TEMPERATURE MEASUREMENTS BEHIND DETONATION FRONTS IN GASES

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In [1] the spectrum line reversal method was used to measure the gas temperature behind a detonation front in acetylene-oxygen mixtures. The details of the wave front structure were not considered in these experiments, but it was noted that a brightness jump exists near the front. This was first ascribed to nonequilibrium emission in the reaction zone. It was also discovered [2, 3] that the oscillograms reveal an initial burst of luminescence, which was ascribed to chemiluminescence or to other nonequilibrium processes in the front. Comparing the length of this burst in acetylene-oxygen mixtures ($\Delta t > 10^{-6}$ sec) with data on the ignition lag in these mixtures [4, 5], it may be concluded that the induction period is shorter by at least a factor of 10 than the duration of the luminescence jump (for example, $\tau \sim 10^{-7}$ sec at T = 2200°–2500° K and $p \approx 2$ atm). Hence the interpretation of the above effect from the standpoint of the kinetic data is inadequate. It is well known that a one-dimensional reaction zone is not usually obtained in a detonation in a gas. Therefore it is desirable to compare the luminescence data with simultaneously recorded pressure data in order to clarify the effect of hydrodynamic factors on the luminescence and temperature distributions behind the front.

1. Temperature measurements and estimation of accuracy. The temperature was measured and the luminescence recorded by photometric scanning of two spectral lines of hydrogen (H_β and H_γ) generated by a ISP-51 spectrograph with a resolution of $\Delta\lambda \approx 2$ Å in the center of the line. This method has many advantages in comparison with the spectrum-line reversal method, namely: a) it eliminates errors introduced by measuring the light temperature of the comparison source, particularly at temperatures $T \gtrsim 4000°$ K, when a pulsed comparison source is used [1]; b) hydrogen atoms are present in the majority of chemical reactions in gases that are of practical interest; c) the relaxation time of atomic hydrogen are small, which suggests the possibility of inertialess recording of the variation of the thermal state of the medium with time, and finally, d) the transition probabilities for the Balmer hydrogen series can be calculated with sufficient accuracy [6].

The main source of limitations of the method is assumed to be the effect of line self-reversal, which is difficult to estimate beforehand. It will be seen from the subsequent discussion that in these experiments the above limitations did not result in perceptible errors. The measurement errors can be estimated as follows. The gas temperature is calculated from

$$T = \frac{E_2 - E_1}{2{,}3k}\left(\lg\frac{I_1}{I_2} - \lg\frac{\lambda_2}{\lambda_1}\frac{g_1}{g_2}\frac{A_1}{A_2}\right)^{-1}.$$

Here E_i [eV] is the energy of the upper level, I_i is the line intensity determined from the light flux (~ 2 Å), g_i is the statistical weight of the level, and A_i is the transition probability. Correspondingly,

$$\delta T = \delta x \frac{kT}{E_2 - E_1} \qquad \left(x = \frac{I_1}{I_2}, \quad \delta x = \frac{\Delta x}{x}, \quad \delta T = \frac{\Delta T}{T}\right).$$

Errors in determining x depend on the precision of calibration of the photometric system, i.e., on its linearity, on the errors in reading the spectral characteristics of the photoelectric device, on the thickness of the oscillograph beam, etc. Control tests to check the measuring apparatus give an estimate $\delta x \leq 3\%$. Consequently, $\delta T \approx 2\%$, i.e., $\Delta T \sim 80°$ for E - 0.5 eV and $T \leq 4000°$ K.

2. Gas temperature behind detonation front in acetylene-oxygen mixtures. The behavior of the temperature behind the detonation front is given by the graphs in Fig. 1. The dimensions of the plastic detonation chamber were 900 × 25 × 3 mm, the detonation was initiated by a high-voltage spark, and the detonation run is of the order of several centimeters. When the initial mixture pressures are of the order of 0.05 atm, "equilibrium" values of temperature, as well as of density and pressure (see [5]), are attained only 4–5 μsec after the front has passed, and near the front, as was pointed out above, there exists an initial burst of luminescence (and temperature). We will first consider data on the "equilibrium" temperatures. Figure 2 shows the results of temperature measurements for various mixtures as a function of the initial pressure. In Fig. 3 these data, extrapolated to $p_1 = 1$ atm, are compared with the equilibrium calculations for a Chapman-Jouget detonation in these mixtures at an initial pressure of 1 atm. It can be seen that for a gas region lagging 4–5 μsec behind the front the measured temperatures are in good agreement with the calculated values.

