STRUCTURE OF THE HEATING LAYER AHEAD OF THE FRONT OF A STRONG INTENSELY EMITTING SHOCK WAVE

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The problem of the structure and brightness of strong shock waves arises in the investigation of such phenomena as the motion of large meteoroids in the atmosphere, optical and electrical discharges, the development of strong explosions, and other similar processes and in the creation of powerful radiation sources based on them. This problem also has a general physics interest. As the propagation velocity of a strong shock wave increases the gas temperature behind its front and the role of emission grow. Part of the radiation emitted by the gas heated and compressed in a shock wave is absorbed ahead of the front, forming the so-called heating layer. The quasisteady structure of a strong intensely emitting shock wave was studied in [1, 2]. In this case a diffusional approximation and the assumption of a gray gas were used to describe the radiation transfer. They introduced the concept of a wave of critical amplitude, when the maximum temperature T_- in the heating layer reaches the temperature T_a determined on the basis of the conservation laws, i.e., from the usual shock adiabat; it is shown that behind a compression shock moving through an already heated gas there is a temperature peak in which the maximum temperature T_+ exceeds T_a. The problem of the quasisteady structure of an emitting shock wave in air of normal density was solved numerically in [3]. The angular distribution of the radiation was approximately taken into account – it was assigned by a simple cosinusoidal law. The spectral effects were taken into account in a multigroup approximation. They introduced 38 spectral intervals, which is insufficient to describe a radiation spectrum with allowance for the numerous lines and absorption bands.

The nonsteady problem of the motion of a strong intensely emitting shock wave is analyzed in the present report, as in [4, 5], with detailed allowance for the spectral composition of the radiation (456 spectral intervals were introduced) and its angular distribution (13 rays in the forward direction and as many in the reverse direction). We used detailed tables [6] of the optical properties of hot air, extended into the high-temperature region (up to 30 eV) and into the region of higher quantum energies ε (up to 250 eV). Absorption and emission in lines were taken into account in the region of $\varepsilon \leq 18.6$ eV (where most of the spectral intervals were concentrated).

The solution of the nonsteady problem allows one to trace the evolution of the temperature peak behind the shock wave front and of the heating layer ahead of it and, in particular, to find the law of growth of the temperatures T_+ and T_- up to their limiting values corresponding to the quasisteady state. To hasten the calcu-

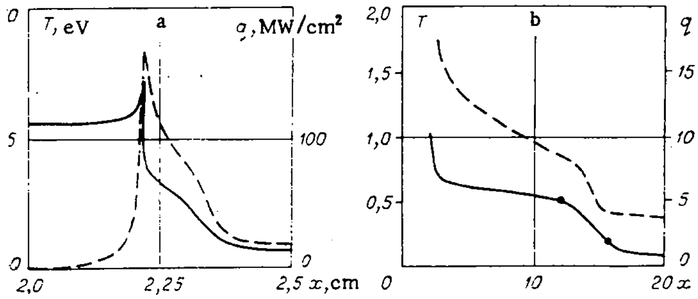

Fig. 1

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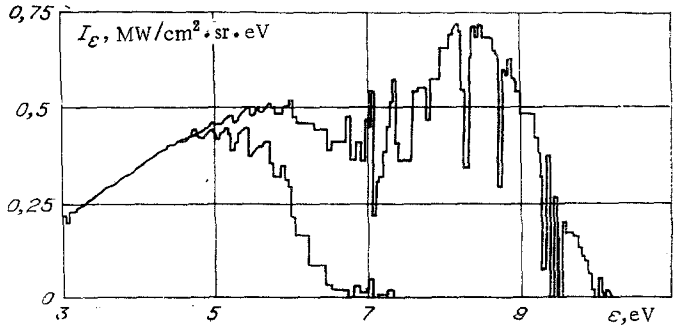

