SPECTRAL BRIGHTNESS OF SHOCK WAVES IN AIR

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The emission spectra and the brightness temperature of shock waves in air were measured in a wide spectral interval, λ = 220–800 nm. Shock waves with velocities 9–14 km/sec were produced by explosive charges. The influence of the relaxation layer of the shock wave front on the shock wave brightness is analyzed.

WITH the aid of explosives it is possible to produce in a sufficiently dense gas strong shock waves that serve as high-temperature surface emitters. The spectra in the investigations of such waves are scanty, qualitative in character, and cover only the visible section of the spectrum. Recently undertaken measurements in the visible light and in the ultraviolet, using optical filters separating narrow sections of the spectrum[1-2], do not give a complete picture of the spectral composition of the shock-wave radiation.

The investigations reported in this article were made in a wide interval of wavelengths, 220–800 nm, which covers the visible as well as the ultraviolet and infrared sections of the spectrum, and supplement the previously obtained results; they also make it possible to draw definite conclusions concerning the brightness of shock waves in gases. The solution of the problem was helped by the recently developed spectral instruments with large time resolution[3,4].

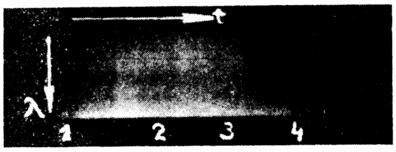

FIG. 1

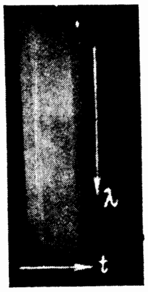

FIG. 2

FIG. 1. Spectrum photograph of radiation of a shock wave (λ = 400–700 nm), obtained with the SFR-2M instrument with SP-77 attachment; the broad bands in the spectrum are connected with the spectral sensitivity of the photographic material: 1–shock wave after the emergence of the detonation from the bottom of the cumulation channel; 2–shock wave with velocity 14 km/sec; 3–spectral markers produced with a mercury lamp, 4–emission spectrum of an attenuating shock wave.

FIG. 2. Spectrum photograph of emission of a shock wave with velocity 10–14 km/sec (λ = 220–400 nm), obtained with the SP-111 instrument with an interchangeable grating of 200 lines/mm.

MEASUREMENT PROCEDURE

The emission spectrum of shock waves in the ultraviolet and visible regions λ = 220–700 nm was investigated with the aid of a spectrophotochronograph (SP-111)[4]; in the visible range λ = 400–700 nm, the SFR moving image camera with spectral attachments SP-77 and SP-78 was also used[3]. Figures 1 and 2 show prints of spectrum photographs of the radiation of a shock wave, obtained with the instruments SP-111 and SFR with the SP-77 attachment. The best spectral resolution in our experiments was 0.07 nm (SP-111 instrument with interchangeable grating of 1200 lines/mm and spectral-temporal slit of 0.1 mm diameter). The time resolution was 10^{-7} sec. The spectrum photographs make it possible to register lines whose brightness differs by 2% from the adjacent continuum.

The spectral brightness temperature is determined from a photometric comparison of the densities of the photographs of the shock wave and of the standard. The standard employed was a ÉV-39 flash source, producing black-body radiation with a temperature 39000°K in a wide spectral interval 250–600 nm[5]. The density markers are printed in during the photography of the standard with the aid of stepwise attenuaters placed in the focal arcs of the instruments SP-111 and SFR. To this end, the rotating mirror of the instrument is synchronized with the flash of the ÉV-39 source, so the photographic film behind the stepwise attenuator is exposed during the time when the flash brightness is constant[1)]. The identity of the conditions of photography of the markers, standard, and of the shock waves with respect to exposure and spectrum, which made it unnecessary to resort to the reciprocity law, and also the closeness of the brightness of the standard to the measured brightness of the wave, reduce the errors of the procedure. The accuracy with which the shock wave brightness was measured was not worse than ±15% in the visible region and ±25% in the ultraviolet. In the section λ = 700–600 nm, where the ÉV-39 standard cannot be used, the brightness temperature was extrapolated from the known spectral sensitivity of the photographic film.

The brightness temperature in the spectral regions with effective wavelengths λ_{eff} = 800 nm, λ_{eff} = 660 nm, and λ_{eff} = 500 nm and with half-width $\Delta\lambda$ = 10 nm, separated by means of the interference filters, was measured with an FÉU-22 photomultiplier calibrated

1)The authors are grateful to G. P. Ilyushin and B. G. Klokov for synchronizing the SP-111 instrument for this purpose.

with an SI8-200 ribbon lamp. The accuracy with which the brightness was measured in this manner was not worse than ±10%. Shock waves with velocities 9–14 km/sec were produced by cummulative-channel charges described in[2]. The air pressure ahead of the wave was $P_0 = 760$ mm Hg, and the temperature $T_0 = 293^\circ$K.

