EXPLOSIVE-TYPE HIGH-TEMPERATURE RADIATOR FOR PHOTOMETRY

E. G. Popov and M. A. Tsikulin

The use of an amplitude-stable powerful shock wave in a gas has been proposed as a high-temperature standard of a black body radiator. In order to produce these waves, an explosive charge with a cumulative channel is used. The emission from such a source has been investigated over a wide range of the spectrum including the quartz ultraviolet, visible, and infrared sections.

In photometry technique, light sources using an incandescent object as the radiator are popular. One example is the reference tube with a tungsten ribbon or a uniformly heated cavity with an aperture simulating a black body. The temperature of these radiators usually does not exceed 3000°K, while in the investigation of certain phenomena brightness temperatures of $\sim 10^4$-10^{5}°K and higher are encountered. The great difference in brightness of the object being investigated and the comparison standard frequently make it very difficult to calibrate the radiation receivers. The high-temperature standard is suitable for this. The requirement for such a standard arises from measurements in the UV region where, because of low brightness, incandescent bodies in practice are unsuitable. Quite good results were given in attempts to adapt for these purposes an electric discharge in gases. Thus, a recently designed pulsed source ÉV-39 (ÉV-45) radiates as a black body with a temperature of 41,000°K over the region λ = 200-600 nm [1, 2].

Experiment and theory show [3, 5] that shock waves in air at atmospheric pressure and temperatures behind the wave front 10,000-50,000°K radiate as a black body over an extremely broad spectral range, spreading into the UV and IR region. The problem concerning a shock wave as a standard of black body radiation at high temperatures, suitable for photometric investigations over a wide spectral range, already has been raised by the authors (Patent No. 1,277,550). This question will be the subject of further study in this paper.

Production of Powerful Amplitude-Stable Shock Waves. In order to know the brightness temperature of a shock wave, using it as a pulsed radiation standard, it is sufficient to measure the velocity of the wave front. For example, by measuring the velocity with an SFR-2 photorecorder to an accuracy of ±1% and resorting to calculated shock adiabats, the temperature can be determined with an accuracy not worse than ±3%. In practice, however, it is preferable to have a source with a previously known brightness temperature which is constant during a certain time interval. In order to satisfy these requirements, an explosive charge with a cumulative channel is used to obtain strong shock waves (Fig. 1.). The charge is cast from TG 40/60 (40% TNT and 60 % hexogen).

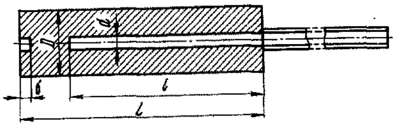

Fig. 1. Shaped charge and tube attachment.

Experiments showed that after initiation of the charge and emergence of the detonation in the head of the channel, the explosion products collapse and form a set in the channel leading the detonation front. The velocity of the jet increases and the velocity of the shock wave in the channel increases correspondingly. In traversing a path ~ 8d, the shock wave gains maximum velocity which is maintained during further motion. Figure 2 shows a

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 164-167, 1970. Original article submitted December 29, 1969.

photochromogram of the shock wave and jet in a glass tube used as the continuation of the channel (we used a shortened charge with $l = 5d$ in the experiment, which made it possible to observe in the tube the acceleration of the jet and the shock wave up to maximum velocity). Excitation of the shock wave on emergence of the detonation at the head of the channel, subsequent collapse of the combustion products and the formation of an amplitude-stable strong shock wave are recognizable on the photochronogram shown in Fig. 3.

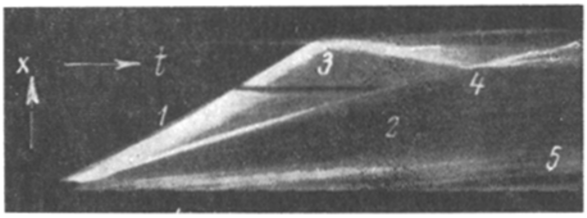

Fig. 2. Photochronogram of shock wave and jet in tube (the slit of the photorecorder is parallel to the tube axis).