Fig. 2

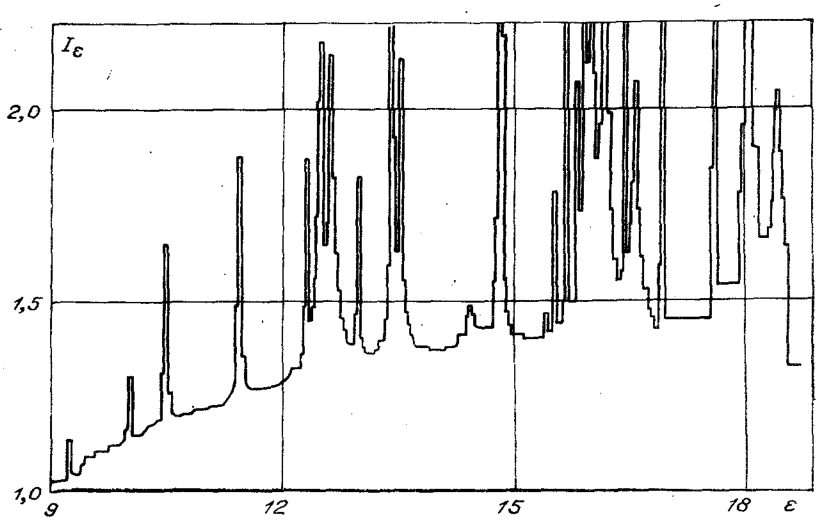

Fig. 3

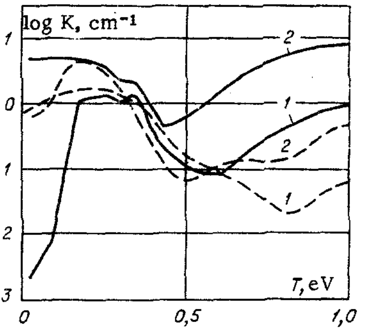

Fig. 4

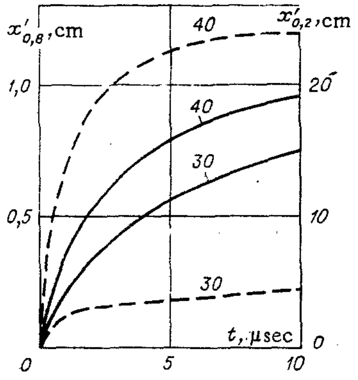

Fig. 5

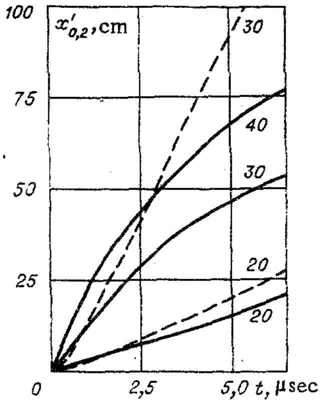

Fig. 6

lations of such a radiation–gasdynamic problem we used the method of averaging of the radiation-transfer equations [7], which has proved to be quite effective.

The propagation of shock waves in air with a density of 0.03-0.01 of normal at velocities of 20-50 km/sec for the piston generating the shock wave was analyzed in [4, 5]. It was shown that the thicknesses of the heating layers reach such great sizes that the establishment of a quasisteady state cannot be observed under laboratory conditions with the limited dimensions of the installations used, usually not exceeding 30-100 cm. In the present report the motion of shock waves in air is studied theoretically in the same velocity range, but the density range is widened in the direction of an increase (up to 0.1 of normal density) in order that the establishment of a quasisteady structure could take place in shorter times and in smaller distances.

In the description and analysis of the calculated results in [4, 5] principal attention was paid to those layers of the heating "tongue" in which the temperature is rather high – on the order of 0.7-1.0 eV or more. At the same time, a detailed analysis made of the results of our calculations, partly described in [4, 5], and of an additional series of calculations showed that the heating layer has a complicated structure. There are two clearly expressed regions in it: a hot zone with a temperature of 0.7-1.0 eV or more and a far more extended cool zone with a temperature of 0.5-0.7 eV or less. Both zones have rather sharply expressed fronts. The presence in the heating layer of two temperature zones differing markedly in extent and of two heating fronts has evidently not been noted before. We will discuss this complicated structure of the heating layer in more detail and analyze the causes of its formation.

