THE PHYSICAL ASPECTS OF GAS DYNAMIC AND THERMAL PHYSICS PROCESSES MATHEMATICAL MODELLING OF DESCENT SPACECRAFT'S

by

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Original scientific paper
https://doi.org/10.2298/TSCI19S2513V

The article discusses the physical aspects and assumptions in the formulation of the gas dynamics and thermal physics models in conditions of "Luna – Resource" spacecraft landing on the Moon surface. It was proposed to divide the problem into two stages: calculation of the gas phase and determination of trajectories and heating of particles of lunar dust. The use of the continuum equations and not taking into account the reverse effect of particles on gas was substantiated. The calculation results of parameters impingement exhaust jet of spacecraft propulsion system with Moon surface are given. It was obtained that a reverse external force is added to the streamlined surfaces equal to 196 N, the gas temperature at the bottom of the cargo compartment reaches 2000 K, and the calculated heat flux was 400 kW. The trajectories of the particles of lunar dust was determined and it was found that with a size of 1 μm the distance of their flight range was 3.5 km.

Key words: *spacecraft, vacuum environment, continuous medium, soft landing engines, Moon surface, particles of lunar dust*

Introduction

Spacecraft designed to land on the surface of the Moon, such as the *Luna Resource* spacecraft, approach the lunar surface using one or more impulsed propulsion system, the nozzles of it which is directed to the landing surface. Since the Moon has no atmosphere, the supersonic jets flowing out of the propulsion system nozzles expand to vacuum away from the spacecraft. When approaching the Moon, the supersonic jets begin to interact with its surface with the formation of the outgoing shock wave and the expansion of the supersonic gas-flow along the surface of the Moon. This stream interacts with the surface layer of the regolith and leads to its erosion. The result is a dusty flow of combustion products. When the spacecraft approaches the Moon surface, the flow of dusty high temperature combustion products reflected from it cover the landing spacecraft, interacting with its streamlined surfaces. These flows can adversely affect the operation of technical devices of the spacecraft and cause damage to them. Because the physical modelling of these processes under terrestrial conditions is extremely difficult and expensive, it is advisable to apply physical and mathematical model-

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Figure 1. General view of the spacecraft *Luna-Resource* [1]

ling using experimental data obtained in previous missions to the Moon. In this article some results of such modelling are presented on the example of the *Luna-Resource* spacecraft, fig. 1, [1].

Statement of the problem and solution method

When solving the 3-D problem of its flow, a simplified 3-D geometric model was used. It included four spherical tanks, four cylindrical spacers between the tanks, a brake and correction engine, two engines of a soft landing and four foot supports. Additionally, the computational domain was included: conical protective casing that provides protection from radiation when the braking of the engine, heat-protective plate with holes for nozzles, and a cylindrical volume of the cargo compartment. All these elements can be seen in the subsequent figures in flat sections of the 3-D volume.

At large distances from the Moon surface the outflow from the nozzles occurs in vacuum and molecular dynamics methods should be used for calculations. At the same time, when approaching the Moon at altitudes of about 1 meter, gas jets reflected from the Moon's surface almost completely flow around the landing platform and, due to their high density, must be calculated using continuous medium mechanics methods. The criterion for the use of these models is the Knudsen number:

$$\mathrm{Kn} = \frac{\lambda}{d_a} \tag{1}$$

where λ is the mean free path of the molecules and d_a – the characteristic size of the body.

It is believed that a medium consisting of molecules can be described by continuum equations when the inequality is satisfied Kn < 0.1. In this model, the Knudsen number was calculated from the diameter, d_a, of the output section of the nozzle of a soft rocket engine. In fig. 2 shows the results of calculating the value lg(Kn) in the cross-section of the 3-D region, passing through the axes of the two nozzles of the soft landing rocket engines at the moment the foot supports touch the Moon surface. From the analysis of the results it follows that the equations of the continuous medium are applicable in the entire computational domain in that lg(Kn) < –1.

The Knudsen number in the flow around a single particle of lunar dust can be defined:

$$\mathrm{Kn}_s = \frac{\lambda}{d_s}, \tag{2}$$

where d_s is thediameter of particle.

Excluding from the relation (1) and (2) the length of the free path of the molecules, λ, we find:

$$\mathrm{Kn}_s = \mathrm{Kn}\frac{d_a}{d_s}$$

For diameter of nozzle d_a = 0.146 m and diameter of particle d_s = 30 μm believing Kn ≈ 0.1 detect $\mathrm{Kn_s}$ = 493, it follows that such particles are practically in a free molecular flow.

