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ON THE MECHANISM OF THERMAL IONIZATION OF AIR

By

T. V. Bashenova and Yu. S. Lobastov

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13. ABSTRACT

The mechanism of thermal ionization of air behind shock waves within a range of Mach 9-12 is considered on the basis of available experimental data on the absorption of radio waves by the ionized gaseous medium. These data show that the time dependence of the absorption of radio waves is given by a curve with a maximum which corresponds to the maximum electron concentration in the nonequilibrium region. An analysis of the time necessary to attain maxima of the absorption and attenuation coefficients is presented on the basis of existing hypotheses on the mechanism of thermal ionization of air. A comparison of the equilibrium and maximum values of electron concentrations behind a shock wave in air at a given pressure in tabular form, and shows that given maximum concentrations approach equilibrium. It is concluded that double collisions are the leading process of air ionization according to a given reaction. Orig. art. has: 1 figure, 1 table, and 11 formulas. [AT4048002]

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Radio Wave Attenuation						
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Air Ionization						
Radio Wave Absorption						
Attenuation Coefficient						

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

ON THE MECHANISM OF THERMAL IONIZATION OF AIR

T. V. Bashenova and Yu. S. Lobastov

The experimental data on the absorption of radio waves by air behind a shock wave in a shock tube, introduced in work [1], were narrowed down on a refined unit. The results showed that the time dependence of the absorption of radio waves behind the shock wave has the form of a curve with a maximum which reaches p_0 = 1-2 mm Hg over 20-100 μs at M = 9-12. The dimension of the region of heated gas under these regimes was 15-20 cm, while the width of the radio-wave beam was no greater than 1-2 cm.

In this work we analyze the time for attaining the absorption maximum and the attenuation coefficient of the radio waves based on existing hypotheses on the mechanism of thermal air ionization.

The attenuation coefficient (in decibels) was measured experimentally at α = 30δ. It is related to gas conductivity σ at a low density of electrons n_e by relationships:

$$\delta = \frac{4\pi\sigma}{c\sqrt{\varepsilon}};$$

$$\sigma = \frac{e^2}{m}\frac{n_e\nu}{\omega^2+\nu^2};$$

$$\varepsilon = 1 - 3{,}18\cdot 10^9\frac{n_e}{\omega^2+\nu^2},$$

where $c = 3 \cdot 10^9$ cm/s; $e = 4.803 \cdot 10^{-10}$; $m = 9.108 \cdot 10^{-28}$; ω - radio-wave frequency; ν - impact frequency of electrons with gas particles.

In determining ν we use the results for measuring the absorption of radio waves for the two frequencies ω_1 and ω_2.

Values T and p behind the shock wave were used as the basis for calculating these parameters by measured number M of the shock wave [3].

At temperatures on the order of 3000-4000°K most of the free electrons can arise in air as a result of the ionization of NO molecules. The equilibrium quantity of free electrons in the air at these temperatures is determined by the reaction

$$NO+M \rightleftarrows NO^+ + e + M \qquad (1)$$

This reaction assumes that the equilibrium concentration of free electrons $x_e^{(p)}$ can be formed in air after equilibrium concentration NO (x_{NO}) is formed during a time determined by the equation

$$\frac{dx_e}{dt} = \alpha_0 x_{NO} n - \alpha_0' x_e^2 n. \qquad (2)$$

Here α_0 and α_0' are the rate constants for the direct and reverse reactions. The constant for the rate of the direct reaction can be expressed through the equilibrium constant and the recombination constant α_0'. Value α_0' according to the Thompson theory at T = 5000°K and p = 0.1 atm is equal to 10^{-30} cm^6/s, and the NO concentration during the reaction does not exceed 10^{-2}. Using these data we can estimate the time for reaching an electron concentration close to equilibrium by expression (1). When T = 5000°K and p = 0.1 atm this time is no less than 10^{-2} s, i.e., it is by two orders greater than the experimental value.