Let the piston causing the motion of the shock wave move with a constant velocity $v = 30$ km/sec in air with a relative density $\delta = 0.1$. In Fig. 1 we present the distribution of the temperature T (solid curves) and radiation flux density q with respect to distance x, measured from the piston, for a time $t = 7.3$ μsec, when a quasisteady structure has already been almost established. Figure 1a, shows the distributions of T(x) and q(x) in the hot zone while Fig. 1b, shows those in the cool zone. In this case the shock wave is subcritical and the maximum temperature in the heating layer is $T_- = 4.0$ eV, whereas the gas temperature near the piston is close to the temperature T_a from the shock adiabat of [8] (5.7 eV). The temperature in the peak is $T_+ = 7.3$ eV. The maximum radiation flux escaping from the shock wave front exceeds the blackbody radiation flux at a temperature T_a owing to the intense emission from the peak, which basically has a volume character. In the period under consideration the quantities T_+, T_-, and q_m hardly vary with time and are already rather close to their quasisteady values. The extent $x'_{0.8}$ of the hot zone (with a temperature of more than 0.8 eV) is about 0.2 cm, and it varies rather slowly with time, while the thickness $x'_{0.2}$ of the cool zone (with a temperature of more than 0.2 eV) is 13 cm and is still growing noticeably. (Here and later distances measured from the shock wave front will be marked with a prime.) The bend in the temperature profile at about 0.7 eV, which separates, as it were, these two temperature zones of considerably different thicknesses, is rather well seen.

An analysis of the spectra and the groups of radiation fluxes shows that the formation of the hot zone is mainly connected with the absorption of radiation with quantum energies $\varepsilon > 10$ eV, i.e., just the radiation which is emitted by the shock wave front for the most part. But the formation of the relatively cool zone is connected with the absorption of radiation of from 6.5 to 10 eV, i.e., that which lies outside the limits of radiation transmission by cold air, on the one hand, while it has not yet been absorbed in the hot zone of the heating layer, on the other. The dependence of the radiation intensity I_ε on the quantum energy ε at the time $t = 7.3$ μsec for the spectral section of $3 \leq \varepsilon \leq 10$ eV in the direction perpendicular to the shock front is shown in Fig. 2. The upper curve corresponds to a point with a temperature $T = 0.5$ eV behind the front of the cool part of the heating layer while the lower curve corresponds to a point with a temperature $T = 0.2$ eV ahead of this front (the points are marked by dots on the temperature distribution presented in Fig. 1b).

We note that in the region of relatively low-energy quanta the spectra almost coincide, while at the point of $T = 0.2$ eV the spectrum is very close to the spectrum of escaping radiation. It is seen that quanta with energies of 6.5-10 eV already play an appreciable role in the radiation spectrum at the start of the cool zone. In this region the spectrum is strongly "jagged," whereas it is smooth at $\varepsilon \leq 6.5$ eV. The spectrum of escaping radiation is also smooth. In the section from 1.5 to 5 eV the effective temperature T_e varies slowly, in the range of 5.6-6 eV. Here it proves to be even higher than the gas temperature T_a. This is connected with the role of the temperature peak. Although the radiation of this layer does have the character of the volume radiation, having rather short wavelengths, which is mostly emitted by this region, this proves to be no longer so for the long-wavelength radiation, particularly the visible range, for which the mean free path of the radiation in the plasma is considerably shorter. At the same time, the increase in brightness temperature owing to the peak is partially compensated for by the absorption of this radiation in the hot zone of the heating layer. In the region of quantum energies $\varepsilon < 1.5$ eV the value of T_e falls rather rapidly, which must be kept in mind when using strong shock waves as brightness standards.

