MECHANISM RESPONSIBLE FOR THE COOLING OF AIR HEATED BY A STRONG SHOCK WAVE

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The problem of the cooling of a spherical volume of air after departure of a shock wave in air of normal density is studied numerically. Based on the results obtained, a conclusion is made that no radiative cooling wave exists in a real atmosphere.

In [1-3] a mechanism is suggested and a theoretical model is developed for radiative cooling of heated air after departure of a shock wave. In the formulation of the problem, the authors ignored the reverse motion arising inside the hot spherical volume. Moreover, it is hypothesized that this region continuously expands. In [4], it is necessary to take into account the air motion due to local cooling at the wave front and an analytical study is made of a complete system of radiative gasdynamic (RGD) equations for this problem under the assumption of stationarity of the cooling wave. Based on the solution obtained, the conclusion is made that with account for the motion the mechanism of cooling by means of a stationary radiative cooling wave is not realized. However, the authors note that the existence of a transient cooling wave remains in question. In order to answer this question, a problem based on a complete system of RGD equations in the nonstationary formulation is studied numerically here.

The authors report the results of modeling of cooling of a hot spherical volume of air after departure of a strong shock wave in an air atmosphere with a density of $\rho = 1.29 \cdot 10^{-3}$ g·cm^{-3}. Temperature profiles are obtained for the time interval bounded below by the moment of establishment of the normal pressure in the region of interest and above by the moment of brightening of the heated volume, i.e., by a decrease in the temperature at the center of the sphere to the temperature of transparency of the air (0.6-0.8 eV).

We consider a problem that models the hydrodynamic expansion and cooling of a large spherical volume of highly heated air with the initial energy E_0 and radius R_0. These parameters are chosen so that the temperature inside is higher than 10^5 K and the linear dimensions of the heated region exceed 100 m. Just such a problem is discussed in [1].

The hydrodynamic regime of expansion of the heated region in this formulation is described by a system of nonstationary equations of gas dynamics for a one-dimensional spherical geometry. For this class of problems it is convenient to write the equations in Lagrange variables [5]:

$$\frac{\partial}{\partial t}\frac{1}{\rho} = \frac{\partial}{\partial s} r^2 v ; \quad \frac{\partial}{\partial t} v = - r^2 \frac{\partial}{\partial s} p ; \quad \frac{\partial}{\partial t} r = v ;$$

$$\frac{\partial}{\partial t}\left(\varepsilon + \frac{v^2}{2}\right) = - \frac{\partial}{\partial s}(p r^2 v) - \frac{\partial}{\partial s} S ; \quad p = p(\gamma, T) , \quad \varepsilon = \varepsilon(\rho, T) . \tag{1}$$

The term $(\partial/\partial s)S$ represents energy release in the medium not associated with hydrodynamic transfer of energy. In our problem, it describes the energy release due to radiation processes in the heated air. In order to evaluate the radiation fluxes, we employ the diffusional approximation, which is valid for our problem in the region under consideration within the whole time interval [1, 3]. Based on the above, we write the equations in a one-dimensional spherical geometry for the multigroup approximation relative to the spectrum:

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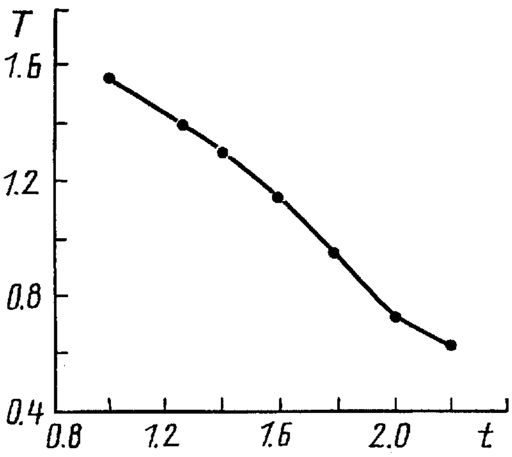

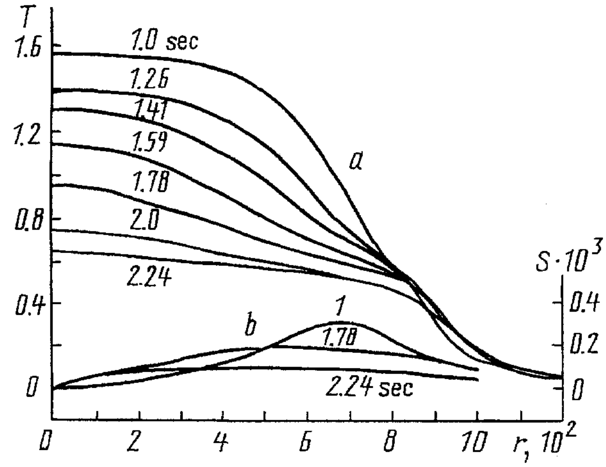

Fig. 1. Time variation of the temperature at the center of the heated region ($r = 0$). T, eV; t, sec.