Faster air ionization can be obtained from the reaction in which the atoms of nitrogen and oxygen which have arisen in the dissociation of the air, combine to form a molecule of ionized nitric oxide [4],

$$N + O \underset{\alpha_1}{\overset{\alpha_1}{\rightleftarrows}} NO^+ + e. \tag{3}$$

The rate of formation of the three electrons in connection with this reaction can be described by the equation

$$\frac{dx_e}{dt} = \alpha_1 n x_O x_N - \alpha'_1 n x_e^2, \tag{4}$$

where α_1 is the constant of the molecule forming rate NO^+; α'_1 – the recombination constant $NO^+ + e$; x_N and x_O – the concentrations of atom nitrogen and oxygen, respectively

$$\alpha'_1 = 10^{-6}\ см^3 \cdot сек^{-1}\ [5].$$

As we see from equation (3) after value α_1 is substituted in it through K_p, the rate of formation of electrons is proportional to the difference of the squares of equilibrium x_e^p and nonequilibrium x_e the electron concentrations

$$\frac{dx_e}{dt} = \alpha'_1 n \left(\frac{x_O x_N}{K_p} - x_e^2 \right) = \alpha'_1 n \left(x_e^{(p)^2} - x_e^2 \right). \tag{5}$$

The distribution of electrons throughout the reaction zone behind the direct shock can be obtained by a numerical integration of equation (5) with consideration of the dependence of α'_1 and x_e^p on the nonequilibrium temperature in the zone.

As noted in work [6], in the zone behind the shock the distribution of atomic nitrogen concentrations has a maximum. In connection with

this the distribution of the equilibrium concentration of electrons can have a maximum at the same point.

In work [5] it has been indicated that at the point where the equilibrium concentration of the electrons has its maximum the actual concentration of electrons also has a maximum. The numerical value of the electron concentration at the maximum is equal to the equilibrium concentration of electrons which corresponds to the nonequilibrium values x_N and x_O at the maximal value x_N in the reaction zone

$$(x_e)_m = \sqrt{\frac{(x_O)_m (x_N)_m}{K_p(T_m)}}. \qquad (6)$$

The time for reaching the maximal concentration of electrons $(x_e)_m$ is equal to the time of obtaining the maximum concentration of atomic nitrogen in the zone.

In the work of Yu. S. Cayasov [5] a calculation is given for the electron concentration throughout the zone at M = 10 and p_0 = 1 mm Hg, based on approximate data on the distribution of concentrations of N and O atoms and temperatures assumed in work [6]. In work [6] the following connection between the atoms of nitrogen and hydrogen at $x_O >> x_{NO}$ was found:

$$\alpha_N = k_4 x_{N_2}^0 \alpha_O / k_5 x_{O_2}, \qquad (7)$$

where $k_4 = 10^{-10} e^{-38/\theta}$ cm^3/s; x_{N2}^0 is the initial concentration of molecular nitrogen; x_{O_2} - the concentration of molecular oxygen equal to $x_{O_2} = x_{O_2}^0 - 1/2 x_O$, $\theta = T \cdot 10^{-3}$.

In the approximations used in work [6] the temperature in the nonequilibrium zone is determined by the concentration of atomic oxygen

$$T = T_2 - 6500 x_O. \qquad (8)$$

Here T_2 is the temperature directly behind the shock, calculated under the assumption of an instantaneous excitation of vibrations and a frozen dissociation. The concentration of atomic oxygen in the approximations of work [6] is related to the time of the law

$$1/\tau = k_1 n (0{,}2 - x_{O/2}) \frac{380}{\theta_2}. \tag{9}$$

Where $k_1 = 10^{-8} e^{-59/\theta}$; n - the total number of particles. By means of relationships (6) and (7) in work [4] values x_e^p of equilibrium concentrations of electrons at nonequilibrium values x_O and x_N were calculated for the coordinate system as a function of time. From these data we calculated the absorption coefficient of 3-centimeter radio waves α behind the shock wave at M = 10 and p_0 = 1 mm Hg. The calculation coincided with the experimental curve.

Value $\alpha = 0.2 \cdot 10^{-1}$ dB, which was obtained in calculating from an equilibrium number of electrons with equilibrium chemical compositions and temperatures, practically coincides with the value of the maximal coefficient of radio wave absorption, which corresponds to the maximal concentration of electrons in the nonequilibrium zone.