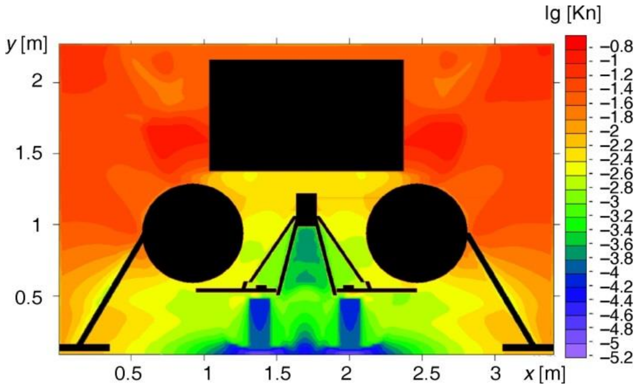

Figure 2. The distribution of the Knudsen numbers
(*for colour image see journal web site*)

Mathematical models of gas flows with particles are based on the model of interpenetrating media, which takes into account the exchange of the amount of motion and energy between the media [2]. This exchange is directly proportional to the drag coefficients and heat exchange of particles with a gas. In [3] to calculate the drag coefficients of spherical particles taking into account the sparsity of the gas phase, a formula is proposed:

$$C_D = \frac{24}{\mathrm{Re}}\frac{\left(1+0.15\,\mathrm{Re}_s^{0.687}\right)\left[1+\exp\left(-\dfrac{0.427}{\mathrm{M}_s^{4.63}}-\dfrac{3.0}{\mathrm{Re}_s^{0.88}}\right)\right]}{1+\dfrac{\mathrm{M}_s}{\mathrm{Re}_s}\left[3.82+1.28\left(-1.25\dfrac{\mathrm{Re}_s}{\mathrm{M}_s}\right)\right]} \tag{3}$$

where $\mathrm{M_s}$ and $\mathrm{Re_s}$ are Mach numbers and Reynolds numbers calculated for flow around particles, respectively.

Calculations using this formula are in good agreement with experimental data, including for sparse flows [4]. The expression in the numerator of eq. (3) is used for particle drag coefficient calculation streamlined by gas under a continuous medium. The denominator in this formula is responsible for the change in the drag coefficient in the rarefied flow. According to [3] the ratio of Mach number to Reynolds number for rocket fuel combustion products is equal to:

$$\frac{\mathrm{M}_s}{\mathrm{Re}_s} = \frac{\mathrm{Kn}_s}{1.26\sqrt{k}} \tag{4}$$

where k is the adiabatic index.

Therefore, the denominator in eq. (3) can be represented:

$$DEN = 1+\frac{\mathrm{Kn}_s}{1.26\sqrt{k}}\left[3.82+1.28\exp\left(-1.575\frac{\sqrt{k}}{\mathrm{Kn}_s}\right)\right]$$

Substituting Kn = 0.1 in this formula we get *DEN* = 1.285. For the value calculated above Kn_s = 493, we get *DEN* = 1820. Thus, the sparseness of the flow leads to a change in the drag coefficient of particles of size d_s = 30 mkm by three orders of magnitude compared with the drag coefficient in terrestrial conditions. The formula for the Nusselt number taking into account the sparsity of the medium is also given in [3]. Given the eq. (4) for a number Kn_s, it can be rewritten in the form:

$$\mathrm{Nu} = \frac{\mathrm{Nu}_{\mathrm{con}}}{1 + 2.714 \dfrac{\mathrm{Nu}_{\mathrm{con}}\,\mathrm{Kn}_s}{\mathrm{Pr}_s \sqrt{k}}} \tag{6}$$

where

$$\mathrm{Nu}_{\mathrm{con}} = 2 + 0.459\,\mathrm{Re}_s^{0.55}\,\mathrm{Pr}_s^{0.33}$$

where Nu_{con} is the Nusselt number for continuous medium, Pr_s – Prandtl number for the flow around the dust particle. From eq. (6) it follows that for particles of lunar dust in the conditions of the use of the spacecraft, the heat fluxes between particles and gas are three orders of magnitude smaller than those in terrestrial conditions.

The estimates for not too high particle concentrations allow one to neglect the influence of the particles on the flow and heat exchange with the gas phase when the spacecraft is landing on the lunar surface. As a result of this approach, the algorithm for solving the problem can be divided into two stages:

– Calculation of the gas phase motion without taking into account the influence of particles.
– Calculation of the movement and heating of dust particles in a known gas field.

Results and discussion

To solve the first problem, 3-D viscous gas equations were integrated [5-10]. The second problem was solved by integrating the 3-D equations of motion and heat exchange of particles [11-13]. In fig. 3 shows the distribution of gas pressure in a plane passing through the axles of low-thrust engines. It can be seen that the maximum pressure is reached at the points of interaction of the supersonic jets with the surface of the Moon. The gas reflected from the surface reaches the elements of the landing platform and exerts pressure on them. The integral of the pressure forces is directed upwards from this surface. It adds force to the thrust of the soft landing engines. At a distance of 1 m from the platform to the surface of the moon, to the thrust of two engines equal to 529 N, an external pressure force is added to the streamlined surface equal to 196 N, which must be taken into account in the landing process.