It may be expected that with the detonation of a sufficiently long charge the length of the jet and column of shock-heated gas leads to their intensive retardation in the channel. Contact between the products of the jet and the shock-heated gas can induce disintegration or detonation of the explosive. In some experiments the length of the channel reached 30d, however the amplitude stability of the shock wave was maintained. Obviously, when $l \leqslant 30d$ friction and interaction with the explosive in the channel by motion of the shock wave have no significant effect. According to [6], these effects appear when $l \geqslant 100d$.

The magnitude of the stable shock wave velocity depends on the ratio of the diameters of channel and charge. When this ratio increases the velocity increases, although when $D/d \geqslant 4$ this increase is slowed down strongly. In experiments with charges having a channel diameter varying from 3-18 mm, the geometrical similarity of motion of the shock wave in the channel was verified. It was found that the similarity and stability of the shock wave are disrupted in the case of thin channel walls when $(D - d) \leqslant 10$ mm. As a result of this, the shock wave velocity is reduced. The instants distinguished can be explained by the proximity of the wall thickness to the critical detonation diameter of the explosive. Experiments with charges of cast TNT further confirm this, for which the deviation from similarity was manifested more strongly. Starting from the results given above, a charge with the following dimensions is taken for investigating the radiation of a stable shock wave: $d = 8$ mm, $D. = 30$ mm, $l = 120$ mm, $L = 150$ mm, depth below detonator $\delta = 10$ mm and charge weight 168 g. Careful measurements of the velocity of the stable shock wave in air, formed by the detonation of this charge, give 13.6 ± 0.1 km/sec. If we use the shock adiabat of air from [7], then the measured value of the velocity corresponds to a gas temperature behind the shock wave front of 24,000 ± 700°K.

With the chosen charge dimensions, observation inaccuracies have little effect on the velocity of the stabilized shock wave, because when $l > 8d$ the maximum velocity is established in the channel, the value of which when $D/d \geqslant 4$ depends weakly on the diameters d and D. From these same considerations, and also for an increase of the shock wave temperature, the choice of the largest possible ratio of D/d is confirmed, if the increase of the charge weight plays no part. Thus, for charges with $D = 60$ mm ($D/d = 7.5$) a velocity of 16.7 km/sec and a temperature of 32,000°K are measured; however, the charge weight was increased by a factor of 4.

Measurement of the Brightness Temperature. The brightness temperature was determined from photometric comparison of the optical densities produced on a photographic film with slit scanning of the shock wave and a brightness etalon on the SFR-2 instrument. The UV ($\lambda_{eff} = 330$ nm), blue ($\lambda_{eff} = 422$ nm) and yellow ($\lambda_{eff} = 560$ nm) regions of the spectrum were separated with color filters, the effective transmission wavelength of which λ_{eff} was found by taking account of the photoactinic correction. A pulsed ÉV-39 source [2] was used as the brightness standard.

Measurements of the brightness temperature were carried out in individual sections of the spectrum with spectral analysis of the radiation. The time resolved UV and visible radiations ($\lambda = 220$–700 nm) of the shock wave were recorded with a high-transmission spectrophotochronograph SP-111. A photochronograph SFR-2 with spectral attachments SP-77 and SP-78 was also used in the visible region. The spectral brightness of the temperature was measured in the range $\lambda = 220$-600 nm by photometric comparison of the optical densities of the spectrophotochronograms of the shock wave and of the ÉV-39 source. The optical density standards necessary for constructing the characteristic curve of the photosensitive layer were sensitized by exposure to the ÉV-39 source (for this purpose, step wedges [4, 5] were positioned at the focal arcs of the SFR-2 and SP-111 instruments). The spectral resolution, using the SP-111 with a

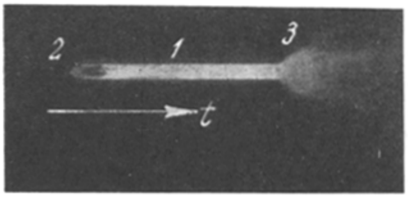

Fig. 3

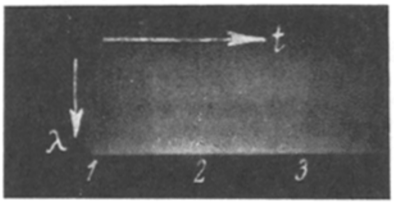

Fig. 4

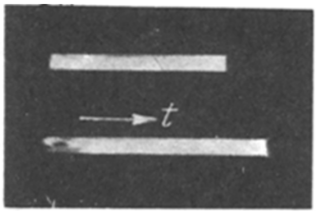

Fig. 5

Fig. 3. Photochronogram of the luminance of a shock wave in the channel (slit of photorecorder perpendicular to the tube axis). 1) Stable shock wave, 2) emergence of detonation at head of channel, 3) dispersal of shock-heated gas from the tube.

