ON THE LENGTH OF THE RELAXATION ZONE OF IONIZATION BEHIND THE FRONT OF A STRONG SHOCK WAVE IN AIR

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ON THE LENGTH OF THE RELAXATION ZONE OF IONIZATION BEHIND THE FRONT OF A STRONG SHOCK WAVE IN AIR

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The kinetics of the formation of air plasma in a strong shock wave has so far been considered in two limiting approximations: for shock-wave velocities $V \geq 10$ km/sec under the assumption of completed dissociation of molecules (^{1,2}), and for $V \leq 9$ km/sec under the assumption that the influence of ionization on the gas characteristics is small (^{3}). For the intermediate region $V = 9$–10 km/sec, in (^{1}) it was predicted and in (^{2}) an interesting fact was experimentally confirmed: an unusual increase in the extent of the nonequilibrium ionization zone L_e behind the wave front with increasing V. In order to clarify the cause of the observed increase in L_e, we solved numerically on a computer the problem of the structure of the relaxation zone behind the front of a strong shock wave in air.

Let us assume that for $V = 6$–10 km/sec in the gas behind the wave front there exists local equilibrium in all internal degrees of freedom (for N_2, the characteristic dissociation time is considerably greater than the time of vibrational relaxation). We shall consider simultaneously nonequilibrium processes of dissociation of O_2, N_2, NO, the chain mechanism of formation and decay of NO, ionization of O_2, N_2, NO, N, O, Ar by impact of heavy particles and electrons, associative ionization, and charge exchange (60 reactions in all). As initial expressions for the rate constants of the processes and for cross sections we take the dependences from ($^{3-6}$); some constants will then be varied. The solution of the kinetic equations for the concentrations of all components (6 neutrals, 6 ions, electrons) confirmed the presence, noted in (^{3}), of a maximum of the electron concentration $[e]_{\max}$ at $V \leq 9$ km/sec at a small distance from the front. With further increase of V ($V \geq 9.5$ km/sec) this maximum disappears, and the greatest concentration $[e]$ is observed only in the equilibrium state $[\bar{e}]$ (Fig. 1). Usually L_e conventionally corresponds to ~ 0.9–$0.95\,[e]_{\max}$; at the moment when the maximum $[e]$ disappears, the value L_e increases abruptly, since in this case $[e]_{\max} = [\bar{e}]$. The principal processes leading to a change in $[e]$ are the reactions of associative ionization

Fig. 1 and Fig. 2

Figure 1: Fig. 1 and Fig. 2

$$\mathrm{N} + \mathrm{O} \rightleftarrows \mathrm{NO}^+ + e, \tag{1}$$

$$\mathrm{N} + \mathrm{N} \rightleftarrows \mathrm{N}_2^+ + e, \tag{2}$$

whereas the role of the reaction $\mathrm{O} + \mathrm{O} \rightleftarrows \mathrm{O}_2^+ + e$ and of ionization by electron impact at $V \leq 10$ km/sec is insignificant. The solution makes it possible to draw the following picture of the ionization process in dissociating air at $V = 6$–10 km/sec.

At first, behind the wave front, as a result of the vigorous dissociation of O_2 and the beginning of the decay of N_2, the rate of electron formation $\dot{S}_e$ rapidly increases. At the same time, intensive charge exchange reduces the number of NO^+ and N_2^+ ions and retards the development of the reverse processes (1), (2). Further, charge exchange leads to the establishment of local equilibrium among all ions in the mixture, while the number of O atoms after the rapid complete dissociation of O_2 becomes practically unchanged. The fall of the temperature T in the nonequilibrium zone is accompanied by a noticeable decrease in the rate constants K_1, K_2 of reactions (1), (2) (K_2—by a factor of 10 in going from 17,000 to 12,000° K); this leads to a considerable decrease in $\dot{S}_e$. If, in addition, dissociation

of nitrogen is still continuing and the temperature is falling, a maximum of $[e]$ is formed. Thus, the main cause of the formation of the maximum of $[e]$ is the considerable rate of associative ionization (1), (2) in comparison with the rate of dissociation of nitrogen.

At $V = 9$–10 km/sec nitrogen at equilibrium dissociates practically completely, while ionization still makes no substantial contribution to the enthalpy;

Fig. 1. Character of the distribution of $[e]$ behind the wave front at velocities 9 km/sec (1), 10 km/sec (2), and 10 km/sec (3) corresponding to the equilibrium level of $[e]$. Dashed line—corresponding

Fig. 2. Length of the nonequilibrium ionization zone as a function of shock-wave velocity at $p_0 = 1$ mm Hg. Vertical hatching—experiments (3), horizontal —(2); line 1—calculation (1) (solid and dashed lines—two variants of the calculation)

therefore, as V increases in this region, the equilibrium temperature $\bar{T}$ increases considerably, which leads to a large increase of $\overline{[e]}$. At $V \geq 9.5$ km/sec the processes (1), (2) do not have time to bring about the formation of $[e] \sim \overline{[e]}$ near the front; in this case, after the slowing down of processes (1), (2) owing to the fall in temperature, there is a slow approach to $\overline{[e]}$, and the maximum of $[e]$ is absent. A decrease in the constants K_1, K_2 leads to a shift of the region of disappearance of the maximum of $[e]$ toward smaller V. Dividing the zone of establishment of equilibrium ionization into sections corresponding to the induction period Δ_i, the period of intensive growth $\Delta_p = [e]_{\max}/(S_e)_{\max}$, and the equalization period Δ_v (Fig. 1), we find that Δ_p undergoes no sharp jump, increasing only somewhat at $V = 10$ km/sec because of the considerable growth of $[e]$; the length Δ_i, decreasing monotonically, at $V \geq$ 7–8 km/sec becomes comparable with the thickness of the wave front. At $V \sim 9.5$ km/sec the length L_e changes from $L_e \sim \Delta_i + \Delta_p$ to $L_e \sim \Delta_i + \Delta_p + \Delta_v$. Decreasing the rate constant of N_2 dissociation by a factor of 20 increases Δ_p by approximately one and a half times (Fig. 2). In the nonequilibrium flow region behind the front, a considerable maximum is observed in the concentration of molecular ions formed as a result of associative ionization and charge exchange. This may serve as an explanation of the radiation peak of air behind the shock-wave front observed in experiments[7].

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