As for the radiation emitted by the front, its spectrum differs strongly from a Planckian spectrum at quantum energies of more than 9-10 eV. As follows from Fig. 3, where the dependence of I_ε on ε is given for the section from 9 to 19 eV, many strong and broad lines are distinguished against the continuous background. And the spectrum is no less complicated at all the intermediate points between the shock wave front and the cool zone. It gradually contracts, as it were, owing to the cutoff on the hard side. Thus, at the point of $T = 0.7$ eV the spectrum still extends to 12 rather than to 10 eV, as occurred at the point with $T = 0.5$ eV. At the same time, the cutoff of part of the spectrum takes place in an uneven way and the spectrum is strongly jagged in the entire region, with lines and absorption bands playing an important role. Thus, in the region of essentially nonequilibrium radiation (in the temperature peak and in the heating layer) the radiation spectrum is complicated.

The results of calculations with detailed allowance for the spectral composition of the radiation are presented above and later. It was interesting to ascertain how necessary is such a degree of detail in the determination of the spectrum. Calculations were made in which the spectrum was taken into account in a 13-group approximation with the following group boundaries: 0 ... 1.596 ... 3.084 ... 4.076 ... 6.524 ... 7.052 ... 7.950 ... 8.663 ... 9.965 ... 10.90 ... 12.38 ... 18.61 ... 80.59 ... 248 eV. It turned out that the values of T_+ and T_- were calculated with an accuracy of about 15-20%, while the difference in the thickness of the cool zone was large.

Thus, for the case of $v = 20$ km/sec and a relative air density $\delta = 0.03$ the thickness $x'_{0.2}$ of the layer with a temperature $T > 0.2$ eV obtained in the solution of the spectral problem at 6.5 μsec already differs more than threefold from the analogous value obtained in the 13-group approximation. It is possible that with an increase in the number of groups in the region of 6.5-10 eV one could reduce this difference, but such a laborious investigation was not carried out, since the expenditures of computer time on the solution of the problem with 456 spectral intervals using the averaging method [7] proved to be almost the same as that for the solution of the problem in the 13-group approximation. This indicates the efficiency of the use of methods like that of [7] in solving problems of such a kind.

It is natural that the form of the radiation spectrum, and with it the structure of the heating layer, are connected with the character of the variation of the spectral coefficients of absorption as a function of temperature and frequency.

The logarithms of the average group coefficients of absorption K_i as functions of the temperature T at a relative air density $\delta = 0.1$ for two groups of radiation are shown in Fig. 4. Curve 1 pertains to the group with boundaries of 6.52-7.95 eV and curve 2 pertains to the group with boundaries of 7.95-9.96 eV. The solid curves correspond to the average Planckian values of the coefficients in these groups while the dashed curves correspond to the variation with temperature of the true average coefficients of absorption calculated in accordance with the method of [7] from the true spectrum occurring at the points with the given temperature in the heating layer at 7.3 μsec. Quanta with energies $\varepsilon > 9.96$ eV are almost entirely abosrbed in the hot zone and do not penetrate into the cool zone, while quanta with energies $\varepsilon < 6.5$ eV, weakly absorbed by the cool zone for the most part, "depart to infinity."

Thus, the formation of the cool zone is dependent on quanta with energies lying in the range of 6.5-10 eV. It is seen from Fig. 4 that in the region of temperatures up to 0.35 eV the average coefficients of both groups of radiation of this range of ε are large (on the order of 1-5 cm^{-1}), thanks to which the leading front of the cool zone develops. Then, in the temperature range of 0.4-0.6 eV, the values of K_i fall sharply, which results in the formation of a temperature plateau. It is interesting to note that, according to Fig. 4, in the temperature range above 0.6 eV the Planckian-averaged group coefficients of absorption exceed by more than an order of magnitude the true average coefficients of absorption which determine the distance to which the radiation is transferred.

