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O. I. Leipunskii, V. I. Kolesnikov-Svinarev, V. N. Marshakov

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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

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Nonstationary Burning Rate of Propellant

(Presented by Academician Ya. B. Zel' dovich on 29 VII 1963)

The purpose of the present work is to detect and measure the nonstationary burning rate of propellant.

The occurrence of a nonstationary burning rate was predicted theoretically in a paper by Ya. B. Zel' dovich devoted to the theory of combustion of smokeless propellant ⁽¹⁾. According to this theory, a nonstationary burning rate should arise in cases of sufficiently rapid changes in the heat flux going to the surface of the propellant from the gas phase, and for a time commensurate with the time of rearrangement of the heated layers at the surface of the propellant. Nonstationary burning rates greater or less than the stationary burning rate depend on whether the heat flux going to the propellant surface from the zone of chemical reaction in the gas phase, which determines the burning rate, respectively increases or decreases. For example, if the pressure is instantaneously increased from p to p_1 , then the nonstationary burning rate at pressure p_1 , $u_n(p_1)$, will be greater than $u_s(p_1)$ —the stationary burning rate at p_1 (Fig. 1a).

Fig. 1

If the pressure is rapidly lowered from p to p_1 , then $u_s(p_1) < u_n(p_1)$ (Fig. 1b). According to Ya. B. Zel' dovich, this should occur because the temperature at the propellant surface T_p (more precisely, in the thin reaction layer near the propellant surface), which determines the rate of decomposition of the propellant mass, is determined by the temperature gradient near the propellant surface in the condensed phase and by the pressure.

When the pressure is increased from p to p_1 , the temperature distribution of the burning propellant should change from Fig. 2,1 to Fig. 2,2. The rearrangement of the temperature distribution in the gas phase occurs faster than in the propellant, in accordance with the values of the thermal diffusivity of the gas and of the propellant. Therefore, with a rapid increase in pressure, the temperature distribution shown in Fig. 2,3 is initially realized; that is, in the gas phase there will already be the temperature distribution (Fig. 2,2) corresponding to the

Fig. 2

Figure 2: Fig. 2

new pressure p_1 , while in the solid phase the temperature distribution (Fig. 2,1) corresponding to the previous pressure p will still remain. From a comparison of Fig. 2,3 with Fig. 2,2 it follows that in the case of Fig. 2,3 the heat removal from the surface into the interior of the propellant is smaller than in the case of Fig. 2,2 (because the temperature gradient is smaller), while the heat supply is the same as in the case of Fig. 2,2. Therefore the propellant surface will heat up, and its temperature will rise somewhat in comparison with Fig. 2,2. The temperature in the gas phase will also rise somewhat, since the temperature distribution in Fig. 2,3 means that combustion of a propellant having a higher temperature than in the case of Fig. 2,2 is taking place.

The increase in the temperature of the propellant surface and of the gas phase leads to the burning rate in the case of Fig. 2,3 being greater than in the stationary case of Fig. 2,2. Over a time commensurate with the relaxation time of the thermal layer at the propellant surface, the distribution of Fig. 2,3 will pass into the distribution of Fig. 2,2, and the value of u_n will approach u_s , as shown in Fig. 1a.

With a decrease in pressure, analogous reasoning leads to the conclusion that the nonstationary burning rate will be less than the stationary one (Fig. 3 and Fig. 1b). With a sufficiently strong decrease in pressure, the powder may go out, i.e. $u_n = 0$.

It follows from what has been said that the nonstationary burning rate at a given pressure does not, however, have a definite value, but depends on the prehistory of the burning powder. Ya. B. Zel' dovich applied the theory of the nonstationary burning rate to explain the well-known phenomenon of powder extinction under a rapid fall of pressure. Apart from this case, when $u_n = 0$, the nonstationary burning rate has not been detected or measured. However, powder extinction under falling pressure has been little studied.

Fig. 2. Temperature distribution in the front: 1 –for $u_c(p)$, 2 –for $u_c(p_1)$, 3 –for $u_n(p_1)$

The following describes a method developed by us for detecting and measuring the nonstationary burning rate in the regime of increasing pressure, and the measurement results.

To characterize the burning rate of the powder and its changes, we used the pressure p and the rate of pressure rise dp/dt in a semi-closed volume V , in which powder with surface area S burned with an opening in the semi-closed volume of area σ . The change of pressure in the chamber is expressed by a formula describing conservation of matter

Fig. 3

Figure 3: Fig. 3

$$\frac{f}{V} \frac{dp}{dt} = u_n \rho S - A p \sigma \quad (1)$$

(ρ is the density of the powder, f is the force of the powder, A is the coefficient of outflow of the powder gases).