Fig. 4. Spectrophotochronogram of the brightness of a shock wave in a channel (λ = 390-700 nm), obtained on the SFR-2 instrument with SP-77 attachment. 1) Exit of detonation at the end of the channel, 2) stable shock wave, 3) dispersion of shock-heated gas from the tube; the broad bands in the spectrum are due to the spectral sensitivity of the photoemulsion.

Fig. 5. Photochronogram of luminance of shock waves giving a rectangular-shaped radiation pulse.

detachable grading of 1200 lines/mm was 0.7 Å. Spectrographs Q-12 and STÉ-1 were used in attempts to detect sharp lines in the shock wave emission spectrum; these gave a resolution of 0.1 Å.

The IR and visible radiation were investigated by means of photoelectric sensors. In the yellow (λ_{eff} = 560 nm), red (λ_{eff} = 660 nm) and near infrared (λ_{eff} = 778 nm) sections of the spectrum, separated by color filters, the radiation was recorded by a FÉU-22 photomultiplier The IR radiation in the section λ_{eff} = 1300 nm was recorded by an FD-GI germanium-indium photodiode. Signals from the FÉU-22 and the FD-GI were fed to OK-33 and OK-17M oscilloscopes.

An SI 10-300 tube was used as the brightness standard in the photoelectric measurements. The brightness temperature of a tungsten ribbon in the region λ_{eff} = 660 nm was measured by means of an ÉOP-51 precision optical pyrometer and in the experiment it was 2800 ± 10°K. From the results of these measurements and the table values of the spectral blackness of incandescent tungsten the brightness temperature of the ribbon in other parts of the spectrum was determined.

In the experiments, the objective was to project the ribbon of the tube or the shock wave onto a screen so that their image completely filled an opening in the screen. Behind the screen a frosted-glass color filter and photoelectric sensor were arranged in succession. The large difference in brightness between the shock wave and the tube ribbon was compensated by the setting of the diaphragm objective; in this case, the electronic equipment recorded only coincidence of the signal amplitudes and the brightness temperature was determined by measuring the diaphragm diameter at the compensator. The light signal from the strip tube was modulated with a rotating disc with openings and it was photographed from an oscilloscope screen.

The photographic and photoelectric procedures used provided a time resolution of 10^{-7} sec.

Analysis of Results. The shape of the radiation pulse on detonation of an explosive charge with a cumulative channel can be judged from Figs. 3 and 4. The luminescence time of the stable shock wave in the charge channel was 5 μsec. If a tube of cardboard or other dense material, not greater than 160 mm in length, was attached to the charge, the shock wave propagated along it without significant damping and its luminescence time was extended to 17 μsec.

Sometimes it is convenient to have a rectangular calibration pulse. The time of formation of the stable shock wave is shortened from 5 to 2 μsec if a long charge (L = 180 mm) is used, in which the bottom of the channel is not plane as in Fig. 1, but is in the form of a conical recess (Fig. 5, lower trace). The leading edge of the radiation pulse can be shortened to 0.1 μsec by cutting off that part of the channel where the stable shock wave is established with an opaque film (for example, carbon paper). The latter is destroyed

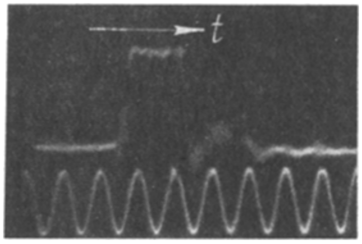

Fig. 6. Oscillogram of shock wave luminance in the IR region, $\lambda_{eff} = 1300$ nm with cutoff of the radiation pulse edges (frequency of markers, 10 μsec).

by the shock wave without introducing noticeable perturbations (upper trace in Fig. 5 and oscillogram in Fig. 6). The trailing edge of the pulse is cut off after ~1 μsec by the cracking of the quartz or glass window mounted on the end of the attached tube by the shock wave (Figs. 5 and 6).*

The emission spectrum of the shock wave is continuous. Lines were absent even on spectrograms with a resolution of 0.1 Å. Estimates of the linewidth under experimental conditions gave ~100 to 1 Å. The minimum width certainly is limited by Doppler broadening to ~0.1 Å. The absence of lines, therefore, is due to the nature of the emission from the shock wave and not to the capabilities of the procedure. This type of spectrum approximates to the shock wave from incandescent bodies.

