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Abstract

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MEASUREMENT OF THE TEMPERATURE OF THE DETONATION FRONT OF EXPLOSIVES

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Calculation of the parameters of a detonation wave shows that the detonation temperature is the quantity most sensitive to the form of the equation of state of the explosion products, and knowledge of it is necessary in checking the latter. However, up to the present time few works have been published on the experimental determination of the detonation temperature. We undertook an attempt to measure the temperature of the detonation front from the end face in transparent and semitransparent charges of liquid and solid explosives by an electron-optical method.

Measurement of the detonation temperature in transparent liquid explosives

The glow of the detonation front in a charge of a liquid explosive placed in a Plexiglas cup with a transparent bottom was recorded from the end surface with the aid of an FEU-29 M photomultiplier, the current of which was recorded on an OK-17 M single-sweep oscillograph. In studying the glow of detonation fronts in nitromethane and methyl nitrate it was found that they have spectra (in the region 400-600 mμ) similar to the spectra of black bodies with temperatures of 3700 and 4500° K, respectively, and equal emission coefficients. The latter permits one to assume that the detonation front glows as a black or gray body and that therefore the temperature can be measured by a color method, consisting in comparison of the brightnesses of the glow in two regions of the spectrum (in our case behind the CC-5 and ZS-1 light filters).

Table 1

Substance	Density (g/cm^3)	T-ra (°K)	D (m/sec)
Nitroglycerin	1.60	4000	7650
Nitroglycol	1.50	4400	7400
Methyl nitrate	1.21	4500	6750
Nitromethane	1.14	3700	6300

Substance	Density (g/cm^3)	T-ra (°K)	D (m/sec)
Tetranitromethane	1.64	3100	6400
Hexogen	1.79	3700	8800
TEN	1.77	4200	8500
Dina	1.70	3700	8000

In the experiment the ratio was measured

$$\frac{\Sigma_{\text{CC}-5}}{\Sigma_{\text{ZS}-1}} = \int_{\lambda_1}^{\lambda_2} S_\lambda b_\lambda \cdot \tau_{\text{CC}-5}\, d\lambda \Big/ \int_{\lambda_1}^{\lambda_2} S_\lambda b_\lambda \cdot \tau_{\text{ZS}-1}\, d\lambda,$$

where S_λ is the spectral sensitivity of the photomultiplier, b_λ is the spectral brightness of the source, $\tau_{\text{CC}-5}$, $\tau_{\text{ZS}-1}$ are the transmission coefficients of the light filters, λ_1, λ_2 are the limits of the spectral sensitivity of the photomultiplier, and the temperature was found from a calibration graph of the ratio $\frac{\Sigma_{\text{CC}-5}}{\Sigma_{\text{ZS}-1}}$ to the reciprocal of the source temperature, constructed by calculation

for an absolutely black body. The spectral sensitivity of the photomultiplier and the transmission coefficient of the optical system were measured beforehand using a standard light source.

The maximum error in measuring the ratio $\frac{\Sigma_{\text{CC}-5}}{\Sigma_{\text{ZS}-1}}$ at the detonation front of transparent liquid explosives was 3%, which corresponds to an error in the temperature measurement of no more than 150° K. Table 1 gives the color temperatures of the detonation front T obtained by us, the initial density ρ_0, and also the detonation velocities for a number of liquid and solid explosives. The detonation velocities D were determined with an accuracy of up to 100 m/sec, either by the electrical-contact method or by the optical method. The accuracy of measuring the detonation temperature for solid explosives was 300° K.

Measurement of the detonation temperature in semitransparent charges of solid explosives

Just as the temperatures of the detonation front were measured in transparent charges of liquid explosives, it is possible to measure temperatures in semitransparent charges of solid explosives with a density close to that of a single crystal. As in the first case, the glow is recorded at the exit of the detonation wave onto the end face of the charge, which makes it unnecessary to measure the absorption of light in the charge. However, the lower transparency of the charge and the bright glow of the air shock wave during the expansion of the explosion products from the end face make it difficult to determine accurately the moment at which the wave emerges. To cut off the glow of the air shock wave, the end face of the charge was placed in water. In the experiments, special attention was paid to the absence of cracks in the charge and of air adhering to the end surface of the charge.