Fig. 2. Spatial distribution of the temperature (a) and radiation flux (b) for different moments of time. r, m; S, $W \cdot cm^{-1}$.

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 S_k) + \kappa_k U_k = \kappa_k Q_k; \quad \frac{l}{3}\frac{\partial}{\partial r}(U_k) + S_k = 0;$$

$$S = \sum_{k=1}^{N_g} S_k, \quad Q = \frac{60\sigma}{\pi^4 k^4}\int_{\varepsilon_k}^{\varepsilon_{k+1}} \frac{\varepsilon^3 d\varepsilon}{\exp(\varepsilon/kT) - 1}. \tag{2}$$

The thermodynamic properties of air in the range of specific internal energies $0.37-2.5 \cdot 10^4$ $kJ \cdot g^{-1}$ were specified in the form of tables [6] as the functional dependence $\log T = f(\ln \rho, \ln \varepsilon)$. For energies below and above the indicated limits, we used the equation of state of an ideal gas for the cold and the fully ionized air, respectively.

The optical properties of air were also described in tables in the multigroup approximation in the form of the functional dependence

$$\ln \kappa_{ijk} = f(\ln \rho_i, \ln T_j, k)$$

$$(i = 1, \ldots, 11, \; j = 1, \ldots, 39, \; k = 1, \ldots, N_g).$$

The spectral properties of the medium are taken into account in the six-group approximation in the ranges 0.015–0.511–1.41–2.71–4.51–6.52. Use was made of absorption coefficients averaged both according to Planck and to Rosseland within the indicated limits. Tables of the coefficients were composed for the temperature range 0.03–1778 eV. For low temperatures of 0.03–2 eV they were obtained using the data from [7], for temperatures above 2 eV the coefficients for air were taken from [8].

We calculated the diffusional system of radiative transfer equations (2) using a scheme obtained by matching, at the nodes of a three-dimensional grid, the analytical solutions of the diffusion equations for optically homogeneous cells under the assumption of spatial linearity of the temperature portion of the radiation sources Q. The system of linear finite-difference equations approximating the diffusion equations was solved by the method of matrix elimination. In the diffusion equations, we used the Planck mean group absorption coefficients for air. Since the expressions for the coefficients of the linear equations of this system are bulky, we do not cite the system. To check the realized algorithm, we performed test calculations of heat propagation in the case of radiant heat conduction. The results of the numerical calculations agree well with the analytical calculation.

To calculate the gasdynamic parameters, we used a completely conservative scheme whose finite-difference form is as follows [5]:

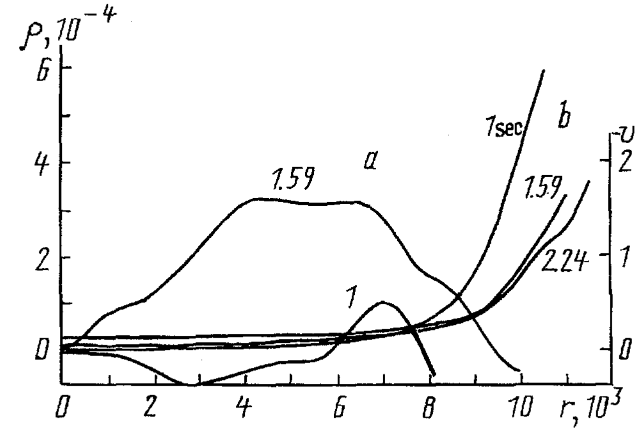

Fig. 3. Spatial distribution of the velocity (a) and density (b) of the heated region for several moments of time. v, m·sec^{-1}; ρ, g·cm^{-3}.

$$v_t = Rp_s^{(\alpha)}; \quad r_t = v^{(0.5)}; \quad \left(\frac{1}{\rho}\right)_t = (Rv^{(0.5)})_s; \quad \varepsilon_t = -\,p^{(\alpha)}\,(Rv^{(0.5)})_s,$$

where $R = (r^2 + r\bar{r} + \bar{r}^2)/3$; α is a free parameter, $0 \le \alpha \le 1$ (in the calculations we used $\alpha = 0.5$); $p_s = (p_{i+1/2} \pm p_{i-1/2})/0.5(h_i + h_{i-1})$ is the derivative of the backward pressure on a nonuniform three-dimensional grid.

