PISTON IN A DETONATING GAS

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Some problems of flows of gas mixtures with exothermal reactions behind shocks were examined in [1-5]. In particular, the problem of a point explosion in a hot gas mixture was examined taking account of the chemical reaction kinetics. Motions of an ideal, non-heat conducting, perfect gas are used below in the case of the problem of a symmetric piston moving in a hot mixture. A model which takes account of the ignition delay time and the subsequent simultaneous occurrence of the direct and reverse reactions [3] is taken for the gas flow.

1. Let a gas medium, at rest at the initial time, be propelled by a piston according to the law $r_p = \lambda_p t^\delta$, where λ_p, δ = const. A shock [6] forms in front of the piston and excites chemical reactions with the liberation of heat.

Let us consider some features of the solution for a model in which the chemical reaction behind the shock front is activated after termination after a period of induction. The reaction governing the period of induction t_{ind} is described by the equation [3]

$$dc/dt = -1/t_{ind} = -k_1 p^{n_1} \rho^{l_1} \exp(-E_1\rho/p), \tag{1.1}$$

where c is the fictitious concentration, E_1 is the activation energy of the period of induction, p is the pressure, ρ is the density, k_1, n_1, l_1 are certain constants. For $n_1 > 0$, $l_1 > 0$ it follows from (1.1) that the induction time is short for large p. The quantity t_{ind} increases as the shock attenuates and p decreases, and, therefore, the spacing between the shock front and the combustion reaction zone also grows, i.e., from some time it is impossible to take the shock and the chemical reaction zone as one surface of discontinuity, a detonation wave. A deduction of the possibility of splitting of the detonation wave in the phenomenon of a point explosion in a detonating gas was made in [1]. Test data on the initiation of hot gas mixtures by using a laser beam [7] were an experimental confirmation of the flow pattern described above.

The equation describing progress of the chemical reaction is taken in the form

$$\frac{d\beta}{dt} = -k_2 \beta^{m_1} p^{n_2} \rho^{l_2} \exp\left(-\frac{E_2\rho}{p}\right) + k_3 (1-\beta)^{m_2} p^{n_3} \rho^{l_3} \exp\left(-\frac{E_3\rho}{p}\right), \tag{1.2}$$

where β is the mass fraction of the unburned gas, E_2 is the activation energy for the direct reaction ($E_2 \geq 0$), E_3 is the activation energy of the reverse reaction, and k, m, n, and l are certain constants.

The reaction (1.1) proceeds without heat liberation. On the shock front the quantity is c = 1.

The disappearance of c denotes termination of the induction period and the beginning of the reaction (1.2) which proceeds with heat liberation. The concentration is $\beta = 1$ up to the beginning of the reaction (1.2).

The gas motion will be described by (1.1) and (1.2) in combination with the mass, momentum, and energy conservation equations, which can be taken in the form

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial r} + j\frac{\rho u}{r} = 0, \quad \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{1}{\rho}\frac{\partial p}{\partial r} = 0. \tag{1.3}$$

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial r} - \frac{1}{\rho}\left(\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial r}\right) = 0, \quad h = \frac{\gamma}{\gamma - 1}\frac{p}{\rho} + \beta Q,$$

where u is the velocity of the medium, γ is the adiabatic index, Q is the heat producing capacity per unit mass of the fuel mixture; and j = 0, 1, 2 for the plane, cylindrical, and spherical cases. If the quantities E_i and Q are constants, the problem can be self-similar in the case of a variable initial gas density $\rho_1 = Ar^{-\omega}$ (ω 3, A = const) under the condition that the initial pressure p_1 can be neglected as compared with the pressure behind the shock. The class of self-similar solutions of the system (1.1)-(1.3) has been studied in [2]. We shall consider $\omega = 0$. The problem is not self-similar in this formulation, hence, a complete investigation can only be conducted by methods of numerical integration of the partial differential equations.

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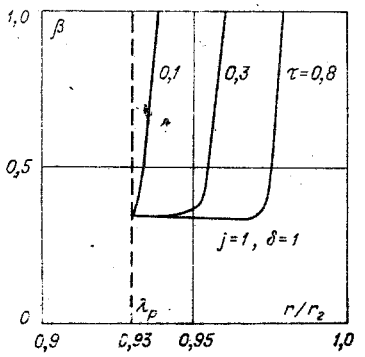

