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EXPERIMENTAL MODELING OF THE BREAKUP OF METEOROIDS IN THE EARTH'S ATMOSPHERE

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Ablation of meteoroids (rock materials and ice) in high-temperature gas flows and in radiation heating is modeled experimentally, and the character of their breakup is considered.

Regardless of the large number of investigation dealing with theoretical models of the breakup (ablation) of meteoroids, the most reliable data can be obtained only experimentally. As is noted in [1], the first experiments relating to the problem of breakup of meteoroids were conducted in the late 50s. Subsequently a good deal of attention was afforded this problem. Some results have been generalized in [1], which points out that isolated conclusions need revision and refinement and, hence, additional investigations.

Entry of a meteoroid into the earth's atmosphere is accompanied by formation of a shock layer, heating, melting, evaporation, fragmentation (scaling), and other physical processes. In this connection, from the standpoint of high-temperature heat and mass transfer an urgent task is studying the interaction of meteoroids or various-shape bodies of materials close to them in chemical composition with a high-temperature gas flow, which, in our opinion, will allow supplementation of some results of other researchers. Such experiments are performed, as a rule, on plasma stands, which most fully model the thermal and gasdynamic action on the object considered.

We carried out experimental modeling of ablation of meteoroids on a "Luch-2" stand that included an "Uran-1" radiation heating unit and an ÉDPG-2 plasma generator. A schematic diagram of the setup (Fig. 1) and methods for determining the basic parameters of the incident flow and conducting investigations are described in detail in [2].

As the objects of inquiry we used rock materials (granites and basalts) and ice. The magnitude of the heat flux at the site of placement of the specimen was $(1.7-2.1)\cdot 10^4$ kW/m^2 ($(1.15-1.5)\cdot 10^4$ kW/m^2 convective + $(0.5-0.6)\cdot 10^4$ kW/m^2 radiative). The working gas was air.

One of the characteristics of the mechanical action of a gas flow on the object in question is the stagnation pressure. In studying the breakup of specimens, the excess stagnation pressure was about $1.0\cdot 10^4$ N/m^2 at a gas flow velocity of ~ 670 m/sec. The enthalpy of flow stagnation was $I_0 = 15\cdot 10^3$ kJ/kg ($T \sim 6000$ K) and the density was $\sim 4.4\cdot 10^{-2}$ kg/m^3, which corresponds to the density of the standard atmosphere at a height of 24.5 km.

In the experiment we carried out frame-by-frame photography with a frequency of 5 Hz and ascertained by a pyrometer the brightness temperature $T_{\rm br}$ of the broken-up surface of the specimen. For basalts and granites it was $T_{\rm br} \approx 2750$ K.

The action of a thermal load on the material surface entails its heating and melting with formation of a melt film and bright boiling bubbles (for granites). The melt film runs onto the side surface not in a continuous flow but rather in "rivulets" and then is entrained by the gas flow in the form of individual particles of different sizes. In the experiment, material particles ablating from the specimen entered a cyclone connected by a pipe to an industrial vacuum cleaner. Their granulometric composition was identified by means of sedimentation analysis (for fractions smaller than 50 μm) on an FS-104 instrument of the Scientific-Production Amalgamation "Analitpribor" (Table 1) and, for fractions larger than 50 μm, by sieving them through a standard set of sieves. The data of the sieve analysis are presented as the ratio of the mass of each granulometric fraction to the mass of the breakup products and are expressed in percent (Table 2).

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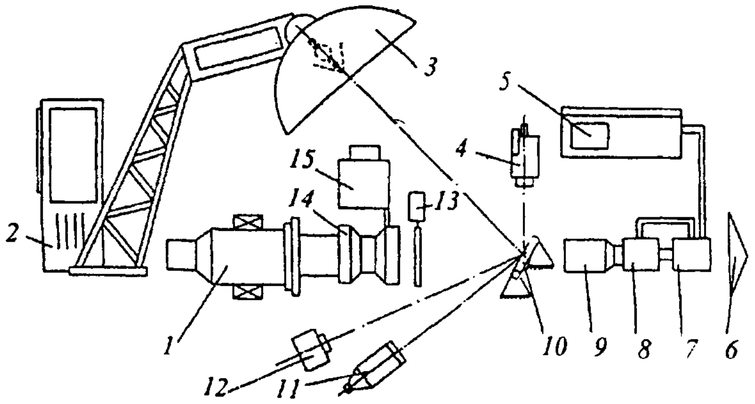


Fig. 1. Schematic diagram of a "Luch-2" experimental setup: 1) ÉDPG-2 plasmatron; 2) feed source of an "Uran-1" unit; 3) radiation heater; 4) RFK-5 camera; 5) industrial vacuum cleaner; 6) exhaust chamber; 7, 8) cyclones; 9) stub tube; 10) investigated specimen; 11) ÉOP-66 pyrometer; 12) ISSO-1 velocity meter; 13) gate; 14) water-cooled dust-distributing nozzle; 15) batcher of solid particles.