Let us estimate the value of $(x_e^p)_m$ at different M numbers of the shock wave and compare them with equilibrium values. For this let us use formula (6) and approximation expressions for the maximal concentration x_O and temperature θ from work [6]

$$(x_O)_m = \theta_2^2/230. \tag{10}$$

The results of calculating the number of free electrons $(n_e)_m = n(x_e)_m$ according to formula (10) and in the case of equilibrium (n^*_e) are given below. The values of temperature θ for $(x_e)_m$ are assumed equal to value θ_2, since then $x_O \sim 10^{-2}$ correction in formula (8) changes value θ in the third place.

Value θ_2 was calculated according to formula $\theta_2/\theta_0 = 0.14\ M^2$, and as in work [6] the values of equilibrium temperature T* were taken from work [3] (see table).

Comparison of equilibrium (*) and maximal values n_e behind shock wave in air at $p_0 = 10^{-3}$ atm.

M	7	8	9	10	11	12
T^*, °K	2400	2800	3100	3300	3550	3920
n_e^*, 1/cm³	$5\cdot10^{7}$	$2\cdot10^{9}$	$2\cdot10^{10}$	$5\cdot10^{10}$	$3\cdot10^{11}$	$0{,}98\cdot10^{12}$
σ_s	2,0	2,6	3,3	4,1	5,0	5,9
$(n_e)_m$, 1/cm³	$2\cdot10^{8}$	$0{,}5\cdot10^{9}$	$0{,}2\cdot10^{9}$	$3\cdot10^{10}$	$2\cdot10^{11}$	$1\cdot10^{12}$

As we see, when M > 9 maximal concentrations behind the direct wave become close to equilibrium.

Let us compare the time of attaining the maximum electron concentration, obtained in the experiments, with the possible time of attaining the maximal electron concentrations for reaction (3).

An estimate of this time can be made according to formula (9), which describes the time for establishing the maximal concentration of nitrogen atoms in the equilibrium zone

$$\tau_m = \frac{2{,}6\cdot10^{9}e^{59/\theta_2}}{n_3(0{,}21 - 0_2^2/460)}. \qquad (11)$$

In the figure the coordinate system related to the shock shows the values for the time of attaining the maximal electron concentration referred to initial pressure for 10 mm Hg. The filled dots correspond to experimental value τp_0 obtained by us, the white dots are according to data of work [8], and the triangular dots - to the data of work [7]. The curve has been drawn based on calculation by formula (11).

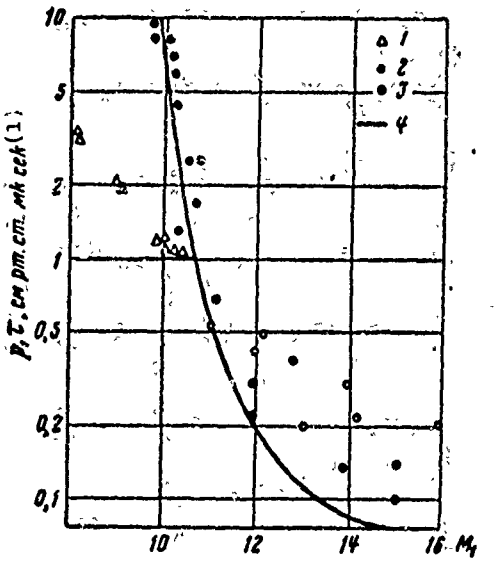

Fig. Time of attaining maximal absorption of radio waves at different M numbers of the shock wave. 1 - Mannheimer and Low [5]; 2 - Blackman [8]; 3 - ENIN; 4 - Sayasov (according to reaction $N+O_2 \rightleftarrows NO^+ + e$)

KEY: (1) p, τ, cm Hg μs.

The data which we obtained has been grouped around values τp_0, calculated according to formula (11), in the region of numbers M ~ 9-12. This indicates that the leading process in air ionization when 9 < M < 12 is that of double impacts

$$N + O_2 \rightleftarrows NO^+ + e.$$

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