LUMINANCE OF SHOCK WAVE FRONTS IN CERTAIN GASES

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The brightness (luminance) temperature of a shock wave front in argon, xenon, and an air-argon mixture is measured. Shocks with fronts having velocities of 4–31 km/sec were generated by means of explosive charges. The temperature was determined from the ultraviolet and visible radiation emitted at 90° and 45° with respect to the front. At high velocities the luminance decreased and was observed to depend on the duration of emission from the front. The results are compared with existing theoretical concepts regarding the luminance of strong shock waves in gases.

ONE of the reasons for our investigation of radiation emitted by strong shock waves is the interest that has been aroused recently in shock waves as sources of brilliant light. Condensed explosive materials are used to generate shock waves in heavy inert gases; high temperatures are produced behind the front along with high densities and fluxes of radiation from the front when using apparatus of small dimensions. Light sources based on this principle have been used to photograph rapidly decaying processes. Another possible use of such sources, - to act on solids with intense ultraviolet light, has been demonstrated by one of the present authors,[1] who observed and studied the intense evaporation of matter that was induced by radiation from an explosive type of light source constructed especially for this purpose. Similar sources are used successfully for other purposes.

Many investigations of shock wave luminosity in gases have been published. In most of this work the shock-heated gas radiates as a three-dimensional emitter. This condition ordinarily occurs in shock tubes where the size of the apparatus and the gas density result in an optically thin heated region. In the present work the shock wave is a surface emitter. This case has not been widely studied experimentally, apparently because it is difficult to generate strong shocks in very dense gases. Conflicting results have been obtained[2,3] from detailed studies of the radiation in the cases of fronts having velocities of ~8 km/sec, which are produced relatively easily by means of high explosives; therefore further investigation of these waves is required. The radiation from shocks in argon, krypton, and xenon with speeds of 17 km/sec has been studied by Model',[4] who observed the screening of radiation from a shock-heated gas. The emission in the cases of shock fronts moving at 37 km/sec in xenon and 47 km/sec in air has been studied in[5]. In the aforementioned studies the visible emission normal to the wave front was measured.

In the present work we have investigated the dependence of the brightness temperature on the shock front velocity for both the ultraviolet and visible spectra of shock waves in argon, xenon, air and an argon-air mixture. In each instance we measured simultaneously both the velocity of the front and its brightness temperatures for emission at 45° and normal to the front. Some of the measurements in the ultraviolet and visible spectra were obtained simultaneously. We have thus been able to compare the results obtained in an individual experiment, eliminating the spread of brightness temperatures among different experiments that occurs with high shock velocities. We monitored the optical thickness of the shock-heated gases; this enabled us to consider the front as a surface radiator without resorting to any theoretical considerations in this respect. The measured dependence of the brightness temperature on velocity is compared with the calculated theoretical dependence of shock-heated gas temperature on the velocity of the front and with existing ideas regarding the luminance of strong shock fronts in gases.[6-8]

TECHNIQUE OF MEASUREMENT AND WAVE GENERATION

The brightness temperature was measured through a photometric comparison of the blackening densities on photographic film registering the sweep of a shock front and of a standard light source, using a high-speed SFR-2 streak camera. The ultraviolet (λ_{eff} = 330 nm), two blue (λ_{eff} = 430 and 440 nm), and yellow (λ_{eff} = 560 nm) spectral regions were discriminated by color filters, whose transmission curves, which we measured with an SF-4 spectro-photometer, are shown in Fig. 1.

For measurements in the ultraviolet region the objectives of the SFR-2 camera are replaced with quartz lenses that were specially calculated for λ = 330 nm by N. M. Sitsinskaya and were prepared in the experimental design bureau of the Institute of Earth Physics. The pulsed standard EV-39 light source radiates as a blackbody at 39 000°K in a broad 250–600-nm band.[9,10] A step attenuator placed inside the SFR-2 on its focal arc registers a blackening scale on the

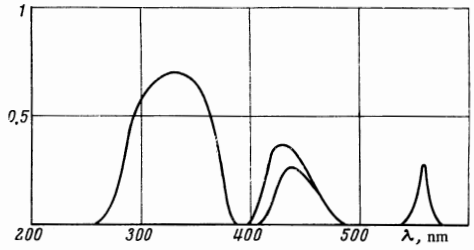


FIG. 1. Transmission curves of the color filters.

film when photographing the standard source. The rotating mirror of the camera is synchronized with the spark of the EV-39 source in such a way that the film behind the step attenuator is exposed while the brightness of the spark is constant. When measured temperatures above the source temperature are expected, the blackening scale is registered in advance following the same procedure except that the diaphragm of the SFR-2 camera is fully opened, so that the blackening density range will always include the densities recorded for the standard source and for the shock front.