Hence

$$u_n = \frac{f}{V \rho S} \frac{dp}{dt} + \frac{A p \sigma}{\rho S}. \quad (2)$$

Fig. 3. Temperature distribution in the burning front: 1 –for $u_c(p)$, 2 –for $u_c(p_1)$, 3 –for $u_n(p_1)$

The stationary burning rate $u(p)$ is obtained, for prolonged burning, by setting (1) equal to zero (for $dp/dt = 0$),

$$u_c = \frac{A p_c \sigma}{\rho S}. \quad (2')$$

Comparison of (2) and (2') (of course, for $p = p_c$) gives

$$u_n - u_c = \frac{f}{V \rho S} \frac{dp}{dt}. \quad (3)$$

By measuring dp/dt , one can, in accordance with (2) or (3), determine u_n . Nonstationary burning was produced by a sharp increase of pressure in a semi-closed volume. The powder was ignited by an igniter (the burning time of the igniter was about 1 sec.) and then for a long time (about 3 sec.) burned in the semi-closed volume at a pressure close to atmospheric; in this process, near the surface of the powder, the temperature distribution of Fig. 2,1 was created. Then the volume was closed by a blow-out diaphragm, the pressure rose rapidly, and then the blow-out diaphragm opened a nozzle calculated so that the stationary pressure would be equal to ~ 100 or ~ 200 atm. The opening of the nozzle occurred when the pressure was 20–40 atm. less than the expected stationary pressure. In this case the temperature distribution

at the surface of the powder corresponded to Figs. 2, 3. The pressure in the semi-closed volume increased and, owing to the nonstationary burning rate, a pressure of ~ 120 or ~ 240 atm., respectively, was reached, which then decreased to the stationary pressure ~ 100 or ~ 200 atm.; i.e., a pressure peak was observed corresponding to the excess of the nonstationary burning rate over the

Fig. 4

Figure 4: Fig. 4

stationary one. The use of a blow-out diaphragm is essential, since it reduces the expenditure of powder in the heated layer for filling the chamber volume, as compared with the case when the nozzle is open all the time. Previous failures in detecting the nonstationary burning rate are explained by the large consumption of mass from the heated layer for filling the chamber volume with an open nozzle.

Fig. 4

Figure 4a shows the pressure–time curve obtained in the experiment (experiment 124), and 4b the theoretical curve. In the calculation it was assumed that the temperature distribution created at atmospheric pressure does not change during the existence of the pressure peak, and that the coefficient of variation of the burning rate with temperature does not depend on the temperature of the powder. 4c is the pressure–time curve in the calculation when the nonstationary rate is all the time close to the stationary burning rate. For this, ignition was carried out under conditions of a very rapid rise of pressure.

Control experiments showed that the pressure peak is not associated with a hypothetical explosive transition of the gases, containing much NO and accumulated in the volume during burning at low pressure, into gases corresponding to complete release of the heat of reaction. The pressure peak could also not be associated with simultaneous burning of the igniter, since the igniter burned out in less than 1 sec., while the blow-out diaphragm closed the chamber volume 2–3 sec. after the igniter had burned out. The pressure peak could also not be associated with erosive burning, since the gas velocity was small and the pressure records of Fig. 4c show the absence of erosive burning. This peak cannot also be associated with a higher temperature and, consequently, a smaller outflow coefficient of the gas filling the chamber with the membrane closed, i.e., under conditions of a closed volume, when the temperature in terms of c_p/c_V is higher than with outflow through an open nozzle. To prove that the pressure peak is not associated with the elevated gas temperature before the start of outflow, control experiments were performed in which the powder in the chamber was rapidly ignited by pyroxyline cotton: after the membrane was blown out, no pressure peak appeared.

The totality of the control experiments showed that the pressure peak is associated with the preliminary formation of a thick heated layer during burning at atmospheric pressure. It is evident from Fig. 4 that the experiments reveal the presence of a nonstationary burning rate in the regime of increasing pressure. The pressure at the peak is found to be half as large as in the above-mentioned calculation; the duration of the peak in some experiments is found to be greater than according to the calculation. These quantitative deviations are presum-

ably associated with incomplete coverage of the powder surface by burning at atmospheric pressure (when burning proceeds in an intermittent regime).

For the experiment under consideration $u_n/u_c = 1.23$.

Institute of Chemical Physics
Academy of Sciences of the USSR

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