RADIATIVE PROPERTIES OF A STRONG SHOCK WAVE IN NEON

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The possibility of heating inert gases to considerable temperatures at the experimentally attainable velocities of shock waves and the transparency of these gases to hard ultraviolet radiation make it possible to use strong shock waves in inert gases as sources of high-power emission [1-4]. The development of a heated layer ahead of the front of an intensely radiating shock wave should, according to [5], limit the fluxes emitted to large distances. Experimental measurements [4, 6, 7] made in narrow sections of the visible region of the spectrum have confirmed the development of a radiating–screening heated layer for shock waves in xenon, argon, and helium. Measurements of the densities of fluxes emitted by shock waves in xenon and argon [8] showed that the screening action of the heated layer in these gases is manifested at higher velocities for radiation of the vacuum-ultraviolet region than for radiation of the visible region of the spectrum. A shock wave in neon is of special interest as an emitter. The first measurements of the brightness of a shock wave in this gas in the violet region of the spectrum [2] did not reveal significant screening action of the heated layer at velocities up to 43 km/sec. If one assumes that this also remains valid for harder radiation, up to the ionization potential of neon, then one finds that a shock wave in neon at velocities above 30 km/sec is a more powerful emitter than a shock wave in argon, which is heavier but has a lower ionization potential. The present article is devoted to a test of this hypothesis.

To investigate the emission of shock waves in neon in the ultraviolet region of the spectrum we measured the density of the radiant flux emitted in practically the entire spectral region of transparency of neon with simultaneous recording of the brightness in the visible region.

The pyroelectric receivers [9] used to record the radiant-flux density had a uniform spectral sensitivity in the wavelength range of 40–1100 nm. Less than 1% of the radiant energy belongs to radiation with wavelengths of more than 1100 nm in the investigated temperature range of shock-compressed gas, while radiation with wavelengths shorter than 57.5 nm is absorbed in the cold neon due to the photoelectric effect. The measurements of radiant-flux density using pyroelectric receivers assured an accuracy of ± 14% with a time resolution of $2 \cdot 10^{-7}$ sec.

In the experiments the shock waves propagated in glass tubes with an inner diameter of 18-40 mm and filled with neon at atmospheric pressure. Neon of "pure" grade containing no more than 0.01% impurities was used.

Simultaneously with the measurement of the density of radiant flux emitted by the shock wave, the propagation velocity of the shock wave was measured in the experiments using two high-speed streak cameras and the brightness temperatures of its surface were measured in two sections of the visible region of the spectrum: in the red region behind a filter with an effective wavelength $\lambda = 660$ nm and a half-width $\Delta\lambda = 60$ nm and in the violet region behind a filter with $\lambda = 432$ nm and $\Delta\lambda = 20$ nm. The measured radiant-flux density was set in correspondence with the radiant temperature, defined as the temperature of an absolutely blackbody emitting the given flux density in the range of quantum energies from zero to the ionization potential of neon, equal to 21.6 eV. Measurements of brightness temperatures T_- and the determination of radiant temperatures T_+ with the given transmission limit are characterized by the relative errors given in Table 1 as a function of the temperature.

Special attention was paid to the accuracy in measuring the propagation velocity of the central part of the shock-wave surface, from which the radiant fluxes were recorded. To eliminate boundary disturbances, which outrun the central part of the shock-wave front and can result in an apparent increase in the shock-wave velocity, we used intercepting diaphragms. The error in measuring the shock-wave velocity did not exceed 4%.

Shock waves were generated in the neon filling the glass tube either upon the emergence of a plane deto-

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TABLE 1

$T\cdot 10^{-3}$, °K	20	30	50	70	100	150
$\Delta T_-/T_-$ (λ=660 nm), %	6	6,5	8	9,3	11	14
$\Delta T_-/T_-$ (λ=432 nm), %	4	5	6	6,7	9	12
$\Delta T_+/T_+$, %	3	3,4	4,3	5,5	7,1	8,3