Fig. 1

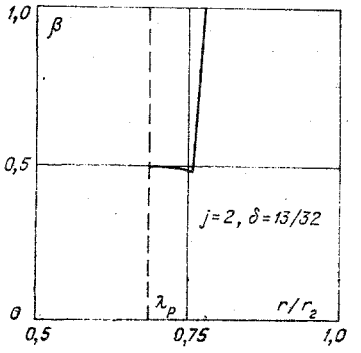

Fig. 2

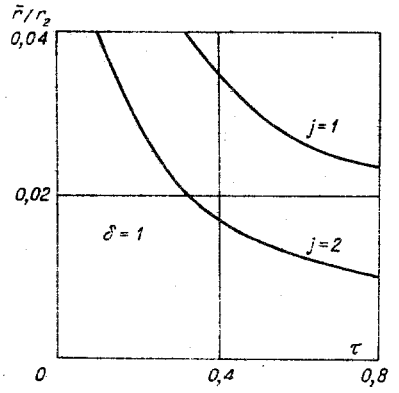

Fig. 3

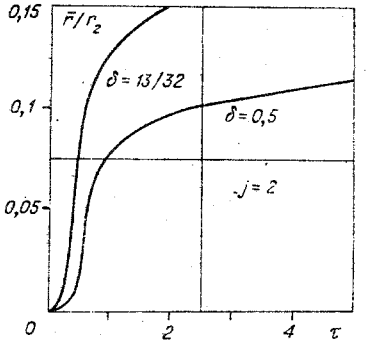

Fig. 4

2. Let us consider gas motion at times close to the initial time. In the initial period of the motion, the magnitude of the total energy being liberated during combustion in a volume bounded by the shock is less than the work of the piston

$$W > U = \sigma_j \int_{r_p}^{r_2} Q(1-\beta)\rho r^j dr, \tag{2.1}$$

where $\sigma_j = 2\pi j + (j-1)(j-2)$ and r_2 is the radius of the shock. Hence, the influence of the chemical reactions on the flow is slight. The work of the piston is

$$W = \sigma_j \int_0^t pur^j dr.$$

For the initial stage when the inequality (2.1) is valid, the solution can be sought by using the method of linearization in the small parameter $\varepsilon = U/W < 1$

$$\begin{gathered} p = p_0 + \varepsilon p_{01} + o(\varepsilon),\ \rho = \rho_0 + \varepsilon\rho_{01} + o(\varepsilon), \\ u = u_0 + \varepsilon u_{01} + o(\varepsilon),\ \beta = \beta_0 + \varepsilon\beta_{01} + o(\varepsilon), \\ c = c_0 + \varepsilon c_{01} + o(\varepsilon),\quad \lim_{\varepsilon\to 0}\frac{o(\varepsilon)}{\varepsilon} \to 0. \end{gathered} \tag{2.2}$$

After substituting the functions (2.2) into the initial equations, we obtain a system of partial differential equations for u_0, p_0, ρ_0, c_0, β_0 and u_{01}, p_{01}, ρ_{01}, c_{01}, β_{01}. The system dissociates into two for the main terms of the expansion. Self-similar functions describing the flow from the piston will be a solution of the gasdynamic equations. This latter problem has been studied well [6, 8]. The chemical reactions hence proceed in the given flow field and are described by (1.1) and (1.2) in which each function should be ascribed the subscript zero.

The boundary conditions for u_0, p_0, ρ_0 agree with the conditions of the gasdynamic problem [6, 8], $c_0 = 1$ on the shock front, $\beta_0 = 1$ on the ignition front. The boundary conditions for the functions with subscript 01 result from the expansion (2.2), the conditions on the piston, the flame front, and the shock front. They can be obtained by standard methods [6, 9].

3. Computations† were performed for values of the parameters $l_1 = 1$, $l_2 = l_3 = 0$, $n_1 = 0$, $n_2 = n_3 = 2$, $k_3 = k_2$, $t_* k_1 \rho_1 = 15$, $E_1/Q = 1.74$, $E_2/Q = 0.347$, $E_3/Q = 1.347$, $t_* = 10^{-7}$ c, $t_* k_2 \rho_1^2 Q^2 = 4.16$, $Q = 4 \cdot 10^{10}$ log/g, $\rho_1 = 0.5 \cdot 10^{-3}$ g/cm^3, $\gamma = 4/3$.

These constants are selected so that the kinetics equations would correspond to the induction times and the resulting reaction for a stoichiometric mixture of hydrogen and oxygen. The computations were executed for shocks moving at the constant velocity $\delta = 1$, and for decaying shocks with $\delta < 1$.

The concentration distribution in space β is given in Figs. 1 and 2. Calculations showed that the role of the reverse reaction is large for the concentration. The spacing $\bar{r}$ between the shock front r_2 and the ignition front r_i is represented in Figs. 3 and 4. It follows from the computations presented that the ignition delay time does not increase for $\delta = 1$ as the time $\tau = t/t_*$ grows, the reaction actually proceeds directly behind the shock front and splitting of the detonation wave into the usual compression shock and the flame front does not occur. For $\delta < 1$ the ignition zone separates from the shock front at times close to the initial time, the induction time grows, resulting in dissociation of the detonation wave into a simple compression shock and a flame front. The computations also showed a strong dependence of the ignition front on the activation energy E_1.