The identical exposure conditions used for the attenuator, standard source and shock front enable us to dispense with the law of reciprocity in determining the temperature and thus to exclude the errors that can arise when the law is used. When the brightness temperature of the standard source is close to that which is to be measured the error of the method is reduced. The error in the relative measurement of the intensity luminance does not exceed ±5% (the error of the method), while the error in the absolute measurement of the intensity luminance (the error of the method and of the source) does not exceed ±15% for the visible and ±25% for the ultraviolet regions. The table gives the corresponding accuracy of the brightness temperature measurements.

Figures 2 and 3 show how the speed and brightness of the front were measured simultaneously at different angles and in the different spectral regions. The shock wave in a tube filled with the experimental gas is recorded, through the end window, in the form of a longitudinal sweep, as a basis for determining the brightness temperature corresponding to the radiation emitted perpendicular to the front. Radiation emitted at 45° to the front is reflected from a mirror forming a 22.5° angle with the tube axis and is registered by the camera in the form of a slanted sweep; this is a basis for determining the brightness temperature corresponding to radiation emitted at 45° to the front. Since the thickness of the post-shock gas layer emitting at 45° exhibits a linear decrease as the tube wall is approached, it is possible to evaluate the optical thickness of a shock-heated gas from the difference in blackening density between the two ends of the slanted sweep. On the other hand, this sweep fixes the temporal position of the wave front and we measure the shock speed from the slope. The error in the velocity measurement did not exceed ±3%.

Accuracy of Temperature Measurements $\Delta T/T$, %

λ_{eff}, nm	10^{-3} T, °K					
	10	20	30	40	60	80
560	7	9	10	11	12	13
430	4	6	8	9	10	11
330	5	10	14	17	19	20

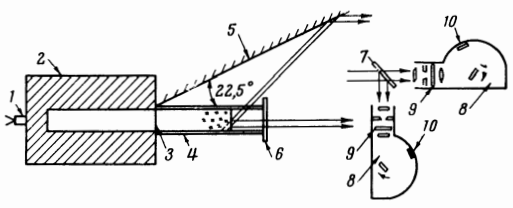


FIG. 2. Experimental arrangement (not drawn entirely to scale; the charge and mirror are arbitrarily rotated 90° about the tube axis). 1—electrodetonator, 2—charge with cumulative channel, 3—cellophane diaphragm, 4—glass tube (1.5 cm diameter) containing experimental gas, 5—mirror, 6—quartz end-window, 7—half-silvered mirror, 8—camera, 9—color filter, 10—step attenuator.

Simultaneous measurements in the ultraviolet and yellow regions were performed for an experimental series using two synchronized SFR-2 cameras and a half-silvered mirror.

Shock waves were generated by explosive charges consisting of 50% trotyl and 50% hexogen. Shock speeds up to 8.5 km/sec resulted when the explosion products were dispersed following the emergence of the detonation wave from the end surface of the cylindrical charge. Charges with a cumulative channel (Fig. 2) yield shock speeds up to 15 km/sec. When these charges are detonated a jet of explosion products formed inside the channel propels the gaseous shock wave ahead of it. By fitting a conical converging nozzle to the end of the channel the speed is raised to 19 km/sec. Speeds up to 31 km/sec are produced by the technique described in [5]. In the gas ahead of the wave the pressure was P_0 = 760 mm Hg and the temperature was T_0 = 293 °K. The argon and xenon contained at most 0.01% of impurities.

DISCUSSION OF RESULTS

Most of our measurements were obtained in the blue portion of the spectrum, where the brightness temperature is determined with greatest accuracy (see the table). Identical results were obtained in this region at λ_{eff} = 430 and 440 nm; therefore the respective data have not been given separately. The experimentally estimated absorption coefficient of the shock-heated gases exceeded 10 cm^{-1} for the given spectral regions; this is consistent with the Unsöld-Kramers formulas. Although the absorption coefficient was not calculated more accurately, this estimate provides a sufficient basis for regarding the shock wave as a surface radiator in the given spectral regions.

