r_a = 8$). The jets influence is small near the screen central part and at the screen periphery pressure reduces a little with increased rate of gas injection.

Pressure level on the screen surface is significantly higher in case of 4 jets, comparing with single central jet, and this causes increase of the screen drag coefficient C_x. It was a reason to choose 4-jet configuration of Martian probe 5M (Fig. 1b).

Report Documentation Page

Report Date 23 Aug 2002	**Report Type** N/A	**Dates Covered (from... to)** -

Title and Subtitle Peculiarities of Gasdynamics of Descent and Landing on Planets With Rarefield Atmosphere	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Institute of Theoretical and Applied Mechanics Institutskaya 4/1 Novosibirsk 530090 Russia	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) EOARD PSC 802 Box 14 FPO 09499-0014	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

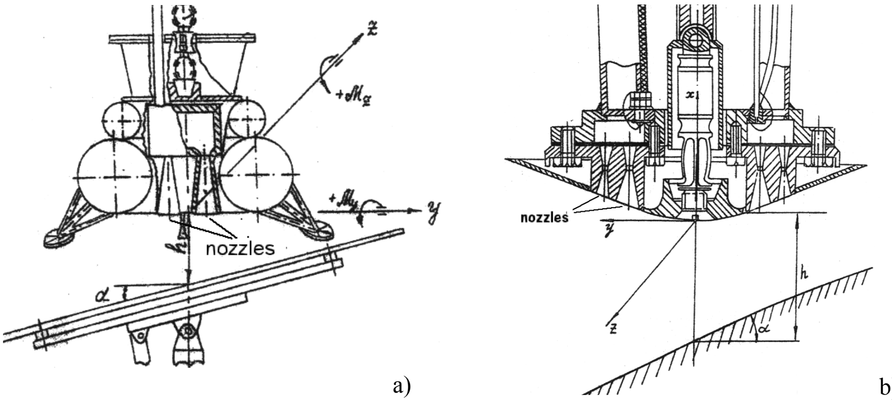
Supplementary Notes
See also ADM001433, Conference held International Conference on Methods of Aerophysical Research (11th) Held in Novosibirsk, Russia on 1-7 Jul 2002

Abstract

Subject Terms

Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU

Number of Pages
5



a) b)

Fig. 1. Principal scheme of the models (a-lunar module, b-Martian probe).

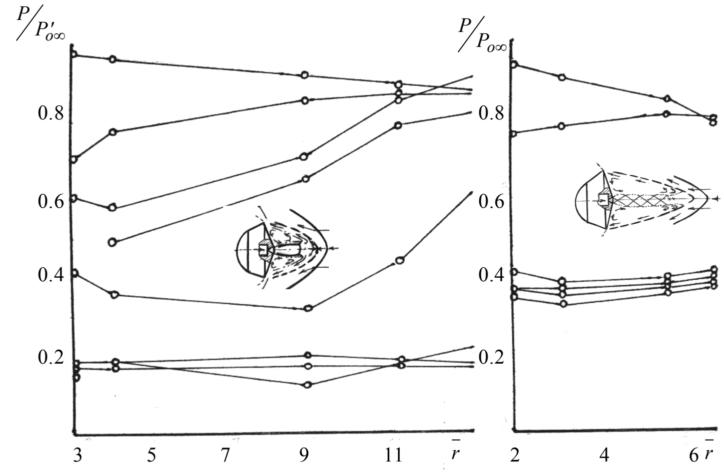


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Fig. 2. Influence of injection of central oncoming jet on pressure distribution over nose screen.

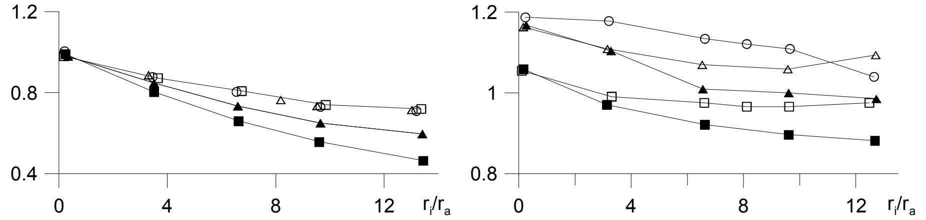

Fig. 3. The influence of four opposite jets on pressure distribution over the nose screen, model 5M, M_a=4.73; $Re_a \approx 10^6$.