When comparing the brightnesses of the glow of the detonation fronts of the explosives studied in the spectral region 400–600 mμ, it turned out that their ratio is the same as it should be for absolutely black bodies at these temperatures (this corresponds to one and the same emissivity coefficient of the detonation front). This makes it possible, when measuring the temperature by the color method, to check it at all times by comparing the brightness of the detonation glow of the explosive under study with the brightness of the glow of some previously studied explosive (in effect, the brightness method of temperature measurement). Since the emissivity coefficient of the detonation front does not change from substance to substance, while the temperature changes from 3500 to 5000° K, it may be assumed that it is close to unity.

Discussion of the results

Among earlier published works on the experimental determination of detonation temperatures, one should mention the work of Alentsev, Belyaev, and others (^{1}), who were the first to measure the detonation temperature of liquid explosives, as well as the later work of Gibson and others (^{2}), who used a light guide, a weakly luminous filling, and an electron-optical method for measuring detonation temperatures. The detonation temperatures of nitromethane and nitroglycerin obtained by us agree with the results of (^{2}), whereas the temperatures of hexogen and tetryl differ.

The measured detonation temperatures are too high to be attributed to the glow of a nonreaction shock front traveling ahead of the detonation complex. Owing to the small thickness of the reaction zone in powerful explosives, the rapid increase in the reaction rate within it, and the strong dependence of the brightness of the glow on temperature, it may be assumed that these temperatures are very close to those that will be in the Chapman—Jouguet plane.

Using the temperatures obtained, as well as the experimental values of the pressure (^{3}) during detonation of tetryl ($\rho_0 = 1.77$ g/cm^3, $p = 340 \cdot 10^3$ atm), hexogen ($\rho_0 = 1.79$ g/cm^3, $p = 390 \cdot 10^3$ atm), nitroglycerin ($\rho_0 = 1.60$ g/cm^3, $p = 250 \cdot 10^3$ atm), and nitromethane ($\rho_0 = 1.14$ g/cm^3, $p = 133 \cdot 10^3$ atm), it is possible to test different types of equations of state for the explosion products. The data presented do not confirm the values calculated in works ($^{4-7}$).

Recently, in the works of Cook (^{4,8}), the equation of state

$$pv = nRT + p \cdot \alpha(v),$$

has been widely used, where n is the number of moles per 1 g of products, R is the gas constant, and v is the specific volume of the products in the C—J plane. With this form of the equation of state, proceeding from our data on pressure and temperature, one could propose the expression for the covolume

$\alpha(v) = v(1.08 - 0.40v)$, which, however, does not coincide with the numerical values given in (^{8}). For the covolume equation of state, the energy conservation equation

$$E - E_0 = Q + \frac{1}{2}p(v_0 - v),$$

is not satisfied, where Q is the heat of explosion taken from (^{8}). In the last equation the internal energy is

$$E = \int^T c_v \, dT,$$

where c_v was calculated for the ideal-gas state of the explosion products (since

$$\left(\frac{\partial c_v}{\partial v}\right)_T = T\left(\frac{\partial^2 p}{\partial T^2}\right)_v = 0$$

).

This indicates that the covolume equation

$$pv = nRT + p \cdot \alpha(v)$$

is not a satisfactory equation of state for the explosion products (especially at large p) and can be regarded only as a certain approximation convenient for calculating p, v, or T, when two of these quantities are known. It is quite probable that the very derivation of a covolume equation of state for explosion products on the basis of data for nitromethane, nitroglycerin, hexogen, and TEN became possible because of their similar detonation temperatures.

If, following Landau and Stanyukovich (^{9}), one introduces into the energy and pressure equations terms that take into account the mutual repulsion of molecules at high pressures, and writes

$$E = \int^T c_v \, dT + E_{\text{rep}} \quad \text{and} \quad p = \frac{nRT}{v} + p_{\text{rep}},$$

then the values E_{rep} for nitromethane, nitroglycerin, and hexogen ($\rho_0 = 1.80$ g/cm^3) will be approximately 4, 37, and 50% of E, respectively, assuming that the remainder is equal to the internal energy of the products in the ideal-gas state. At the same time,

$$\frac{nRT}{v}$$

changes little and is equal, for nitromethane, to $23 \cdot 10^3$ atm, for nitroglycerin to $24 \cdot 10^3$ atm, and for hexogen to $28 \cdot 10^3$ atm, which amounts to approximately 17.3, 9.2, and 7.2% of the pressure p. The results obtained indicate the importance of experimental determination of temperature for deriving and verifying the equation of state of explosion products and the expression for internal energy, without which it is difficult to calculate the parameters of the detonation wave.

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Note: Figure translations are in progress. See original paper for figures.