MEASUREMENT OF THE TEMPERATURE
OF THE DETONATION FRONT
OF EXPLOSIVE SUBSTANCES

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- USSR -

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MEASUREMENT OF THE TEMPERATURE OF THE DETONATION FRONT
OF EXPLOSIVE SUBSTANCES

[Following is the translation of an article by I. M. Voskoboinikov and A. Ya. Apin entitled "Izmerenie temperatury detonatsionnogo fronta vzryvchatykh veshchestv" (English version above) in Doklady Akademii Nauk USSR, Vol. 130, No. 4, 1960, Moscow, pages 804-806.]

Calculation of the parameters of the detonation wave shows that the detonation temperature is the value most sensitive to the form of equation of state of explosion products, and knowledge of it is necessary in the verification of the latter. Up to the present time, however, little work has been published on experimental determination of the detonation temperature. We undertook measuring the temperature of the detonation front from the front in transparent and semi-transparent charges of liquid and solid explosive substances by the electronic-optical method.

Measurement of the detonation temperature in transparent liquid explosive substances

The luminescence of the detonation front in a charge of liquid explosive substance placed in a Plexiglas flask with a transparent bottom was recorded from the frontal surface by means of a FEU-29 M photomultiplier whose cur-
rent was registered on an oscillograph with a single OK-17 M scanner. In the investigation of luminescence of detonation fronts in nitromethane and methyl nitrate it was found that they have spectra (in the region of 400-600 m\(\mu\)) similar to the spectra of black bodies with a temperature of 3700 and 4500\(^\circ\) K respectively and equal emission coefficients. The latter permits us to suppose that the detonation front shines like a black or gray body and that it is possible therefore to measure the temperatures by a chromatic method consisting of comparison of the brightness of the luminescence in the two sections of the spectrum (in our case behind light-filters SS-5 and ZS-1).

In the experiment measurement was made of the relationship

\[ \frac{\Sigma_{SS-5}}{\Sigma_{ZS-1}} = \int_{\lambda_1}^{\lambda_2} S_{\lambda} b_{\lambda} \tau_{CC-5} d\lambda \left/ \int_{\lambda_1}^{\lambda_2} S_{\lambda} b_{\lambda} \tau_{ZS-1} d\lambda \right. \]

where \(S_{\lambda}\) is the spectral sensitivity of the photomultiplier, \(b_{\lambda}\) the spectral brightness of the source, \(\tau_{SS-5}\) and \(\tau_{ZS-1}\) the emission coefficients of the light-filters, \(\lambda_1\) and \(\lambda_2\) the limits of spectral sensitivity of the photomultiplier, and the temperature was found according to a graduated graph of the relationship of \(\Sigma_{SS-5}\) to \(\Sigma_{ZS-1}\) the reciprocal of the temperature of the source, constructed by calculation for an absolutely black body. With the aid of a standard source of light a preliminary calculation was made of the spectral sensitivity of the photomultiplier and the emission coeficient of the optical system.

The maximum error in measurement of the relationship \(\frac{\Sigma_{SS-5}}{\Sigma_{ZS-1}}\) of the detonation front of transparent liquid explosive substances amounted to 3\%, which represents an error in measurement of temperature not greater than 150\(^\circ\) K. Table 1 shows us for the detonation front, the initial density \(\rho_0\) and the rates of detonation for a number of liquid and solid explosive substances. The rates of
detonation D were determined with an accuracy of up to 100 m/sec either by the electrical contact or by the optical method. The accuracy of measurement of the detonation temperature for solid explosive substances is 300° K.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Density (g/cc)</th>
<th>Temp. (°K)</th>
<th>D (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitroglycerin</td>
<td>1.60</td>
<td>4300</td>
<td>7650</td>
</tr>
<tr>
<td>Nitroglycol</td>
<td>1.50</td>
<td>4400</td>
<td>7400</td>
</tr>
<tr>
<td>Methyl nitrate</td>
<td>1.21</td>
<td>4500</td>
<td>6750</td>
</tr>
<tr>
<td>Nitromethane</td>
<td>1.14</td>
<td>3700</td>
<td>6300</td>
</tr>
<tr>
<td>Tetranitromethane</td>
<td>1.54</td>
<td>3100</td>
<td>5400</td>
</tr>
<tr>
<td>Hexogen</td>
<td>1.79</td>
<td>3700</td>
<td>8800</td>
</tr>
<tr>
<td>TEN</td>
<td>1.77</td>
<td>4200</td>
<td>8500</td>
</tr>
<tr>
<td>DINA</td>
<td>1.70</td>
<td>3700</td>
<td>8000</td>
</tr>
</tbody>
</table>

Measurement of the detonation temperature in semi-transparent charges of solid explosive substances

In the same way as measurements were made of the detonation front in transparent charges of liquid explosive substances it is possible to measure temperatures in semi-transparent charges of solid substances with a density near a monocrystal. As in the first case, the luminescence is recorded upon the emergence of the detonation wave on the face of the charge, which does not permit making a measurement of the absorption of light in the charge. But the slight transparence of the charge and the bright luminescence of the shock wave of the air during the dispersion of explosion products from the face makes it difficult to determine the moment of emergence of the wave exactly. The face of the charge is placed in water in order to intercept the luminescence of the air shock wave. Special attention was given in the experiments to the absence of fissures in the charge and the adhesion of air to the facial surface of the charge.