Therefore, in solving the multigroup problem using Planckian coefficients a considerable portion of the radiation with quantum energies of 6.5-10 eV will be absorbed at the edge of the hot zone at a temperature of 1 eV, which leads to a considerable decrease in the propagation velocity and thickness of the cool zone in comparison with the solution of the spectral problem.

Various processes contribute to the value of the total coefficient of absorption. But in the roughest approximation the absorption by relatively cool air in the region of 7-9 eV takes place mainly in the dissociation continuum of molecular oxygen adjacent to the Schumann–Runge bands and the bands of nitric oxide. The clearing of air at temperatures above 0.4-0.5 eV is connected with the dissociation of O_2 and NO. In fact, according to the Tables of [8], at temperatures of 2000, 3000, 4000, 5000, and 6000°K and a relative air density $\delta = 0.1$ the O_2 concentration is 0.205, 0.166, 0.048, 0.005, and 0.001, respectively, while the NO concentration is 0.008, 0.043, 0.056, 0.032, and 0.018. So the increase in the coefficient of absorption at low temperatures in some regions of this part of the spectrum is connected with the formation of NO, with the excitation of molecules, and with the strengthening of absorption in the molecular bands of O_2 and NO.

Thus, the clearing of air in the plateau region of the low-temperature zone of the heating layer is connected mainly with the dissociation of molecular oxygen and nitric oxide, while the leading front of the cool zone can be called a wave of dissociation of O_2 and NO with subsequent dissociation of N_2 and ionization.

A complicated structure of the heating layer can evidently develop in the propagation of shock waves not only in air but also in other molecular gases, as well as in mixtures of atomic gases with considerably different ionization potentials of individual components of the mixture.

The complicated two-front and two-zone structure of the heating layer was observed in the entire range of velocities of shock wave motion and relative air densities analyzed. The distance $x'_{0.8}$ (the point with a temperature $T = 0.8$ eV (dashed curves)) and the distance $x'_{0.2}$ (the point with a temperature of 0.2 eV (solid curves)), which characterize the thicknesses of the hot and cool layers, respectively, are given in Fig. 5 as functions of the time t for the case of a relative air density $\delta = 0.1$. The numbers near the curves give the piston velocity v, km/sec. It is seen that the extent of the cool zone considerably (by almost 2 orders of magnitude) exceeds the extent of the hot zone. A similar situation is also retained for other air densities.

The values of $x'_{0.2}$ for relative densities $\delta = 0.01$ and 0.03 (dashed and solid curves, respectively) are presented in Fig. 6. As follows from Figs. 5 and 6, as well as from the results presented in [4, 5], the thicknesses of the hot and cool zones increase with an increase in the velocity of the shock wave front or the piston velocity and with a decrease in the air density. With this the thickness of the cool zone can reach very large sizes. For example, according to Fig. 6, for the case of $v = 30$ km/sec and $\delta = 0.01$ the value of $x'_{0.2}$ has already reached 100 cm by 5.5 μsec, and it continues to grow rapidly. We note that T_+ and T_- have already reached almost their limiting values by this time; the thickness of the hot zone, which is about 7 cm, also continues to grow, but slower than $x'_{0.2}$. Thus, the quasisteady state of the wave structure is still far from being reached, on the whole. Such large values of the thickness of the heating layer lead to requirements of a very large transverse size for the channel in which the shock wave propagates in those cases when such a shock wave structure is investigated experimentally, which greatly hinders such investigations because of the increased demands on the total energy of the installation. At the same time, the effect of "clearing" of great thicknesses of gas for ultraviolet radiation with relatively low air heating ahead of the shock wave front can evidently be used both for various technical purposes and for diagnostics of the radiation within the heating layer. It therefore seems desirable to verify it experimentally.

In conclusion, we note that in future theoretical investigation of the structure of the heating layer ahead of the front of a strong intensely emitting shock wave it is desirable to clarify the possible influence of some nonequilibrium in the state of the gas in this zone.

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