Symbol	o	Δ	▲	□	■
φ	45°, 90°,180°	45°	90°,180°	45°	90°,180°
L_k	0	5.1	5.1	7.2	7.2

1. Vacuum chambers for studying gasdynamic process of interaction between vacuum jets and obstacle

It is necessary to solve two problems during simulation of space vehicles soft landing on surfaces of planets with rarified atmosphere. The first one is connected with required value of model jet pressure ratio, and the second – with reproduction of general gasdynamic similarity parameters M_a, κ_a, Re_a, etc. These problems may be solved only with the help of vacuum chambers and specific test techniques. In order to simulated more completely all elements of the full-size vehicle which are situated in the reflected flow of the jet, it is necessary to fabricate large-scale models which may be tested in the large-scale vacuum chambers. U-22M vacuum chamber with volume V=170 cu.m, initial pressure P~1Pa, and U-22 vacuum chamber with volume V=930 cu.m, initial pressure P~0.1Pa give opportunity to obtain required values of jet pressure ratio in a wide range [8].

Pulse ignition of the model engine is realized using gasgenerator of powder combustion products with combustion temperature 2200-2400 K, or with the help of diaphragm unit with compressed air or another gases as working body.

The model scale is chosen from the point of view to simulate Re_a and provide required critical section of the model nozzle, its weight, initial jet pressure ratio with initial pressure in the vacuum chamber, and time period when gasdynamic parameters are recorded.

a) M_∞=1.1; M_a = 1.0; $Re_a = 16.2\cdot10^6$ b) M_∞=1.5; M_a = 3.2; $Re_a = 9.4\cdot10^6$

Usually it is based on the condition $\frac{(P_{oc})_{model}}{(P_{oc})_{vehicle}} = \frac{(d_*)_{model}}{(d_*)_{vehicle}}$, where P_{oc} – pressure in the engine chamber, d_* – the nozzle critical section diameter.

Pulse ignition of the model generator and a small period of time for recording parameters ($\Delta\tau$=0.05-0.15 s) impose definite requirements on instrumentation, which have to measure very small values and operate in extreme conditions – at high temperature and under shock and vibration loading.

A system for measurement of forces and moment was developed with present level of dynamic errors (<10%), and natural frequency of the system model-balance-suspension satisfies a condition $f_n \cdot \Delta\tau \geq 3$ (f_n – natural frequency). The weight is also limited, because at f_n >90-100 Hz its weight should be less 120-150 g.

In accord with present techniques a measurement error for forces and moment is ±(10-15)%, measurement error for pressure acted on the model is ±(8-10)% with confidence probability P=0.95.

Thus the test technique [9] permits to conduct all necessary measurements and optical study with light models (scale 1:5 – 1:20, d_* >2 mm) during the time interval 0.05-0.15 s).

2. Peculiarities of gasdynamic aspects of soft landing

Investigation of gasdynamics related to soft landing requires study of interaction between one/several jets and landing surface and between reflected flow and structure elements of a landing module.

Interaction between jets with moderate pressure ratio and an obstacle is investigated in details [10-12]. Information about interaction of rather underexpanded (exhausting into vacuum) jets is presented in works [13-15].

For case of several jets interacting with an obstacle there are only some works related to study of physical flow pattern and loads acted on the obstacle surface [16].

Experimental studies had shown that values of distributions of the gasdynamic loads acted on the obstacle are sensitive to the variation of M_a, κ_a, β, h, δ. The typical profile of pressure variation over the surface for case of two jets is presented in Fig. 4 and it is characterized by maximum in the region where a stream with low entropy impinges the surface. The ranges of the parameters variation were the following: M_a=3-5, κ_a=1.12-1.4, angle of inclination of the jet axis to the surface β=0-20°, h/δ=2-5 (h- a distance from the nozzle exit to the surface; δ - a distance between centers of the nozzles exit sections, Fig. 4).

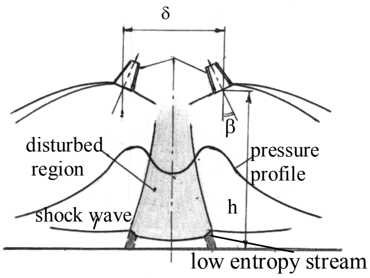

Fig. 4. The scheme of interaction of double jets block with the surface.

