Technical Notes

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Extinction of Propellant near the Contact with a Metal

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THE observation and analysis of unsteady phenomena accompanying extinction can give useful information on the combustion mechanism, allowing one to draw conclusions about the validity of different theoretical considerations.

This paper describes a method of investigation of the extinction–the method of "freezing" the combustion zone. This method differs from the other methods described in the literature, such as the method of pressure drop,[1] the method of combustion zone cooling by means of liquid coolant injection,[2] and the method of limit diameter.[3] In the present method the thermal interaction between the combustion zone and powder-metal contact was used to produce the extinction.

In the experiment the cylindrical specimen of nitroglycerine powder "N" (10 mm diam and 10 mm height) was mounted at a massive copper polished plate. The side surface of the specimen was covered by a thin layer of Plexiglas. The close contact between metal and powder was achieved by grinding the lower surface of the specimen, with addition of a small amount of acetone.

The specimen was burned in a constant-pressure bomb with a nitrogen atmosphere. The specimen of powder was ignited at the upper surface.

After ignition, when the distance between the combustion front and contact is greater than the characteristic thermal layer thickness, the combustion front propagates steadily with velocity corresponding to a given pressure and initial temperature. When the combustion front approaches the contact, the influence of the high thermal conductivity of the copper plate on the conditions in the combustion zone increases. The heat transfer from the combustion zone and the temperature gradient at the condensed phase surface increase. The combustion temperature decreases and the combustion regime becomes unsteady.

In the vicinity of metal-powder contact, the burning rate varies and the extinction takes place at some distance from the contact. A layer of unburned powder remains at the copper plate. The thickness of this layer depends on the pressure. The thickness of unburned powder was determined by weighing the plate with the remainder and by subsequent calculations. The weight of metal plate was determined beforehand.

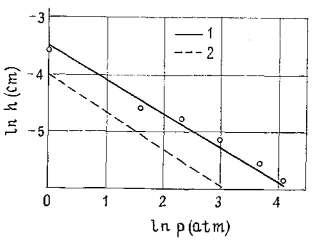

Fig. 1 Effect of pressure on thickness of the unburned powder slab. 1—experiment, 2—theory.

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The results of measurements of unburned powder layer thickness are represented in the form of a relation between the thickness h and pressure p. This relation is close to a linear one on a logarithmic scale. The negative slope of this straight line equals the burning rate exponent

$$\ln h = a - \nu \ln p \tag{1}$$

The experimental curve (1) is represented by a continuous line in Fig. 1.

As a check, a powder specimen was burned at an ebonite bed to prove the thermal nature of the observed phenomenon. The thermal conductivity of powder "N" and of ebonite are very close. The experiments showed that within the whole pressure range under consideration there was no unburned powder at the ebonite.

A comparison was made between the experimental data and Zeldovich's theory.[4,5] The principal assumptions of this theory are that the unsteady-state burning rate of powder is a function of pressure and of the temperature gradient at the burning surface, and that this function is the same for unsteady-state burning rate as for steady-state burning rate. The equation for steady-state temperature gradient at the burning surface is

$$\zeta \equiv (\partial T/\partial x)_s = (u^\circ/k)(T_s - T_0) \tag{2}$$

where u° is the steady-state linear burning rate, k is the thermal diffusivity of powder, T_s is the temperature at the burning surface, T_0 is the initial temperature of powder, and subscript s denotes surface conditions.

It is assumed that the dependence of the steady-state burning rate on pressure and initial temperature is known. The experimental dependence of the steady-state burning rate of powder "N" on initial temperature and pressure was obtained, for example, by Pokhil and others.[6,7] This dependence can be approximated by the following formula[8]

$$u^\circ(p,T_0) = u_1 p^\nu f(T_0),\ f(T_0) = (1 + \alpha T_0)/(1 - \beta T_0) \tag{3}$$

The values of α, β, u_1, and ν are given constants. The equation for unsteady-state burning rate $u(p,\zeta)$ follows immediately by eliminating the value T_0 from Eqs. (2) and (3)

$$u(p,\zeta) = u_1 p^\nu f[T_s - \varkappa\zeta/u(p,\zeta)] \tag{4}$$

According to Zeldovich's theory the extinction of powder takes place when the temperature gradient at the burning surface becomes equal to a certain critical value which is

$$\zeta^* = (u^*/k)(T_s - T_0^*),\ u^* = u^\circ(p,T_0^*) \tag{5}$$

Here T_0^* is the minimum initial temperature of powder at which the steady-state combustion is still possible; u^* is the steady-state burning rate corresponding to this initial temperature. The values T_0^* and u^* can be determined from the condition of maximum of the temperature gradient at the burning surface of powder under the steady-state combustion. Differentiating Eq. (2), one obtains the following equation for T_0^*

$$[1/u^\circ(p,T_0)](\partial u^\circ/\partial T_0)_p = 1/(T_s - T_0),\ T_0 = T_0^* \tag{6}$$