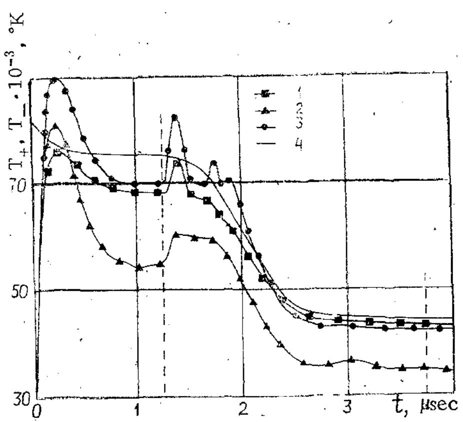

Fig. 1

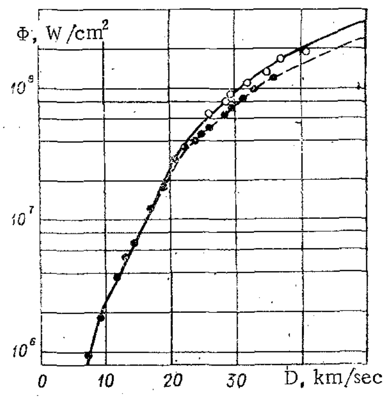

Fig. 2

nation wave at the flat end of a cylindrical explosive charge or using an explosive gas compressor [10], the spherical compression chamber of which was separated from the neon-filled tube by a thin Dacron diaphragm. The experimental setup and the measurement procedure are described in more detail in [8].

Nonsteady shock-wave emission was recorded in the experiments with neon at shock-wave velocities above 25 km/sec. The behavior of the brightness and radiant temperatures of a shock wave in neon with time in one of the experiments is presented in Fig. 1 as an example: points 1) radiant temperature; 2) brightness temperature at a wavelength of 660 nm; 3) brightness temperature at 432 nm; curve 4) temperature behind the shock-wave front, calculated on the basis of velocity measurements using the shock adiabatic curve of neon from [4]. The instants the shock wave passes through the intercepting diaphragms are marked by dashed lines. The nonsteadiness was expressed in the fact that after reaching the maximum values, even for a constant shock-wave velocity, the brightness temperatures and emission fluxes decreased sharply and arrived at lower constant values in a time of 0.3-0.6 μsec. The brightness temperature varied especially strongly (by about 30%) in the red region of the spectrum. Subsequently, the temperatures follow the variation in the velocity, which decreases after the wave passes through the intercepting diaphragm and arrives at a new constant value. The brief temperature pulsations visible in Fig. 1 after the time of 1.2 μsec are connected with the influence of shock waves reflected from the intercepting diaphragm. The large scatter of brightness temperatures in the first experiments with neon [2] is connected just with the phenomenon of nonsteadiness at the start of shock-wave motion in neon. Such nonsteadiness was not observed in experiments with xenon and argon [8].

This nonsteadiness indicates that in neon the heated layer ahead of the shock front is established in a time of 0.3-0.6 μsec. In this basis, in Figs. 2 and 3, where the experimental results for a shock wave in neon are presented, the maximum values of the measured quantities are given by light dots while the values established during the time the shock wave maintained a constant velocity are given by dark dots.

From Fig. 2, where measured values of the density of flux emitted by a shock wave in neon as a function of the wave velocity are presented, it is seen that the maximum values of the radiant-flux density in the velocity range from 7.8 to 41 km/sec coincide with the calculation based on the shock adiabatic curve of neon with the spectrum cut off at the ionization potential of neon, 21.6 eV (solid curve). And above 22 km/sec the steady-state values of the radiant-flux density lie below this calculation.

A calculation of the spectral coefficients of hot neon [11], made with allowance for the photoelectric effect from the ground and excited states of the atom and ion, bremsstrahlung absorption, and absorption and emission in lines, showed that absorption lines are already excited in hot neon at a temperature of $1.4\cdot 10^4$°K before the ionization potential, and these broaden with further heating. This results in the fact that even at a temperature of $2\cdot 10^4$°K the transmission limit of neon decreases to 19.5 eV with a rather broad absorption

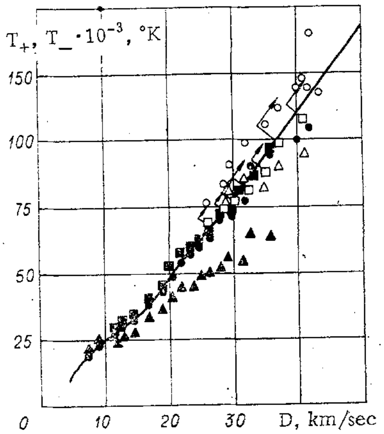

Fig. 3

line for quanta with an energy of about 16.7 eV.