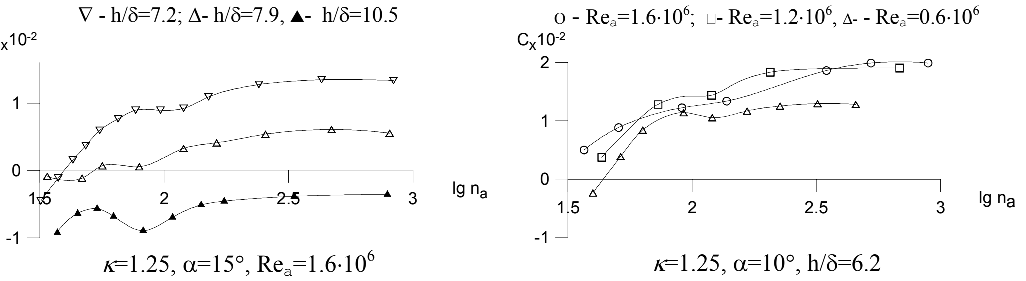

Fig. 5. Axial force coefficient C_x of lunar landing module.
a) one central nozzle; b) two central nozzles.

Interaction of reflected flow with structure elements of the landing module has individual behavior in each case, and a small volume of available experimental data about integral loads were obtained during onground development of specific vehicles.

Integral characteristics of the landing lunar module model with central position of a brake-engine (single nozzle) and four disk-shaped supports placed on landing units (Fig. 1a) were investigated (by Melbard, TSNIIMash) in the next ranges of initial parameters:
$M_a = 3.36$, κ_a= 1.25; 1.4; 1.67, α=0-30°, $\bar{h}=h/r_a$=5-15, $Re_a=(1\text{-}4.5)\cdot 10^6$, n_a = 10-1000.

Axial force coefficient C_x for this vehicle is plotted against n_a with various Re_a and $\bar{h}$ is presented in Fig. 5. Here $C_x=X/(q_a \cdot S_a)$, X – axial force, $q_a = 0.5\kappa_a M_a^2 P_a$, S_a-the nozzle exit area.

Integral gasdynamic characteristics for the landing module of similar configuration but with twin nozzle (Fig.1a) were investigated with the following initial parameters: $M_a = 3.26$, κ_a = 1.25; 1.4; 1.67, α=0-30°, $\bar{h}$=10-30, $Re_a=(0.5\text{-}40)\cdot 10^5$, n_a = 30-6000.

In this case, on the contrary to the landing module with one central nozzle (Fig. 5a), jets interact among themselves, beginning with certain value of n_a, generating disturbed region with more dense flow (Fig.4). Although dependencies of integral characteristics versus general initial parameters are analogous to the dependencies for vehicle model with single nozzle, the absolute values of C_x are significantly greater for the model with twin nozzle.

Investigation of gasdynamic parameters for Martian landing module (Fig. 1b) was carried out in the ranges $Re_a=(0.5\text{-}2)\cdot 10^6$, n_a = 6-50, α=0-30°, $\bar{h}$=2-11. This vehicle has four twin nozzles, which exits are flush-mounted on the nose screen surface, and the screen is blunted cone with vertex angle 140°. The nozzles had non-uniform distribution of Mach number at exits and κ_a = 1.4. At sharp edge of large and small nozzles Mach numbers were equal to 4.7 and 4.9, correspondingly. In above range of jet pressure ratio, each of four compound jets interacts with the obstacle as isolated one. Parameters of back flow inside twin-jet volume were defined by parameters of large jets.

Integral characteristics are plotted against large jet pressure ratio in Fig. 6.

When jet pressure ratio is close to its real value ($n_a \approx$ 10-12), all gasdynamic characteristics depend significantly on this parameter. Axial component increases with increased n_a, and it always has direction opposite to the vehicle motion. Normal component may increase or decrease (its absolute value) with increased n_a, and it changes its direction.

Increased number of nozzles_ makes influence of geometrical parameters h and α on gasdynamic parameters more complicated and causes appearance of alternating loads acted on the landing module.

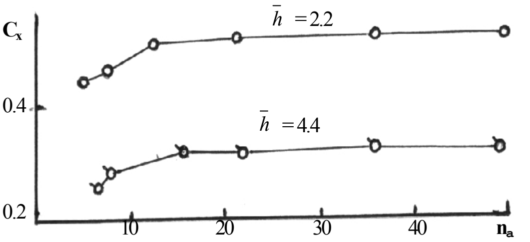

Fig. 6. Axial force coefficient C_x of Martian landing vehicle with four nozzles (κ_a = 1.4; α = 5°).