3. Comparison with pressure measurements. Evaluation of the emissivity of the gas. Figure 4 shows pressure and luminescence oscillograms for H_β obtained at different initial pressures in stoichiometric and equal-volume mixtures. A comparison of luminescence and pressure shows that near the front (up to 4 μsec) the elevated temperature zone (T ~ 5000° K) also corresponds to an elevated (by approximately 30%) pressure zone. It also follows from interferometer measurements [5] that the pressure maximum has a corresponding gas density maximum. Thus, the burst of luminescence (and temperature) near the detonation front can be explained from the hydrodynamic standpoint [5] in the following manner: on the basis of the properties of a multifront detonation structure in a gas, the additional compression of the combustion products can be related to the burning of part of the fresh mixture which has "erupted" through the "flanks" of the shock waves which make up the leading edge of the locally nonstationary detonation front. We emphasize that the observed zone of elevated variables behind the front has nothing in common with the so-called "chemical spike" in the front of a one-dimensional detonation wave.

Spectroscopic studies of the state of a gas behind a detonation front cannot be complete without an estimation of the emissivity of the radiating combustion products. These measurements were performed in [2] for supercompressed detonation waves. The measurement method reduces to calibration of the photometric channels with respect to the absolute magnitude of the light flux using a calibrating ribbon-filament incandescent bulb and to comparison of the light flux thus obtained with the expected amplitude of the signal for a black body. For the "equilibrium" sections of our measurements the emissivity in a stoichiometric mixture was found to be equal to $a_1 = 0.18$ and $a_2 = 0.16$ for H_β and H_γ, respectively, which is in agreement with the measurements of [2] in the region of other spectral emission lines.

In conclusion, we note that the results of the measurements described above fully confirm the feasibility of using the method of relative hydrogen line intensities for inertialess measurement temperatures of 4000°–5000° K with an accuracy within the limits of the expected scatter of apparatus (~ 2% with respect to magnitude and 0.5 μsec with respect to time). Taking into account the satisfactory reproductability of the detonation process in acetylene-oxygen mixtures, the given method can also be regarded as a "calibration" method in designing measuring apparatus (temperature and pressure) for the study of high-speed high-temperature processes in gases.

