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

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SUMMARY

The structure of the relaxation zone behind a shock wave front in the air is studied by computer so as to ascertain the reasons of the increase of the zone of nonequilibrium ionization. It is found that a substantial maximum is observed in the concentration of molecular ions forming as a result of associative ionization and charge-exchange.

* * *

The kinetics of aerial plasma formation in the strong shock wave was considered up to the present time in two extreme approximations: for shock wave velocities $V \geqslant 10$ km/sec in the assumption of ended molecule dissociation [1, 2] and for $V < 9$ km/sec in the assumption of smallness of influence of ionization on gas characteristics [3]. It was forecast in [1] and experimentally confirmed in [2] that, as V increases, there is an unusual increase in the extension of the zone of nonequilibrium ionization L_e behind the shock wave front, fact, which is itself of considerable interest. With the view of ascertaining the cause of such a revealed increase L_e, we undertook to resolve numerically by means of a computer the problem of the structure of the relaxation zone behind a strong shock wave front in the air.

Assume that at V = 6 - 10 km/sec there exists in the gas behind the wave front a local equilibrium by all inner degrees of freedom (for N_2 the characteristic dissipation time is significantly greater than the time of oscillatory relaxation). Let us consider simultaneously the nonequilibrium dissociation processes of O_2, N_2, NO, the chain formation and decay mechanism of NO, the ionization of O_2, N_2, NO, N, O, Ar at heavy particle and electron impact, the associative ionization and charge-exchange (60 reactions in all). We shall use for initial expressions for constants of velocity processes and cross-sections the dependences of [3 - 6]; we shall then vary some of the constants. The solution of kinetic equations for concentrations of all components (6 neutral, 6 ions, electrons) have confirmed the presence of electron concentration maximum $[e]_{max}$ for $V \leqslant 9$ km/sec at small distance from the front, noted in [3]. With further increase of V, ($V \geqslant 9$ km/sec), this maximum disappears and the greatest concentration [e] is observed only in the state of equilibrium $[\bar{e}]$ (Fig.1). Usually L_e conditionally corresponds to $\sim 0.9 - 0.95\ [e]_{max}$; at time of $[e]_{max}$ disappearance the value of L_e increases by jump, inasmuch as in this case $[e]_{max} = [\bar{e}]$. The basic processes leading to the variation of [e] are the associative ionization reactions

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

$$N + N \rightleftarrows N_2^{+} + e, \tag{2}$$

while the role of the reaction $O + O \rightleftarrows O^{+}_2 + e$ and the ionization by electron impact for $V \leqslant 10$ km/sec is insignificant. The solution allows us to draw a pattern of the ionization process in dissociating air at V = 6 to 10 km/sec.

At the outset, as a result of stormy dissociation of O_2 and the beginning of N_2 decay, the rate of electron formation S_e behind the front rises rapidly. At the same time the intense charge-exchange curtails the number of NO^+ and N_2^+ ions and decelerates the development of reverse processes (1), (2). Subsequently, the charge-exchange results in the settling of local equilibrium between all ions in the mixture, while upon rapid total dissociation of O_2 the number of O atoms becomes practically invariable. The drop of temperature in the nonequilibrium zone is attended by a notable decrease of constants K_1, K_2 of reactions (1) and (2) (K_2 by a factor of 10 at passage from 17,000 to 12,000°K); this leads to a significant decrease of S_e. If at the same time the nitrogen dissociation still continues and the temperature drops, a maximum of [e] is formed. In this way, the basic cause of $[e]_{max}$ formation is the substantial rate of associative ionization (1), (2) by comparison with the dissociation rate of nitrogen.

At V = 9 - 10 km/sec nitrogen in equilibrium dissociates practically entirely, while the ionization still does not contribute significantly to enthalpy; this is why, as V increases in this region, the equilibrium temperature $\bar{T}$ increases substantially, which results in a great rise of $[\bar{e}]$. For $V \geqslant 9.5$ km/sec, processes (1) and (2) do not have the time to form $[e] \sim [\bar{e}]$ near the front; in this case, because of temperature drop, a small rapprochement to [e] takes place after deceleration processes (1) and (2), and $[e]_{max}$ is absent. The decrease of constants K_1, K_2 leads to the shift of the region of $[e]_{max}$ vanishing toward the side of smaller V.

Subdividing the zone of settling of equilibrium ionization into areas corresponding to the induction period Δ_i to the period of intensive rise $\Delta_p = [e]_{max} / (S_e)_{max}$ and to the period of Δ_B equalization (Fig.1, next page), we detect that Δ_p undergoes no sharp jump, only increasing somewhat at V = 10 km/sec on account of significant increase of [e]; the length Δ_i, decreasing monotonically, becomes comparable with the thickness of the wave front vor $V \geqslant 7 - 8$ km/sec. For $V \sim 9.5$ km/sec the length of L_e passes from $L_e \sim \Delta_i + \Delta_p$ to $L_e \sim \Delta_i + \Delta_p + \Delta_B$. The decrease of the constant of the rate of N dissociation by a factor of 20, increases Δ_p by about 1.5 times (Fig.2).

In the nonequilibrium zone of the flow behind the front a significant maximum is observed in the concentration of molecular ions forming as a result of associative ionization and charge-exchange. This may serve as an explanation of the peak of air radiation behind the wave front, observed in experiment [7].

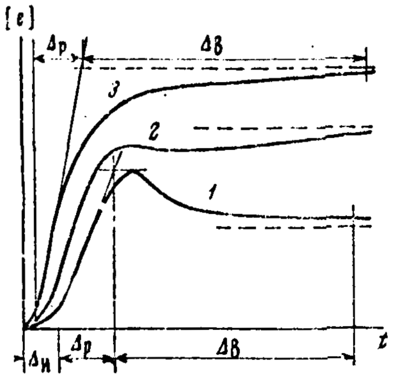

Fig.1

Character of [e] distribution behind the shock wave front at a velocity of 9 km/s (curve 1), 10 km/sec (curve 2) and 10 km/sec (curve 3). The dashed lines correspond to the respective equilibrium level of [e]

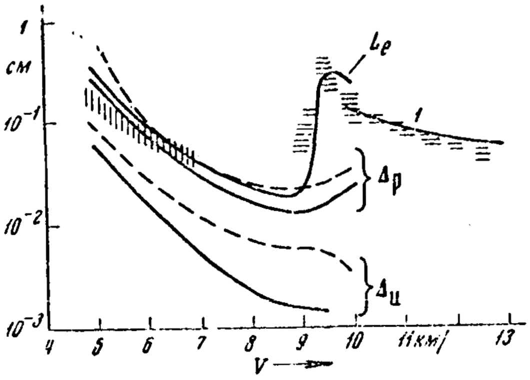

Fig.2

Length of the zone of nonequilibrium ionization as a function of shock wave velocity at p_0 = 1 mm Hg. The vertical strokes indicate the experiments of [3], the horizontal ones - those of [2]; the line 1 corresponds to the calculation of [1], the two variants being respectively shown by solid and dashed curves

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*** THE END ***

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