Let us note that the case of piston motion for $\delta < 1$ can simulate the influence of the explosion products from a cylindrical charge on the development of detonation. The variant $\delta = \delta_1 = 13/32$ was computed specially to compare with the development of a piston in a point explosion $\delta = \delta_0 = 2/5$ without the piston ($\delta_1 - \delta_0 < 0.01$). It turns out that in the neighborhood of the shock the flows are close to each other (see [3, 4, 10] for a comparison with the explosion case).

The accuracy of the computation of the gasdynamic functions can be judged from the following results. Seven significant figures were kept in the integral mass conservation law in the calculations. Furthermore, the system (1.3) admits an adiabatic integral [6] for $Q = 0$, which was satisfied to the accuracy of thousandths of a percent in the computations. In all the computations the ratio between the energy liberated during combustion and the work of the piston did not exceed 10%, $\varepsilon \leq 0.1$.

Therefore, the motion of the chemically active gas displaced by a piston moving according to the law $r_p = \lambda_p t^\delta$ can be separated into two stages. The initial stage is when the quantity of energy being liberated during combustion is small compared to the work of the piston. In this stage the flow is described by formulas yielding the solution of the piston problem. Chemical reactions occur in the background of this flow. The second stage is distinguished by the fact that the energy being liberated in the chemical reactions must be taken into account. Solutions obtained in the initial stage can be the initial data for a computation of the later stages by using finite-difference methods. The method considered above can also be used in problems on the excitation of nonequilibrium states in a gas and the computation of energy level populations of molecules and atoms behind shocks (or in expansion flows). Here (1.1) and (1.2) are replaced by the kinetic equations of nonequilibrium processes.

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THE EARTH'S NEGATIVE CHARGE

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The phenomenon of the earth's negative electrical charge, discovered in the eighteenth century, has attracted the interest of many scholars.

In the nineteenth century attention was called to the fact that with a constant loss of charge from the liquid and solid surface of the earth the terrestrial sphere should be discharged over the course of 10 min. After this, intensive studies commenced to determine the mechanism of maintenance of this negative charge.

However, even at present no satisfactory solution to this problem has been presented.

The nature of the generator which continually maintains a negative charge on the surface of the earth has not yet been discovered. It has been generally accepted that in regions of fair weather, due to the conductivity of the atmosphere the earth only loses negative charge, while this loss in compensated in inclement weather regions by supply of negative charge from the atmosphere. Over the course of this century new theories have been put forward continually to explain the nature of the generator which compensates charge loss.

The present study will consider a mechanism for supply of negative charge from the atmosphere. In [1] the term "electrogravitation generator" was introduced, but Frenkel' did not apply the concept to the problem of the negative charge of the earth.

The existence of negative charges in the lower portion of clouds has been confirmed by many investigators (see, e.g., [2]). Under the action of gravitational forces the droplets comprising a cloud are in a state of continuous fall. During the fall from the lower part of the cloud the droplets move into a region of decreased relative humidity, located below the cloud. The drops falling from the cloud carry a negative charge. Evaporating, they transfer this charge to the air. In [1] the process of evaporation of falling droplets was considered, however it was not concluded that ions are transferred into the air volume in which evaporation took place.

The specific gravity of the air beneath the cloud, cooled by evaporation of droplets entering from the lower cloud region, and thus carrying a negative charge, increases. This leads to formation of a descending flow beneath the cloud, which carries negative charges off with itself.

It is such negative charges which Kelvin observed when he detected a potential gradient inversion in the lower layers of the atmosphere up to 30 m [3].

Similar effects were noted at the Eifel Tower in [4]. Chalmers [2] calls attention to the enigmatic nature of these phenomena. He considers the explanation of the maintenance of the earth's negative charge to be one of the major problems of atmospheric electricity.

Both these effects can be explained by descending air flows, made heavy by droplet evaporation and carrying negative charges. The cold air, reaching the surface of the earth, spreads out horizontally and transfers its negative charge primarily to projecting objects, which, when a sufficient charge density is reached, may product a scintillation known as "St. Elmo's Fire." The descending flows below storm clouds may traverse considerable distances, of the order of magnitude of km, and by transferring their negative charges can produce all the known potential gradient anomalies described in [2]. These anomalies are easily observed in mountainous regions near the bases of clouds. In less frequent cases the bottom of a cloud may bear a positive charge. The cold flow descending to the earth will then transfer positive charge. It can be shown that if in a given volume of air there exists a quantity of water in the liquid phase, upon evaporation of this water, i.e., transformation from the liquid to the gaseous phase, the specific gravity of this closed volume will increase significantly.

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