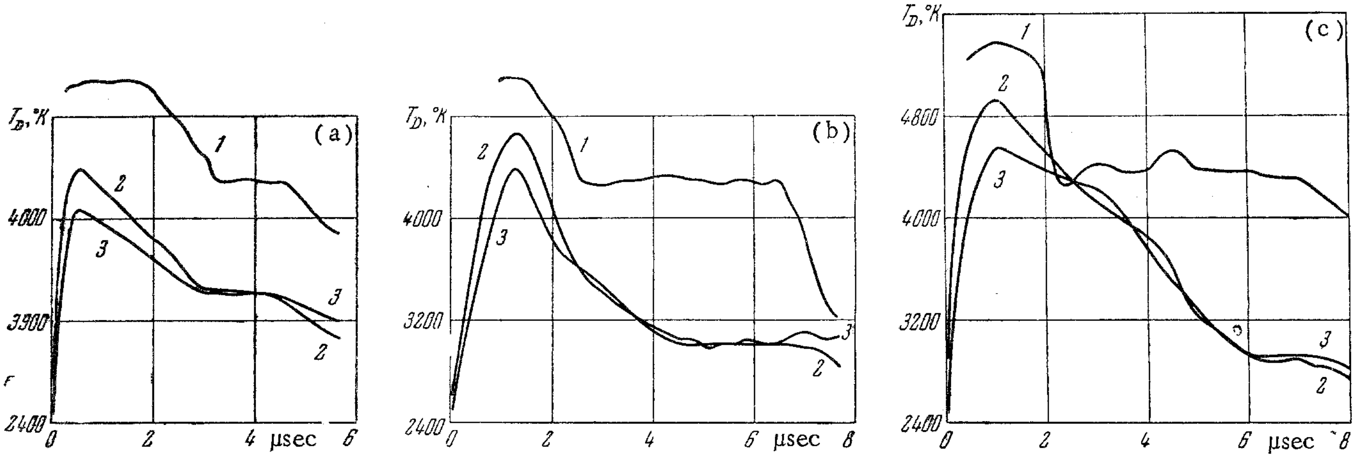

Fig. 1. Change in temperature T_D, °K; behind a detonation front in acetylene-oxygen mixtures at p_1 = 0.76 atm for: a) 30% C_2H_2; b) 40% C_2H_2; c) 50% C_2H_2. The curves are: 1) temperature; 2) luminescence of H_β; 3) luminescence of H_γ.

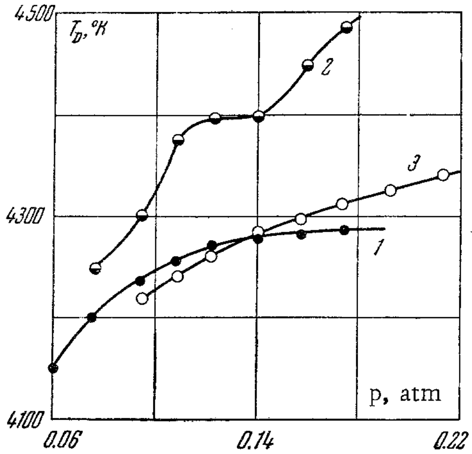

Fig. 2. Dependence of "equilibrium" temperature on initial pressure of mixture: 1) 30% H_2C_2, 2) 40% H_2C_2; 3) 50% H_2C_2.

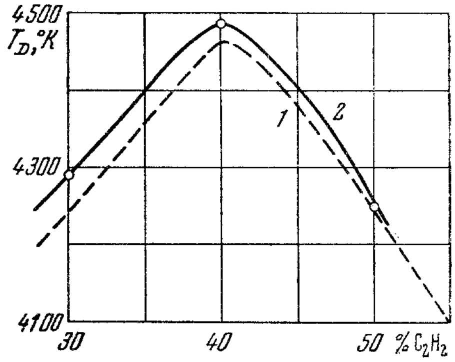

Fig. 3. Comparison of measured temperatures extrapolated to p_1 = 1 atm with calculated values: 1) Calculated; 2) experimental.

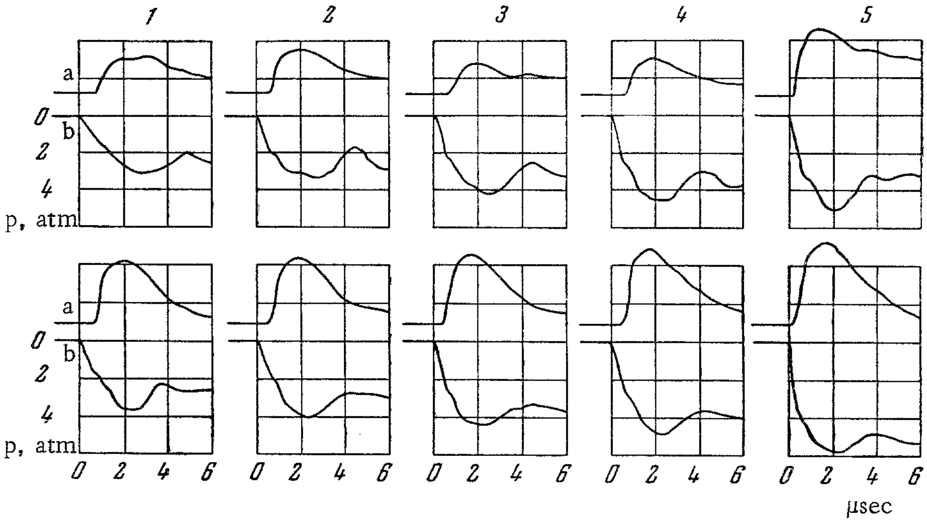

Fig. 4. Oscillograms of luminescence (a) and pressure (b) for stoichiometric (top row) and equal-volume (bottom row) mixtures: 1) p_1 = = 0.06 atm; 2) 0.076 atm; 3) 0.093; 4) 0.11; 5) 0.14.

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