Investigations of different landing modules have shown that increased number of engines for soft landing causes growth of loads acted on the vehicle. Maximum axial force for the vehicle with one brake-engine was about 0.02 of engine thrust, for the vehicle with double nozzle (Fig. 1a) – about 0.2 of total engines thrust (R_Σ), and for Martian module – 0.5 R_Σ. Normal component was $0.005R_\Sigma$, $0.02R_\Sigma$, $0.06R_\Sigma$ correspondingly. The same is true for moment values.

Conclusion

The investigations have shown that processes of drag and soft landing of the space vehicle on the planet surface is a complex gasdynamic problem. General peculiarities of gasdynamic parameters behaviour and loads acted on the vehicle were examined. But unique configuration, strong dependence of aerogasdynamic characteristics from $\kappa_a, \mathrm{Re}_a, n_a$, etc., during landing, complicated flow patterns with generation of regions with continuum, rarified gas and transitive zone – require experimental simulation of gasdynamics related to the landing process using vacuum chambers and low density wind tunnels.

REFERENCES

1. **Stolyarov E.P**. Similarity at Strongly Underexpanded Gas Jets Exhausting Upwards Oncoming Flow // Uch. Zap TSAGI. 1977. Vol. 8, No. 1. P.122-126.
2. **Stolyarov E.P.** About Underexpanded Gas Jets Exhausted Upwards Supersonic Flow // Uch. Zap TSAGI. 1977. VOL. 8, N2, p.p.33-43.
3. **Kalinin E.M., Melbard A.M**. Similarity Parameters in a Problem on Supersonic Jet Exhausting Upwards Supersonic Flow // Izv.Ac.of Sciences USSR. MJG. 1980. No. 3. P.83-89.
4. **Finley P.J.** The Flow of a Jet from a Body Opposing a Supersonic Free Stream. Fluid Mech. 1966.Vol.26, pt. 2. P. 337-369.
5. **Jarvinen P.O, Adams R.H.** The Effects of Retrorockets on the Aerodynamic Characteristics of Conical Aeroshell Planetary Entry Vehicles. AIAA Pap.N70-219, 1970. 10 p.
6. **Keys J.W., Hefner J.N.** Effect of Forward-Facing Jets in Aerodynamic Characteristics of Blunt Configuration at Mach Number 6 // J. Spacecraft and Rockets. 1976. Vol. 4, No. 4. P. 533-534.
7. **Karpman I.M.** Underexpanded Jet Flow Upwards Supersonic Flow // Izv. Ac. of Sciences USSR, MJG. 1977. No. 1. P. 89-96.
8. **Anfimov N.A., Prochukhaev M.N.** TSNNIMash's U-22 Gasdynamic Vacuum Chamber. AIAA Paper, No. 93-1841, June 1993.
9. **Khramov N.E., Bachin A.A., Maksimenkov V.S., Kovalev A.V.** Investigation of Jet Gasdynamics High-Altitude Problems during the Development of Products of Rocket Space Technology // Intern. Aerospace Congress. Moscow, 1994.
10. **Gubanova O.I., Lunev V.V., Plastinina L.N**. About Central Stalling Zone at Interaction of Underexpanded Supersonic Jet With an Obstacle // Izv. Ac. of Sciences USSR, MJG. 1971. No. 2. P.1 35-138.
11. **Semiletenko B.G., Uskov V.I.** Experimental Dependencies which Define Position of Shock Waves in a Jet Impinged an Normal Obstacle // Inzhenerno-fizicheskii Zhurnal. 1972. Vol. 23, No. 3.
12. **Semiletenko B.G., Sobkolov B.N., Uskov V.I.** Peculiarities of Unsteady Interaction Between Supersonic Jet and Infinite Obstacle // Izv. SO Ac. of Sci. 1972. No. 13. Ser. techn. nauk. Iss. 3. P. 39-42.
13. **Khramov N.E.** Calculation of Interaction between Axisymmetric Supersonic Underexpanded Jet and an Obstacle // Izv. Ac. of Sciences USSR, MJG. 1966. No. 5. P.129-132.
14. **Lebedev M.G., Savinov K.G.** Impingement of Supersonic Gas Flow and a Flat Surface // Izv. Ac. of Sciences USSR, MJG. 1969. No. 3. P. 165-171.
15. **Mironchuk N.S., Nikulin A.N., Khramov N.E.** On Calculation of Interaction between a Supersonic Underexpanded Jet and Obstacle // Izv .Ac. of Sciences USSR, MJG. 1981. No. 1. P. 157-160.
16. **Rudov Yu.M.** Multi-Jet Interaction with Obstacles. Supersonic Gas Jets. Novosibirsk: Nauka, 1983. P .155-163.