The value of the temperature gradient at the burning surface is related to the thickness of the powder slab. This relationship can be determined from the solution of a complicated nonlinear problem of the unsteady temperature profile

Table 1 Numerical values

α	$= 4\cdot10^{-4}(°K)^{-1}$
β	$= 14\cdot10^{-4}(°K)^{-1}$
u_1	$= 2\cdot07\cdot10^{-2}$ cm/sec·atm$^{2/3}$
ν	$= 2/3$
T_0	$= 300°K$
k	$= 0\cdot8\cdot10^{-3}$ cm²/sec
T_s	$= 600°K$

in a powder specimen with a moving boundary (combustion front).

As the first approximation, we suppose that the temperature profile under the extinction is a linear one

$$\zeta^* = (T_s - T_c)/h \tag{7}$$

where T_c is temperature at the powder-metal contact and h is the powder layer thickness at the moment of extinction.

The thermal conductivity and the mass of the metal plate are very great. Therefore, we can assume that the temperature of a powder-metal contact is constant.

One can calculate the value of the unburned powder slab thickness, h, from Eqs. (5) and (7) if one knows the values of k, T_s, T_c, T_0^*, and u^*. The corresponding formula is

$$h = k(T_s - T_c)/u^*(T_s - T_0^*) \tag{8}$$

The temperature of a powder-metal contact T_c equals room temperature. The values of powder thermal diffusivity and of the temperature of a burning powder surface can be taken from Refs. 8 and 9.

Utilizing the solution of Eq. (6) in Eqs. (3) and (8) and substituting corresponding numerical values from Table 1, one finds the relationship between the thickness of unburned powder and pressure. This relationship has the form

$$\ln h = -3.95 - \nu \ln p \tag{9}$$

The theoretical line (9) is represented by a dotted line in Fig. 1. As the figure shows, the agreement between the theoretical result and the experimental one is good.

For a more rigorous comparison of theory and experiment, the following facts must be kept in mind. 1) The metal thermal conductivity is high but finite, and during the burning the temperature of metal-powder interface does not remain constant. 2) The burning surface temperature depends on pressure. 3) The empirical relation between the steady burning rate and pressure and initial temperature in the form (3) is approximate, and the extinction criterion (5) is not quite accurate.

The method presented can be used also to obtain reliable experimental data on the dependence of the unburned layer powder thickness on initial temperature.

It should be noted that there is at present no correct nonsteady combustion theory that deals with combustion instability, ignition, and extinction.[10] The method presented can be useful in investigation of the extinction and for verification of nonsteady combustion theories.

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Effect of Eccentricity on the Attitude Stability of a Nonspinning Satellite

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RECENTLY, considerable attention has been given to the study of the attitude of a rigid body carrying a rotor that can rotate relative to an axis fixed in the body. Of the several papers that have been published pertaining to this subject, two are of particular interest in this Note. Kane and Barba[1] studied the influence of orbit eccentricity on the attitude stability of a spinning, symmetric satellite. Their study revealed that an increase in eccentricity tended to cause existing instability regions of a nondimensional system parameter space to grow; also, new regions of instability occurred in regions where instabilities were not encountered for circular orbits. Shippy and Robe[2] studied the influence of a spherical rotor on the attitude stability of a nonspinning, symmetric satellite in a circular orbit. The spin axis of the rotor was placed perpendicular to the symmetry axis of the satellite and the symmetry axis was perpendicular to the orbit plane for the reference motion. Their study revealed that the inclusion of a laterally oriented rotor, spinning at a constant rate s, acts either as a stabilizer or destabilizer depending on the point in the system parameter space.

The purpose of this Note is to present a generalized study of the work by Shippy and Robe by including the effect of orbit eccentricity, ϵ. By utilizing the usual assumption of independence of mass center motion to attitude motion, the nondimensionalized orbit equations for the satellite-rotor mass center are[1]

$$\begin{gathered} \zeta'' + \zeta^{-3}(\epsilon^2 - 1) + \zeta^{-2} = 0 \\ \theta' = (1 - \epsilon^2)^{1/2}\zeta^{-2} \end{gathered} \tag{1}$$

The prime denotes differentiation with respect to the scaled time, $\tau = nt$, and $\zeta = r/a$ is a nondimensional radial position. The "mean motion," n, is defined in terms of the period T as $n = 2\pi/T$; a is the semimajor axis of the orbit; and θ is the orbit angle from the perigee. By utilizing the attitude angles $(\theta_1,\theta_2,\theta_3)$ relative to a rotating orbit triad,[2] the absolute

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