DISCUSSION OF RESULTS

A shock wave whose amplitude changes insignificantly over a path amounting to several radiation units is almost a classical example of an absolutely black radiator, namely an optically dense region of uniformly heated substance bounded by a surface with a sharp temperature drop. The radiation from this region, which is in thermodynamic equilibrium, is distorted by a relaxation layer on the front of the shock wave. In gases, the layer is narrow and does not screen the visible and ultraviolet radiations. Thus, the width of the layer, for shock waves in air of normal density with front velocities 5–14 km/sec is, according to[6], of the order of 10^{-4}–10^{-5} cm, which is smaller by one order of magnitude than the range of the visible and ultraviolet radiation in shock-heated gas. However, as follows from the Kramers-Unsold formula, the range decreases with increasing radiation wavelength, and when $\lambda > \lambda_1$ it is comparable with or smaller than the width of the relaxation layer[2)]. The value of λ_1, starting with which the screening by the relaxation layer comes into play, depends on the amplitude of the shock wave. For a shock wave in air with a temperature $T = 2.5 \times 10^{4\circ}$K in air, we have $\lambda_1 \approx 4 \times 10^3$ nm; at lower temperatures, the boundary of λ_1 shifts towards longer wavelengths.

In addition to the infrared radiation $\lambda > \lambda_1$, the relaxation layer can screen also the radiation of lines in which the gas absorption coefficient is higher than in the continuum. Such a screening of the shock wave in gases of normal density, as shown by estimates of the photoabsorption in the lines, is significant only for resonance lines, which for most elements are located in the vacuum ultraviolet.

The radiation from the front is screened in individual sections of the spectrum by the cold gas ahead of the front. This includes also the cutoff of the short-wave part of the radiation by photoionization, as well as the absorption in the resonance lines. In polyatomic gases there are also other photoabsorption mechanisms.

As shown by Zel'dovich and Raĭzer[7], the temperature profile of the shock wave, having the form of a step and corresponding of a black-body radiator, is distorted at large wave amplitudes. The gas ahead of the front, being heated by the short-wave radiation of the front, becomes opaque to the long-wave (particularly, visible) radiation of the front. The brightness temperature of such a wave is lower than the temperature of the gas behind the front. At shock-wave velocities 9–14 km/sec in air, as in our experiments, there is still no screening by the heated gas ahead of the front[2,7].

The shock-compressed air plasma in the experiments is sufficiently dense, so that the thermodynamic equilibrium is not disturbed in it by radiant cooling—this follows from estimating formulas presented by Kuznetsov[8], who investigated this question.

In light of the foregoing, let us consider the experimental results.

When the shock wave moves and the geometrical thickness of the gas behind the front increases, the brightness of the wave remains constant, thus indicating a large optical thickness of the heated gas in the experiments. The radiation spectrum of the shock wave turns out to be continuous. The absence of lines in the emission spectrum of gas heated to high temperatures, 12000–25000°K, makes the shock-wave radiating properties similar to those of incandescent bodies.

The brightness temperature of the shock-wave front, measured by various methods, is constant over the spectrum and coincides with the temperature of shock-heated gas obtained by calculation. Thus, the spectral brightness temperatures corresponding to wave velocities 9 and 14 km/sec are respectively 1200 and 25000°K. The noted agreement offers evidence that there is no screening of the gas radiation behind the front.

A criterion for the presence or absence of screening was proposed and experimentally verified earlier in[2]; this criterion does not require laborious calculations of the shock-wave parameters under ionization conditions or absolute measurements of its brightness—it is sufficient to compare the brightness of the shock-wave front at different angles.

The absence (presence) of lines in the radiation spectrum of the shock wave can also serve as proof of the absence (presence) of screening. Indeed, since the absorption coefficients in the lines is higher than in the adjacent continuum, even weak screening leads to the appearance of lines in the spectrum. The obtained spectrum photographs of the shock wave show that the screening of the radiation of shock-heated gas in the lines, and all the more in the continuum, did not exceed 2%. A spectrum photograph of the radiation of a shock wave with a spectral resolution 0.01–0.03 nm without time resolution[3)], obtained with the Q-12 quartz spectrograph, also revealed no lines. Estimates of the line broadening resulting from gas-kinetic collisions show their half-width to be not smaller than 0.01 nm at the air densities used in the experiments. Therefore the absence of lines is due to the character of the radiation of the shock wave, and not to the capabilities of the procedure.

Thus, the absolute black radiation of shock-heated gas at wave velocities 9–14 km/sec is screened only by the cold air in front of the wave in the ultraviolet region of the spectrum[4)] and by the relaxation layer on

[2)] If the degree of ionization and the population of the excited levels in the relaxation zone are smaller than the equilibrium values, the layer becomes somewhat more transparent than would follow from the Kramers-Unsold formula, which is applicable to a heated gas in equilibrium.

[3)] The glow of the shock wave was not cut off when the shock wave velocity dropped below 9 km/sec.

[4)] The ultraviolet transparency limit of air is $\lambda = 186$ nm [7].

the front of the wave in the infrared region.

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