TABLE 1. Particle Size Distribution of the Products of Rock Breakup, %

Specimen	Particle sizes of fraction, μm						
	1–2	2–3	3–5	5–10	10–15	15–30	30–50
Granites	4.5	8.1	17.3	42.6	23.4	4.0	0.1
Basalts	2.0	3.4	7.6	30.0	37.0	15.0	2.0

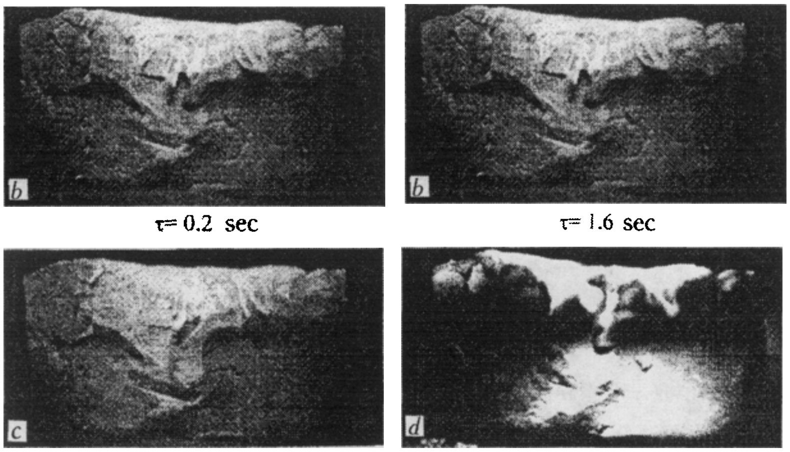
TABLE 2. Mass Content of Particles in the Breakup Products, %

Specimen	Particle sizes, mm						
	< 0.05	0.05–0.1	0.1–0.2	0.2–0.4	0.4–1.0	1.0–7.0	7–15
Granites	14.80	10.00	13.36	20.85	17.74	12.92	10.33
Basalts	15.83	10.13	12.40	15.23	16.25	25.89	4.27

As is seen from the results of the investigations, breakup (ablation) of rock materials in high-temperature gas flows that model the flight of stony meteoroids in the earth's atmosphere gives rise to particles with a wide range of linear dimensions and, in a quantitative respect, mostly to particles smaller than 50 μm. At the same time, the mass of particles larger than 50 μm is about three times that of small particles. Here it should be noted that the formation of particles results from two breakup mechanisms, namely, separation of drops from the melt film due to gasdynamic forces and breakup of the specimen proper due to thermal and mechanical loads. Figure 2 shows rock (basalt) breakup during the experiment.

The specimen material was exposed to the thermal action for 2 sec, and then, after a lapse of 15–20 sec (a cooling process), under the effect of residual stresses caused by thermal loads the specimen broke up into individual fractions of different sizes, from several microns to several millimeters.

The breakup of rock materials due to thermal loads alone is especially vivid in heating of the specimen by radiant energy ($0.5 \cdot 10^4$ kW/m^2, the spectral composition corresponds to the solar). It is established that, in the first instant of the action of the heat flux from the side of the heated surface, fragments of the rock material are split off and ejected counter to the flow. This breakup mechanism is ascribed to the appearance of thermal stresses in the material due to unsteadiness of the heating and temperature gradients across the specimen thickness of up to 1000 deg/mm. While heated, a specimen breaks up further, this process being unsteady and persisting after the themal load is terminated.



τ= 0.2 sec τ= 1.6 sec

τ= 1 sec τ= 2 sec

Fig. 2. Ablation of basalt during the experiment. $q = 1.7 \cdot 10^4$ kW/m^2.

Fig. 3. Limestone specimen after tests. $q = 0.5 \cdot 10^4$ kW/m^2.

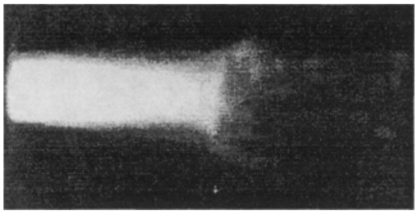


Fig. 4. Ablation of ice during the experiment.