The following values of the brightness temperature of the stable shock wave were measured in different parts of the spectrum:

λ, nm	230	330	432	560	600	660	778	1300	
$T \cdot 10^{-3}$ °K	24.5	23.5	23.5	24.6	25.2	—	—	—	(from spectrophomochromogram)
$T \cdot 10^{-3}$ °K	—	23.0	23.0	24.0	—	—	—	—	(from photochronogram)
$T \cdot 10^{-3}$ °K	—	—	—	23.0	—	22.6	23.0	25.1	(photoelectric measurements)

Temperature pulsations with time and over the channel cross-section did not exceed ±1000°K. These same limits include the temperature spread from experiment to experiment. For charges prepared from 50/50 TNT/hexogen, the brightness temperature is 1000°K lower. By avoiding inhomogeneities when casting the charge and by initiating the charge precisely along the axis, the pulsation could be reduced to ±400°K. The constancy of the brightness temperature with motion of the shock wave, when the geometrical thickness of the heated gas increases, confirms its large optical thickness.

If air is replaced by some other gas, the temperature can be increased and shifted into the region of the vacuum ultraviolet. If the channel is filled with neon, the temperature increases to 32,000°K. In argon the shock wave temperature in blue light was 40,000°K, although in argon and the heavier inert gases nonstationary screening and instability of the plane shock front [4] complicate the production of stable radiation pulses.

The experimental results obtained, supplementing the previous investigations [4, 5], confirm the conclusions that shockwaves in the specified range of amplitudes radiate as an absolutely black body. Shock waves formed by the detonation of a charge with a cumulation channel were found to be a source of comparatively stable radiation pulses. The source described here was used by the authors as a brightness standard for investigating the radiation properties of shockwaves in inert gases [8]. The small mass and dimensions, the nondependence on mains electricity and simplicity of manufacture permit the source to be used not only in laboratories (bomb-chambers) but also under field (test site) conditions.

The authors are grateful to Yu. A. Zatsepin and S. V. Kondrat'ev for assistance in the experiments.

LITERATURE CITED

1. N. N. Ogurtsova, N. V. Podmoshenskii, and M. I. Demidov, "A Pulsed light source with radiation similar to the radiation of an absolutely black body at a temperature of ~40,000°K," Optiko-Mekhan. Prom-st', No. 1 (1960).
2. M. I. Demidov, N. N. Ogurtsova, I. V. Podmoshenskii, and V. M. Shlenina, "Energy Calibration of the radiation from a pulsed light source ÉV-45(ÉV-39) in the ultraviolet region of the spectrum," Zh. Priklad. Spektroskopii, 10, No. 3 (1968).
3. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena [in Russian], Nauka, Moscow (1966).

---

*The cutoff of the pulse edges was used when investigating the emission from the stable shock wave by means of the Q-12 and STÉ-1 spectrographs.

4. Yu. A. Zatsepin, E. G. Popov, and M. A. Tsikulin, "Brightness of the front of shock waves in certain gases," Zh. ÉTF, 54, No. 1 (1968).
5. E. G. Popov and M. A. Tsikulin, "Spectral brightness of shock waves in air," Zh. ÉTF, 56, No. 2 (1969).
6. A. S. Zagumennov, N. S. Totov, Yu. I. Fadeenko, and V. P. Chistyakov, "Detonation of long charges with cavities," Priklad. Matemat. i Teor. Fiz. No. 2 (1969).
7. N. M. Kuznetsov, Thermodynamic Functions and Shock Adiabats of Air at High Temperature [in Russian], Mashinostroenie, Moscow (1965).
8. E. G. Popov and M. A. Tsikulin, "Spectral distribution of radiation from shock waves in inert gases," ZhÉTF, 57, No. 2 (1969).