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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

AERODYNAMICS

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MEASUREMENT OF THE TIME FOR ESTABLISHMENT OF THE EQUILIBRIUM ELECTRON CONCENTRATION BEHIND A SHOCK WAVE IN AIR

(Presented by Academician V. N. Kondrat’ ev, 2 XI 1962)

The measurement of the absorption of 3-centimeter radio waves by the gas behind the discontinuity in a shock tube was carried out on an apparatus similar to that described in work (1). The horns of waveguides with a cross section of 10 × 70 mm were installed perpendicular to the direction of propagation of the shock wave, at a distance of 5 m from the diaphragm in a tube with a cross section of 70 × 70 mm.

To check the relation between the dimensions of the sample of ionized gas and the geometry of the waveguide, control photographs were made of the scans of the schlieren pattern of the motion of the incident shock wave S, the contact surface K, and the reflected shock wave R for various values of M_S.

The schlieren records showed that, for the smallest sample dimensions ($M_S = 10,\ p_0 = 10^{-3}$ mm Hg), the distance from the discontinuity to the contact surface is more than 15 cm, which corresponds to 65 μsec of laboratory time. The reflected wave reaches the location of the waveguides 60 μsec after passage of the incident shock wave. The velocity of the reflected wave corresponds to the calculated value (2) to within 50 m/sec.

Fig. 1. a—oscillogram of the absorption of radio waves behind a shock wave in air ($M_S = 9,\ p_0 = 10^{-3}$ atm.). S—incident shock wave; K—contact surface; R —reflected wave;
b—pressure oscillogram.

To establish the correspondence between the onset of radio-wave absorption and the arrival of the shock wave, the sweep of the oscilloscope recording the radio-wave absorption was triggered by the signal from the same piezoelectric pressure

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Fig. 2. Maximum values of n_e behind a shock wave in air as a function of the Mach number M_S of the shock wave ($p_0 = 10^{-3}$ atm.)

Figure 2: Fig. 2. Maximum values of n_e behind a shock wave in air as a function of the Mach number M_S of the shock wave ($p_0 = 10^{-3}$ atm.)

transducer from which the sweep for recording the pressure was triggered. Comparison of the pressure and radio-wave absorption curves (Fig. 1) shows that the beginning of the absorption curve coincides with the arrival of the shock wave at the pressure transducer, located in the same cross section as the waveguides, with an accuracy of up to ±5 μsec. The second step on the absorption curve corresponds to the arrival of the reflected shock wave; the subsequent decrease in absorption is caused by the arrival of cold gas. At large values of M_S, the gas behind the reflected wave near the end face completely reflects the radio waves.

These control experiments make it possible to judge that the principal energy of the radio waves is transmitted through the space between the horns of the waveguides in the shock tube practically along a straight line.

When decoding the absorption curves obtained, the dependence of the transmission coefficient of the radio waves A on the number of free electrons behind the shock wave n_e was calculated from the electrodynamic formulas for a plane wave (6).

The temperature, pressure, and composition of the air behind the shock wave under conditions of chemical equilibrium were calculated by the method described in (2), on the basis of the measured value of the shock-wave velocity. The parameters of the air in the nonequilibrium zone were estimated from the data of (4,5).

The effective number of collisions ν was determined, for the given temperature and pressure, according to the classical theory (6). The inaccuracy of such a determination of the number of collisions may lead to an error in determining ν by a factor of 3-4; therefore the comparison of experiment with calculation was carried out within an order of magnitude of the obtained values of n_e.

Fig. 2. Maximum values of n_e behind a shock wave in air as a function of the Mach number M_S of the shock wave ($p_0 = 10^{-3}$ atm.).

Control experiments were carried out to measure the absorption of radio waves by argon at a temperature behind the discontinuity of 2500-3000°K and a pressure behind the discontinuity of 0.1 atm. These experiments showed that the electron density arising as a result of ionization of impurities of alkali metals in the shock tube and in the gas, at the indicated temperatures and pressures, does not provide measurable absorption of 3-centimeter radio waves. In addition, for the experiments with air an estimate was made of the ionization potential from the temperature dependence of the quantity $\ln n_e^2$, calculated on the basis of the measured maximum values of the radio-wave absorption coefficient behind the incident shock wave, as in $^{(1)}$.