The spread in the size of the breakup products is very large, from 10^{-2} to 10^{-7} m. Their proportion probably depends on the chemical and mineralogical composition of the material. Figure 3 shows a limestone specimen that broke up after being exposed to the radiation flux for 5 sec.

The breakup of ice meteoroids was studied using specimens of solid ice (without pores or foreign inclusions) in the form of cylinders with a diameter of about 50 mm and a length of about 130 mm. Experiments were conducted under the effect of an initial convective heat flux of $0.8 \cdot 10^4$ kW/m^2 and an excess stagnation pressure of $1 \cdot 10^4$ N/m^2 at a stagnation enthalpy $I_0 = 18$ MJ/kg, which corresponds to a velocity of entry into the earth's atmosphere of ~6 km/sec.

The experiments revealed that ice breakup proceeds without splitting or scaling because of thermal and gasdynamic loads, due to its melting, water heating and evaporation, and entrainment in the liquid phase (Fig. 4). In this case, the rate of breakup is about 4.5–5.3 mm/sec. The characteristic thickness of the heated water layer under quasisteady conditions of ablation is

$$\delta = a/v \sim 0.33 \text{ mm}$$

where a is the thermal diffusivity of water and v is the linear rate of the ice breakup. In view of the fact that the dynamic viscosity of water decreases by more than 6 times from 0 to 100°C, the bulk of the water runs over the surface in its most heated part (at the boiling temperature). With allowance for blowing of the ablation products in the turbulent boundary layer, the heat flux reaching the surface is determined by the equation [3]

$$q = q_0 \left[1 - 0.19 \left(M_e/M_w\right)^{0.7} \overline{G}\right], \tag{1}$$

which can be represented as

$$q = q_0 (1 - AKG), \tag{2}$$

where q_0 is the heat flux to an impenetrable surface; G is the mass rate of ice melting; $\overline{G}$ is the dimensionless blowing parameter, M_e and M_w are the molar masses of air and water vapor, respectively; $A = 0.19(M_e/M_w)^{0.7} 1/(\alpha/c_p)$; α/c_p is the coefficient of heat transfer on an impenetrable surface; $K = G_1/G$ is the portion of the evaporated water (G_1 is the mass velocity of the evaporated water). This energy is spent on the melting of ice ΔH_1, heating to the boiling temperature ΔH_2, and evaporation of water ΔH_3. Then, proceeding from the condition of heat balance on the broken-up surface it is possible to write that

$$q (1 - AKG) = G (\Delta H_1 + \Delta H_2) + KG\Delta H_3, \tag{3}$$

and to evaluate the portion of the evaporated water in the boundary layer

$$K = \frac{q_0 - G (\Delta H_1 + \Delta H_2)}{G (q_0 A + \Delta H_3)}. \tag{4}$$

For our experimental conditions, the portion of the evaporated water is ~0.13, the remaining part runs over the specimen surface forming a trail of drops of different sizes behind it, and the effective enthalpy of breakup is

$$I_{\mathrm{eff}} = q_0/G \approx 1.5 \cdot 10^6 \ \mathrm{J/kg}, \tag{5}$$

Here, with increasing enthalpy of stagnation of the incident flow an ever larger part of the water is evaporated and blown in the boundary layer, and the effective enthalpy of the ice breakup [4] rises:

$$I_{\mathrm{eff}} = \Delta H_1 + \Delta H_2 + K \left[\Delta H_3 + \gamma (I_0 - I_w)\right], \tag{6}$$

where γ is the blowing coefficient, and $(I_0 - I_w)$ is the drop of the enthalpy of gas flow in the boundary layer.

Thus, the investigations show that, while flying in an air medium, meteoroids consisting of rocks like basalts and granites ablate (become evaporated and entrained by the flow in the form of melt) and disintegrate into particles of different sizes, and ice meteoroids become melted and entrained in the form of drops, forming a water cloud from drops and vapor.

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REFERENCES

1. V. A. Bronshtén, *Physics of Meteoric Phenomena* [in Russian], Moscow (1981).
2. A. P. Iskrenkov, V. V. Mazak, M. S. Tret'yak, and V. V. Chuprasov, *Inzh.-Fiz Zh.*, 52, No. 1, 37-42 (1987).
3. F. B. Yurevich and V. V. Chuprasov, *Izv. Akad. Nauk BSSR, Ser. Fiz. Énerg. Nauk*, No. 3, 110-120 (1970).
4. Yu. V. Polezhaev and F. B. Yurevich, *Thermal Protection* [in Russian], Moscow (1976).