In [12] it was shown, on the example of a shock wave in helium, that such absorption by excited levels in the heated layer ahead of the shock front results in an effective limit, 3.6 eV lower than the ionization potential of helium, for the transmission of radiation from the front.

Estimates of the maximum temperature in the heated layer ahead of the shock-wave front in neon show that at a velocity of 25 km/sec the temperature in the heated layer can reach $2 \cdot 10^4$°K. At such a temperature a noticeable decrease in the transparency limit of neon will set in when the width of the heated layer is about 1 mm. If one assumes, on the basis of the behavior of the spectral dependence of the coefficient of absorption of neon, that radiation from the shock front is cut off not at the quantum energy equal to the ionization potential of neon, 21.6 eV, but at a lower value (an effective value of 19 eV), then the experimental values of the steady-state radiant-flux densities agree well with the corresponding calculation from the shock adiabatic curve of neon, which is represented by a dashed line in Fig. 2.

In Fig. 3 we present the steady-state values of the radiant temperatures, now determined from the transparency limit of 19 eV. But the maximum values of the radiant temperature, for which the influence of the heated layer is still weak, are given for a transparency limit equal to the ionization potential of neon. Their possible change upon a shift of the transparency limit to 19 eV is shown by arrows. The measured values of the brightness temperatures of a shock wave in neon are also given here. The notation is the same as in Fig. 1. The solid curve is the shock adiabatic curve of neon from [4].

The measurements in different sections of the spectrum show that a shock wave in neon radiates as an absolutely blackbody at velocities of 7.8-10 km/sec. At velocities of 12 km/sec and higher the brightness temperatures in the red region of the spectrum are lower than the calculated gas temperature behind the shock front. This difference reaches 36% at a velocity of 36 km/sec. Despite the clearly expressed screening in the red region of the spectrum, the brightness temperatures in the violet region and the radiant temperatures, allowing for narrowing of the transparency window of neon, are close to the calculated temperature of shock-compressed neon in the entire range of shock-wave velocities investigated. At velocities above 25 km/sec the maximum brightness temperatures in the violet region of the spectrum exceed the temperature behind the shock-wave front by 15-20%. This indicates a degree of elevation of the temperature in the shock wave due to the fact that it encounters gas already heated by radiation. With the development of a heated layer this temperature elevation is compensated for by the screening action of the heated layer. Then the brightness temperature in the violet region and the radiant temperature are lowered to the temperature level of the shock-compressed gas calculated without allowance for radiative effects.

During the rise in the brightness of the shock wave at the start of its motion one can determine the coefficients of absorption of the shock-heated gas using the method of [6]. With a wave velocity of 9.3 km/sec and a compression of 6.5, according to Ref. 4, the temperature of the shock-heated neon was $2.37 \cdot 10^4$°K. In this case the coefficient of absorption of neon averaged over the emitted spectrum was 7.7 cm^{-1} according to the measurement results, while the coefficients of absorption in the violet and red regions of the spectrum were 10 and 36 cm^{-1}, respectively. The earlier appearance of screening in the heated layer in the red region of the spectrum is explained by the sharp increase in the coefficient of absorption of hot neon in the red region compared with the violet and ultraviolet regions for a shock wave in neon.

In the experiments the pyroelectric receivers recorded radiation in a narrow solid angle in the direction perpendicular to the surface of the shock-wave front. In determining the radiant-flux densities it was assumed that the angular distribution of emission intensity obeys the Lambert law. This law is not satisfied when a heated layer develops which screens the radiation. Let us estimate the possible change in the flux density of shock-wave emission due to the greater absorption in the heated layer of radiation emerging at small angles to the surface of the front. We consider a semiinfinite space consisting of an absolutely blackbody in front of which there is a layer with a thickness a having a coefficient of absorption $\varkappa$ which is constant over the thickness and the spectrum. For weak screening the self-emission of the heated layer can be neglected. Then the flux density of the outgoing radiation has the form

$$\Phi = 2\pi \int_0^{\pi/2} I_0 \cos\alpha \cdot e^{-\varkappa a/\cos\alpha} \sin\alpha d\alpha,$$

where I_0 is the intensity of the emission of an absolutely blackbody; α is the angle between the direction of motion of the quanta and the normal to the surface.