In comparison of the brightness of the luminescence or detonation fronts to investigations of explosive substances in the area of the spectrum of 400-600 μμ it was found that their relationship is the same as it must be for absolutely black bodies at these temperatures (this
corresponds to one and the same emission coefficient of the detonation front. This enables us, in measuring temperatures by the chromatic method, to check it all the time by comparing the brightness of luminescence of the detonation of the explosive substance being investigated with the brightness of luminescence of any explosive substance studied previously (practically a brightness method of measuring temperatures). Since the emission coefficient of the detonation front does not change from substance to substance, and the temperature changes from 3500 to 5000° K, it can be assumed that it is near unity.

Discussion of the results

Of previously published work on the experimental determination of detonation temperatures, reference should be made to that of Alentsev, Belyaev et al. [1], who first measured the detonation temperatures of liquid explosive substances, and to the more recent work of Gibson et al. [2], who used light conductors, weakly shining changing and the electro-optical method to measure detonation temperatures. The detonation temperatures of nitromethane and nitroglycerin obtained by us agree with the results in [2] and the temperatures of hexogen and TEN differ.

The measured detonation temperatures are too large to be attributed to luminescence of non-reactive shock front preceding the detonation complex. Because of the small depth of the reaction zone in powerful explosive substances with rapid growth of the reaction rates in it, and the strong dependence of brightness of the luminescence on temperature, it can be assumed that these temperatures are very near those which will be in a Chapman-Jouguet plane.

By using the temperatures obtained, and likewise the experimental values of the pressure [3] during detonation of TEN (\(\rho_0 = 1.77\) g/cc, \(p = 340.10^3\) atm), hexogen (\(\rho_0 = 1.79\) g/cc, \(p = 390.10^3\) atm), nitroglycerin (\(\rho_0 = 1.60\) g/cc, \(p = 250.10^3\) atm) and nitromethane (\(\rho_0 = 1.14\) g/cc, \(p = 133.10^3\) atm) it is possible to check the different types of equations of state of the explosion products. The data given do not confirm the values calculated in papers [4-7].
Recently in Cook's work [4, 8] there is extensive use of the equation of state \( pv = nRT + p_a(v) \), where \( n \) is the number of moles per gram of products, \( R \) is the gas constant, \( v \) is the specific volume of the products in the Chapman-Jugle plane. With this form of the equation of state, proceeding from our data for pressure and temperature, it would be possible to assume an expression for the co-volume \( a(v) = v(1.08-0.40v) \), which, it is true, does not agree with the numerical values given in [8]. With a co-voluminous equation of state the equation of the conservation of energy is not satisfied: 
\[
E = E_0 + Q + \frac{1}{2} p(v_0 - v),
\]
where \( Q \) is the heat of explosion taken from [8]. In the latter equation the internal energy is 
\[
E = \int_c v dT,
\]
where \( c_v \) was calculated for an ideal gaseous state of the explosion products [since \( \frac{\partial}{\partial v}(c_v) \frac{1}{T} = T \left( \frac{\partial^2 p}{\partial T^2} \right) = 0 \)].

This indicates that the co-voluminous equation \( pv = nRT + p_a(v) \) is not a satisfactory equation of state for the explosion products (especially at large \( p \)) and can be considered only as somewhat of an approximation suitable for calculating \( p, v \) or \( T \) when two of these values are known. It is entirely probable that obtaining the co-voluminous equation of state for the explosion products on the basis of the data for nitromethane, nitroglycerin, hexogen and TEN became possible as a result of these close detonation temperatures.

If, following Landau and Stranyukovich [9], terms are introduced into the energy and pressure equations which take into consideration the mutual repulsion of the molecules at high pressures, and we write 
\[
E = T \int c_v dT + E_{simp} \quad \text{and} \quad p = \frac{nRT}{v} + p_{simp},
\]
then the values of \( E_{simp} \) for nitromethane, nitroglycerin and hexogen \( p_e = 1.80 \text{ g/cc} \) will be 4, 37 and 50% respectively of \( E \). At the same time \( nRT \) changes little and for nitromethane is 23.103 atm, nitroglycerin 24.103 atm and hexogen 28.103 atm, which averages 17.3, 9.2 and 7.2% of the values of pressure \( p \). The results obtained indicate the importance of experimental determination of temperature for deriving
and checking the equation of state for explosion products and the expression for the internal energy, without which it is difficult to calculate the parameters of the detonation wave.

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