In fig. 4 shows the results of calculating the gas temperature in the vicinity of the platform elements. The figure shows that when braking gases on the bottom of the cargo compartment, their temperature reaches 2000 K. The calculated heat flux at the bottom is 400 kW. This fact indicates the need for thermal protection of the cargo compartment. A temperature of 2000 K is also reached in gas flows flowing around spherical tanks and other structural elements. To protect them, it is also necessary to apply a heat shield. In fig. 5 shows the trajectory of dust particles 1 mkm in size. It follows from the figure that such particles fly apart from the landing platform.

The speed of these particles is 80 m/s, and the angle of inclination of the trajectory to the surface of the Moon does not exceed 30°. When moving away from the landing site of the spacecraft such particles move only under the influence of gravity. Therefore, the flight range was calculated according to the known formula:

$$L_s = \frac{u_0^2 \sin 2\alpha}{2g_{moon}} \left(1 + \sqrt{1 + \frac{2g_{moon} y_0}{u_0^2 \sin^2 \alpha}} \right) \tag{8}$$

where g_{moon} is the acceleration of gravity on the Moon, u_0 – the initial speed, y_0 – the departure point height, and α – the particle departure angle.

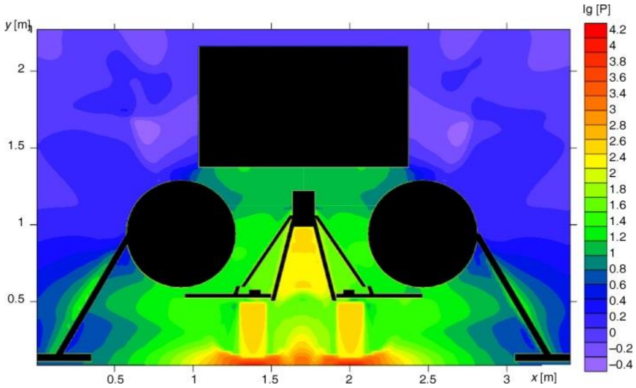

Figure 3. The distribution of pressure
(*for colour image see journal web site*)

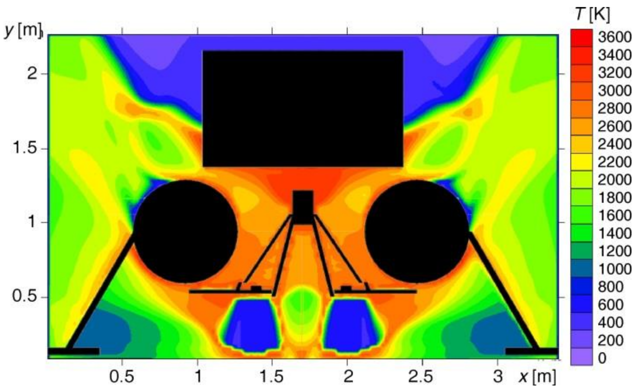

Figure 4. The distribution of temperature
(*for colour image see journal web site*)

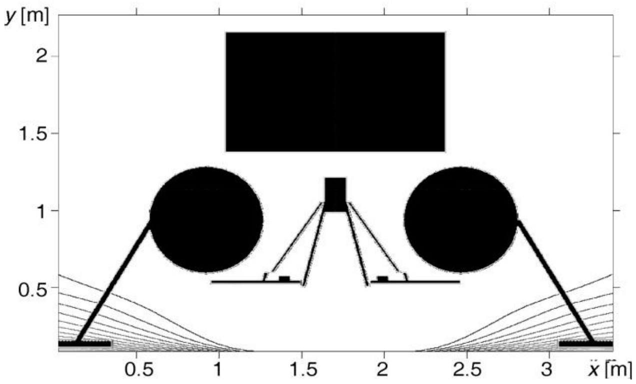

Figure 5. Particles trajectories

When u_0 = 80 m/s and α = 30 the range calculated L_s, by the eq. (8), was 3.5 km. The results of the study of particles of larger sizes showed that they have lower speeds and a shorter scattering distance.

Conclusion

The mathematical modeling of gas-dynamic and thermophysical processes of descent spacecraft in the conditions of the Moon on the example of the spacecraft *Luna-Resource* was carried out. An algorithm for solving the problem in conditions of strong sparsity was proposed, where the application of the gas phase calculation without taking into account the influence of particles using the continuum equations was justified. A calculation of the motion and heating of the particles to perform on a known gas field. During the landing of the *Luna-Resource* was obtained that jets of spacecraft influence on the platform surface in 196 N, and in the vicinity of the platform elements when gas is broken, the temperature reaches 2000 K. The trajectories of the dust particles of the Moon regolith were shown and their range of flight was estimated for 1 mkm particles, the flight range was 3.5 km.

Acknowledgment

This research was supported by grant (8.2.12.2018) from *The Tomsk State University competitiveness improvement programme*.

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Paper submitted: October 31, 2018
Paper revised: December 5, 2018
Paper accepted: December 11, 2018