Introducing the variable $z = 1/\cos\alpha$ and replacing the intensity by the equilibrium radiation density, $I_0 = cU_0/4\pi$, we obtain

$$\Phi = \frac{cU_0}{2} \int_1^{\infty} e^{-\varkappa a z} z^3 dz,$$

where c is the speed of light.

Since $cU_0/4 = \sigma T^4 = \Phi_0$, where σ is the Stefan–Boltzmann constant, the flux density of the radiation upon emergence from the absorbing layer will finally be

$$\Phi = 2\Phi_0 E_3(\varkappa a) = \Phi_0 [e^{-\varkappa a} - \varkappa a e^{-\varkappa a} + \varkappa^2 a^2 E_1(\varkappa a)], \qquad (1)$$

where $E_n(x)$ is an integral exponential function.

The width of the heated layer ahead of a shock-wave front in neon at the temperature level of $2.4 \cdot 10^4$°K can be estimated from the coefficient of absorption measured in the red region of the spectrum and the recorded difference between the emission intensity I of the shock wave in the red region and the calculated value I_0 through the relation $a = (\ln I_0 - \ln I)/\varkappa$. For a shock wave in neon at a velocity of 36 km/sec such an estimate gives $a = 1$ mm for the width of the heated layer. The corresponding decrease in the radiant-flux density estimated from Eq. (1) is $\Phi = 0.81\Phi_0$. At the same time, the intensity of emission at an angle $\alpha = 0$, which is measured by the pyroelectric receiver, is also attenuated to $I = 0.89 I_0$. Therefore, the possible difference between the flux density of shock-wave emission in neon and the flux density determined in experiments under the assumption that the Lambert law is satisfied does not exceed 9%, i.e., it is small.

The measured densities of the flux emitted by a shock wave in neon reached $1.8 \cdot 10^8$ W/cm^2. The small thickness of the heated layer developing ahead of the front and its transparency to ultraviolet radiation allow us to assume that a considerable increase in the emitted fluxes is possible when higher shock-wave velocities are reached. The velocities needed for this are considerably lower than in the case of a shock wave in helium. This allows us to consider a shock wave in neon as one of the most promising powerful emitters of ultraviolet radiation. The main screening action of the heated layer in neon appears in the lowering of the energy of the emitted quanta to 19 eV and in the considerable attenuation of radiation in the red region of the spectrum.

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INDUCTION METHOD OF CONTINUOUS RECORDING OF THE VELOCITY OF A CONDENSED MEDIUM IN SHOCK-WAVE PROCESSES

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Methods of continuous recording of the velocity of a medium in shock-wave processes can yield useful information in the investigation of complex phenomena occurring during shock compression of compressed media (elastic–plastic waves, phase transformations, etc.). A magnetoelectric method of continuous recording of the velocity of dielectric media [1] and a capacitive method of measuring the instantaneous velocity of a moving metal surface [2] are well recommended in a number of investigations. Unfortunately, quantitative measurements are practically impossible by using a magnetoelectric method for relatively high pressures produced by metal impactors because of the distortion of the initial magnetic field by the impactor motion. The capacitive method is quite responsive to interference and does not permit realization of measurements of the velocity of the metal–condensed dielectric interface because of changes in the dielectric permittivity of the medium filling the interelectrode spacing behind a strong shock front.

A method [3] without the above-mentioned constraints inherent to the magnetoelectic and capacitive methods, and permitting the realization of continuous recording of the velocity of the condensed medium at higher shock-compression pressures is considered in this paper. Methods of measuring the parameters of shock-compressed media, which are similar in the physical principles to the principle of the method proposed, are examined in [4, 5].

1. Principles of the Induction Method

Let a turn of radius R_1 with a negligibly small conductor section be connected to a stabilized dc current source and located in a condensed dielectric medium 1 (Fig. 1a) at a height h_0 above a conducting half space 2 with the electrical conductivity $\sigma \to \infty$, while there is a stationary magnetic field in all space. The magnetic permeability of the media are $\mu_1 = \mu_2 = \mu_0$, where μ_0 is the magnetic permeability of a vacuum. If a change in the magnetic field should occur in the dielectric medium 1 for any reason, an electromotive force (emf) of induction $\mathcal{E}_1$ will appear in the turn.

Let us trace the behavior of the induction emf in the turn of a plane shock whose front is parallel to the interface of the medium is propagated from bottom to top over the system. Although the wave front moves over the conductor, no induction emf originates in the turn. This deduction follows from [6, 7] in which it is shown

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