The estimate showed that the experimental values of n_e are grouped around a straight line with a slope characterized by the ionization potential of NO ($E = 9.5$ eV), and not around a straight line with the ionization potential of alkali metals ($E < 5$ eV).

The measured maximum values of n_e behind shock waves with various Mach numbers M_S are presented in Fig. 2. The calculated curve for the dependence of the equilibrium value of n_e on the Mach number M_S of the shock wave is also plotted there.

The calculation of the equilibrium value of n_e for the reaction $\mathrm{NO} \rightleftarrows \mathrm{NO}^+ + \mathrm{e}$ was carried out from the equilibrium values of the temperature and pressure behind the discontinuity $^{(2)}$ on the basis of the law of mass action; moreover, the ratio of the statistical sums of the molecules NO^+ and NO was taken, in this temperature range, to be ~ 0.2 on the basis of $^{(3)}$. The experimental points are grouped around the equilibrium curve.

The time for establishment of the electron concentration close to equilibrium can be measured from the absorption oscillograms (Fig. 1). This time varies from 10 to 7 μsec in the laboratory system when the Mach number M_S of the shock wave is varied from 7 to 11.

An estimate of the ionization time of NO by the reaction

$$\mathrm{NO} + \mathrm{M} \underset{\alpha_0'}{\overset{\alpha_0}{\rightleftarrows}} \mathrm{NO}^+ + \mathrm{e} + \mathrm{M}$$

from the value of the recombination coefficient α_0' according to Thomson' s theory and from the value of the equilibrium constant of this reaction K_p leads to the conclusion that

at $M_S = 10,\ p_0 = 10^{-3}$ atm, the time for the electron concentration to reach one-half of its equilibrium value is 10^4 μsec. (8). Consideration of another possible ionization mechanism (7)

$$\mathrm{N} + \mathrm{O} + \mathrm{M} \underset{\alpha_1'}{\overset{\alpha_1}{\rightleftarrows}} \mathrm{NO}^+ + e + \mathrm{M}$$

leads to shorter times for reaching a maximum electron concentration x_e close to the equilibrium one. Indeed, in this case

$$\frac{dx_e}{dt} = \alpha_1' n \left(x_e^{p\,3} - x_e^2\right).$$

Here x_e^p denotes the equilibrium electron concentration corresponding to nonequilibrium values of the O and N concentrations:

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$$x_e^p = \frac{x_o x_N}{K_p}.$$

As shown in (8), the electron concentration at the maximum is close to the equilibrium value, and the time for attaining the maximum electron concentration in the nonequilibrium zone is equal to the time for attaining the maximum O concentration. An estimate of this time for $M_S = 10$, $p_0 = 10^{-3}$ atm, using the formulas of (5), gives values of 10^{-5} sec in the laboratory coordinate system, which corresponds to the experimental data.

Conclusions. 1. It has been established in this work that the absorption of radio waves by air heated behind an incident shock wave corresponds to an electron concentration close to equilibrium at low shock-wave velocities ($M_S =$ 7—9, $T =$ 2000—3000°K) and is somewhat below the equilibrium values at higher shock-wave velocities ($M_S =$ 9—11, $T =$ 4000—5000°K). The time for establishing a concentration close to equilibrium is less than the known time for establishing the equilibrium NO concentration behind a shock wave.

2. On the basis of the data obtained, conclusions have been drawn about the mechanism of thermal ionization of air behind a shock wave. The time for establishing the maximum electron concentration close to equilibrium, and the values of the maximum electron concentrations at $M_S > 9$, agree with the calculation of the formation of free electrons due to the reaction $\mathrm{N} + \mathrm{O} + \mathrm{M} \rightleftarrows \mathrm{NO}^+ + e + \mathrm{M}$, with a recombination constant of $2 \cdot 10^{-6}$ cm^3/sec, whereas calculation according to the reaction $\mathrm{NO} + \mathrm{M} \rightleftarrows \mathrm{NO}^+ + e + \mathrm{N}_2$ gives times for reaching the equilibrium electron concentration that are several orders of magnitude higher than the experimental values.

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