To calculate the shock wave, an artificial viscosity was introduced: the quadratic $W_\alpha = 1.2$, the linear $W_\beta = 0.6$. These coefficients were chosen based on results obtained by test calculations. Calculations of the common test problems of breakdown of pressure discontinuity, a point explosion, and a piston moving at a constant speed showed good agreement with analytical solutions, thus giving the possibility of correctly describing the physics of processes upon solving real gasdynamic problems. In such a manner we obtained a closed finite-difference scheme for modeling the problem of the cooling of air after departure of a shock wave.

For modeling, we used a nonuniform mass grid with a fixed number of cells. When a disturbance reaches the bounds of the calculation region, the sizes of the cells are doubled. In the calculation, upon reaching the required moment (1 sec in our case) the calculation region was localized within the heated volume to allow a detailed description of the medium parameters in this region.

The calculation results in Figs. 1-3 show the dynamics of the cooling of a spherical volume of heated air with $R \sim 10^3$ m. At a late stage (by 1 sec), the shock wave is far beyond the grid used for our problem. By this moment, the pressure within the entire region is 1 atm and, as seen in Fig. 2, the heated region continues to broaden slightly – the velocity inside the volume is less than 100 m·sec^{-1}. Simultaneously, in the region with the maximum temperature gradient reverse motion develops, which is caused by a pressure gradient due to local cooling at the place where the radiation flux is at its maximum. The form of the temperature profile at this and subsequent moments actually resembles that in the case of a cooling wave [1], though no distinct step is seen. At the subsequent moments, the profile preserves its form and position in space. Changes due to a decrease in the temperature are observed only in its high-temperature part. In Fig. 1 the temperature is seen to monotonically decrease at the center for the whole time interval, which is contradictory to the concept of a cooling wave. By the moment 1.59 sec (Fig. 3), almost the entire space of the hot volume is involved in the reverse motion, while the radius of the heated region remains constant. In this zone, an equilibrium state is attained: the greater the energy transferred by radiation, the higher the pressure gradient and the more intensely the cold air flows in and becomes heated by radiation, thus preventing the distinct small temperature step from moving inward. At the same time, the air density at the boundary of the hot sphere decreases, but inside the volume it increases and by the moment 2.24 sec it increases more than fourfold. With an overall decrease in the temperature, the peak of the radiation flux becomes less pronounced and is displaced toward the center but not as rapidly as the temperature decreases. Already by the moment 1.4 sec, when the temperature at the center is still high, the heated region becomes quite transparent, thus indicating volume energy losses. However, energy losses for radiation are not the main factor responsible for the temperature decrease in the heated region. The basic portion of the energy is consumed for radiative heating of the incoming air.

To sum up, the heated air after departure of a shock wave releases energy as a result of volume energy losses and intense inflow of cold air into the heated region.

REFERENCES

1. Ya. B. Zel'dovich, A. S. Kompaneets, and Yu. P. Raizer, Zh. Éks. Teor. Fiz., **34**, 1278-1289 (1958).
2. Ya. B. Zel'dovich, A. S. Kompaneets, and Yu. P. Raizer, Zh. Éks. Teor. Fiz., **34**, 1447-1455 (1958).
3. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena [in Russian], Moscow (1966).
4. G. S. Romanov and D. É. Skoromnik, Inzh.-Fiz. Zh., **61**, No. 3, 437-442 (1991).
5. A. A. Samarskii and Yu. P. Popov, Difference Schemes of Gas Dynamics [in Russian], Moscow (1975).
6. N. M. Kuznetsov, Thermodynamical Functions and Shock Adiabatic Curves of Hot Air [in Russian], Moscow (1970).
7. I. B. Alibova, L. M. Biberman, V. S. Vorob'ev, et al., Optical Properties of Hot Air [in Russian], Moscow (1970).
8. S. I. Kas'kova, G. S. Romanov, L. K. Stanchits, et al., Tables of Thermophysical Characteristics, Composition, and Radiative Losses of a Multicharge Air Plasma in the Local Ionization Equilibrium State [in Russian], Deposited in VINITI, No. 5268-1390 (1991).