The brightness temperature measurements are shown in Figs. 4—7, along with the theoretical velocity dependence of shock-heated gas temperature taken from [4,11]. With increasing wave amplitude the brightness temperature of the front coincides at first (in air) with the calculated gas temperature behind the front or is close to the latter (in argon and xenon); this relation is followed by divergence.

According to the existing theoretical treatments,[6-8] when the gas ahead of the front is heated by short-wave radiation from the front it becomes opaque, in the case of high-amplitude waves, to long-wave (specifically,

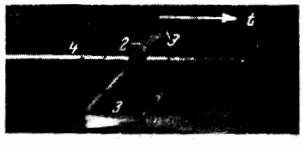


FIG. 3. Streak photo of the experiment in argon. 1—sweep of front registered through end-window, 2—sweep of front reflected in mirror, 3—time markings, 4—sweep of standard source and blackening scale.

visible) radiation from the front; consequently, the brightness temperature of the front decreases for this radiation. The experimental results in[2,4,5] have been interpreted on the basis of this theory.

Satisfactory agreement with the same theoretical ideas is found in the lag of our experimental brightness temperature for the yellow portion of the spectrum from shock waves in air with velocities D = 25—30 km/sec. (According to the calculations in[7,8], which we have applied to yellow light, this lag should be observed for D = 30—35 km/sec.) The absence of lag for ultraviolet radiation is evidently associated with the greater transparency of the heated pre-shock gas for this portion of the spectrum.

In addition to the lag of the brightness temperature behind the calculated temperature of a shock-heated gas, the investigated gases exhibited a difference between the brightness temperatures corresponding to radiation emitted normal and at 45° to the front; the normal radiation is associated with the higher temperature. Independently of any comparison with the calculated post-shock gas temperature, the described difference provides an experimental proof that a low-temperature gas layer exists, screening radiation from the high-temperature region behind the front. The optical thickness τ of this screening layer can be determined experimentally if we neglect its own radiation in the case of weak screening. Then, representing the radiation intensity normal to the front by $I_1 = I_0 e^{-\tau}$ and that at 45° by $I_2 = I_0 e^{-\sqrt{2}\tau}$, where I_0 is the intensity from the heated post-shock gas, we have

$$\tau = \frac{1}{\sqrt{2}-1} \ln \frac{I_1}{I_2}, \quad I_0 = I_1 \left(\frac{I_1}{I_2}\right)^{1/(\sqrt{2}-1)}. \tag{1}$$

The intensity I_0 determined in this way from the experimental intensities I_1 and I_2 leads to the true post-shock gas temperature. (In the absence of screening, based on the criterion of equal I_1 and I_2, the true temperature is the brightness temperature.) Figures 4 and 5 shows that some of the post-shock gas temperatures

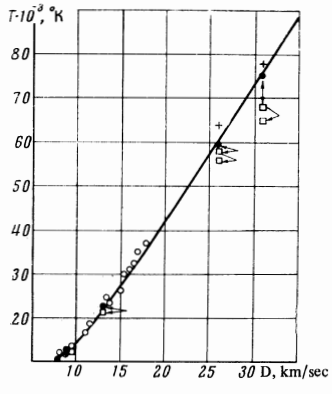


FIG. 4. Brightness temperature of shock front in air, in different regions of the spectrum: ●—λ_{eff} = 330 nm, ○—λ_{eff} = 430,440 nm, □—λ_{eff} = 560 nm; + designates the temperature of the gas behind the front, determined from the experimental brightness temperature. Simultaneously measured values are connected by arrows; an arrow is directed from an experimental point corresponding to radiation that is emitted normal to the front and reaches the related point for radiation at 45°, whenever the points do not coincide. The curve represents the calculated post-shock gas temperature.

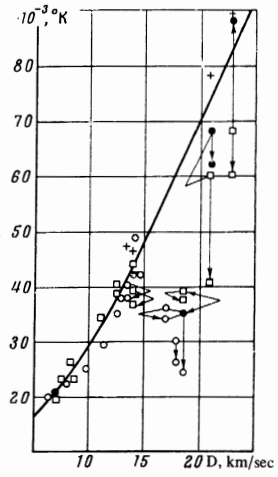


FIG. 5. Brightness temperature of shock front in argon (with the same symbols as in Fig. 4.)

derived in this manner agree within error limits with the theoretical values. We note that the foregoing discussion does not involve the causes and structure of the screening layer.

Calculated brightness temperatures of shock fronts in argon and xenon, assuming on the basis of[6-8,12,13] that the pre-shock gas in the screening layer exists in a state of thermodynamic equilibrium, show that the difference between the brightness temperature of visible light and the post-shock gas temperature should not exceed one percent up to shock velocity D = 23 km/sec in argon and 12 km/sec in xenon. At higher velocities the visible radiation from the front should be more strongly screened. In the experiments with argon the decrease of shock brightness was observed at the much lower velocities 13—14 km/sec. A similar divergence from the calculations was observed for an argon-air mixture, where the earlier arrival of screening could not be accounted for even by broadening of the screening layer due to the added air. We note that the brightness temperature in argon and xenon is also below the calculated level at lower wave velocities. These discrepancies show that the hypothetical thermodynamic equilibrium does not exist when the pre-shock gas is xenon or argon.

The temporal diminution of shock brightness, observed in the experiments with argon and xenon, was especially marked whenever the shock velocity did not vary; the brightness decreased very appreciably within a few microseconds. For example, in one xenon experiment the brightness temperature dropped from 67 000°K to 22 000°K within 2 μsec at D = 12 km/sec. Roth[2] observed a decrease of shock brightness in argon at 8.3 km/sec. This time dependence of luminosity is associated with the large spread of brightness temperatures for D > 10 km/sec in xenon and D > 13 km/sec in argon. We can thus account for the fact that in the experiments where the shock velocity increased steeply the maximum brightness temperatures were obtained. We believe that the dependence of luminosity on both velocity and acceleration of the front is associated with delay in the formation of the screening layer.

In some experiments with xenon and air-argon, where the time resolution was 10^{-7} sec (compared with 2×10^{-7} sec in the remaining experiments), we observed

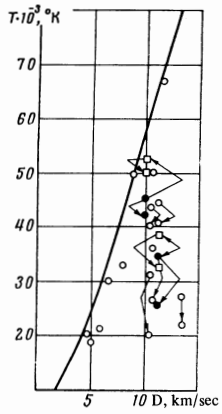
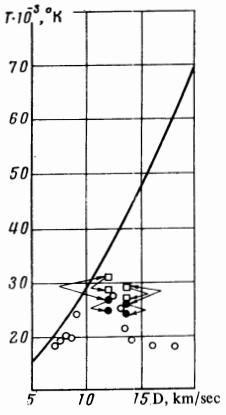


FIG. 6. Brightness temperature of shock front in xenon (with the same symbols as in Fig. 4).

FIG. 7. Brightness temperature of shock front in a mixture of argon and air. The air admixture was 5% for the measurements in the ultraviolet and yellow regions. The curve represents the calculated post-shock temperature for argon. The brightness temperature for blue light was not measured at 45°. Otherwise the symbols are as in Fig. 4.



a rise of shock brightness as the front approached close to the end window, as though a screening layer 0.5—1 cm wide preceded the front.

As a shock wave moves along a tube containing argon the front is observed to curve strongly toward the tube wall in the direction of the forward motion; in about 10 μsec the entire front becomes curved (Fig. 3). The brightness temperature corresponding to this formation lies in the range 15 000—25 000°K for all the measured velocities. This curvature appears to be associated with heating of the tube wall and of the adjacent gas by radiation from the front. In experiments where the gas along the tube axis was irradiated longer, as a result of the technique used for wave generation, similar brightness structuring was observed arising at the axis and propagating to the tube wall; the shape of the front was not studied in these experiments. In xenon and air slight curvature of the front was observed at the wall, but no difference in brightness as compared with the flat portion of the front. Because the brighter flat portion of the front disappears in time at higher wave velocities in argon, we were unable to measure the minimum brightness temperature that is established as the shock brightness diminishes with time.

CONCLUSIONS

1. The brightness temperatures corresponding to radiation in different spectral regions and at different angles with respect to the front are in agreement among themselves and with the calculated air temperature at shock velocities of 8—20 km/sec. This is evidence that the front radiates like a black body at a temperature equal to the true gas temperature behind the front. For the same reasons we can assume that near-blackbody radiation is emitted from the front up to velocities of 10 km/sec in xenon and 14 km/sec in argon.

2. The temperature of a shock-heated gas can be determined when the front is screened weakly by measuring the brightness of the front at different angles.

3. The measured brightness temperatures of 70 000 to 90 000°K place shock waves among the brightest light sources.

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