kinetic energy accommodation coefficient; ε, emissivity; σ, Stefan–Boltzmann constant; ΔQ, specific energy release of the processes of fusion, vaporization, etc. of the material; Bi, Biot number; Fo, Fourier number; E, a dimensionless number representing the thermal state of material subjected to thermoerosive action; y, coordinate perpendicular to the wall surface. Indices: 0, initial; w, surface; s, mean-integral; M, wall material; p, particle; Σ, sum; 00, total; T, thermal, turbulent; ef, thermochemical; er, erosion; e, edge of boundary layer; st, calculation based on relations for the quasisteady degradation regime; ast, calculation based on analytic solutions of the heat-conduction equation; *, critical value; ', stagnation parameter.

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SOME QUESTIONS IN THE THEORY AND DESIGN OF EXPLOSIVE PLASMA GENERATORS

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Methods are presented for calculation of the thermophysical parameters of the plasma produced by operation of explosive plasma generators and for the design of such generators.

The method of producing high temperature dense plasma using gas impermeable plates which collide at a small angle, i.e., under acute angle geometry conditions, is widely known [1]. Explosive plasma generators which realize this method have found practical application [2-5]. The most widely used is the generator in which collision of a plane plate with the internal surface of a hollow hemisphere is used [3-5].

Observation of processes occuring in this accute angle geometry is difficult, so that they remain insufficiently studied. As a result, design of generators for plasma production with prespecified parameter values is impossible, and it is difficult to estimate the parameters of plasmas produced by existing generator constructions [2].

An infinite number of explosive generator configurations is theoretically possible, although the authors are aware of only several actual construction techniques. To form an overall picture of the given problem it is desirable to consider the gas dynamic processes which occur in the acute angle geometry, and obtain the expressions which relate the final parameters of the compressed gas to the properties of the colliding bodies and their relative velocities. After deriving such relationships it becomes possible to solve problems of explosive plasma generator design. Therefore the goal of the present study is to derive such relationships and analyze possible methods of increasing plasma temperature.

We will consider the compression of a gas included between two infinite parallel plates A and B, which beginning at time $t_0 = 0$ approach each other, moving with identical velocities v, exceeding the speed of sound a_0 in the unperturbed gas. Let P_0, ρ_0, T_0 be the pressure,

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density, and temperature of the unperturbed gas. For simplicity we assume the adiabatic index k to be constant. The thickness H of the gas layer compressed ahead of each plate at an arbitrary time t will be given by $H = \rho_0/\rho\, vt$. If d_0 is the initial distance between the plates, then the boundaries of the shock compressed gas zones come in contact at time t_1: $t_1 = d_0\rho/2v(\rho + \rho_0)$.

This time corresponds to the commencement of shock braking of the identical meeting gas flows moving at the velocities of the plates. If d_1 is the distance between the plates at time t_1, then the boundaries of the braked gas zone reach the plates at time t_2: $t_2 = d\rho_2/2v(\rho_2 + \rho_1)$. All gas between the plates is immobile at that time, and there then commences a secondary compression of the nonmoving gas by the moving plates A and B. Thus, in the given process the gas between the plates is accelerated multiple times up to the velocity of plate motion and then braked to a state of rest. During each acceleration or braking of the gas its pressure P, temperature T, density ρ, and speed of sound a increase. After rereflections, the number of which is given by the expression

$$n = \left(1 - \frac{a_0^2}{v^2}\right)\frac{2k}{k-1},$$

the equality $a = v$ is realized. Further compression of the gas is then subsonic. If we take $k = 5/3$, and $v \gg a_0$, then $n = 5$.

In the case under consideration the equations for the energy and shock adiabat can be written in the form:

$$\frac{k}{k-1}\frac{P_{m+1}}{\rho_{m+1}} = \frac{k}{k-1}\frac{P_m}{\rho_m} + \frac{v^2}{2}, \tag{1}$$

$$\frac{P_{m+1}}{P_m} = \frac{(k+1)\rho_{m+1} - (k-1)\rho_m}{(k+1)\rho_m - (k-1)\rho_{m+1}}, \tag{2}$$

where m is the ordinal number of the compression. Using Eq. (1), we can derive expressions for the temperature, speed of sound, and enthalpy T_m, a_m, i_m for $m < n$. To do this we rewrite Eq. (1) in the form

$$\frac{P_m}{\rho_m} = \frac{P_0}{\rho_0} + m\frac{k-1}{2k}v^2.$$

Hence

$$a_m^2 = a_0^2 + m\frac{k-1}{2k}v^2; \tag{3}$$

$$T_m = T_0 + m\frac{v^2}{2C_p}; \tag{4}$$

$$i_m = C_pT_0 + m\frac{v^2}{2}. \tag{5}$$

Using Eqs. (1), (2), it is simple to obtain expressions defining the pressure and density corresponding to the first compression:

$$P_1 = \frac{k+1}{4k}\rho_0v^2\left(1 + \sqrt{1 + \frac{P_0 8k^2 - k}{\rho_0v^2(k+1)^2} + \left(\frac{P_0}{\rho_0v^2}\right)^2\frac{16k}{(k+1)^2}}\right); \tag{6}$$

$$\rho_1 = \frac{P_1}{\frac{P_0}{\rho_0} + \frac{v^2(k+1)}{2k}}.$$

The pressure and density corresponding to each subsequent compression are determined by calculating repetitively with Eq. (6) through all preceeding compressions.

For the case where the plates A and B are not parallel, the angle between them is small ($\sin\phi \ll 1$) and the plates move along their respective normals with velocities of identical magnitude, it can be assumed that the process of gas compression between them is described by Eq. (6). However, in the given case the gas compression differs qualitatively from that described above. Subsonic compression of the gas is excluded because of the nonvarying geometry of the space between the plates. At each moment in time within this space regions can be distinguished in which the gas undergoes all successive shock compressions including the n-th compression. Thus, we have a region where $a = v$. However in this region the gas is not subjected to compression. This situation is characterized by the fact that the plates A and B always have a line of contact which moves along the bisectrix of the angle ϕ with a phase velocity v_p: $v_p = v/\sin\phi/2$.

Since $v_p \gg v$, the gas in the region of the acute angle undergoes a single shock compression. The pressure P_4 and density ρ_4 of the gas in the acute angle region can be determined approximately with Eq. (6), substituting in place of P_0, ρ_0, the quantities P_3, ρ_3, corresponding to the region in which $a = v$. The temperature T_4, enthalpy i_4, and speed of sound a_4 in the acute angle region are defined by the expressions

$$
\begin{aligned}
T_4 &= T_0 + \frac{v^2}{2C_p}\left(n + \frac{1}{\sin^2\varphi/2}\right);\\
i_4 &= C_pT_0 + \frac{v^2}{2}\left(n + \frac{1}{\sin^2\varphi/2}\right);\\
a_4^2 &= a_0^2 + \frac{k-1}{2k}v^2\left(n + \frac{1}{\sin^2\varphi/2}\right),
\end{aligned} \tag{7}
$$

which are easily derived from Eqs. (3)-(5).

The pattern of gas compression wave reflection in the region included between plates A and B is shown in Fig. 1. Four types of gas compression zones can be distinguished: zones 1 with gas motion at the plate velocity; zones 2 in which the gas is nonmoving; zones 3, corresponding to $a = v$; and zones 4 in which the gas moves at the phase velocity.

It is evident from Eq. (7) that the gas in zone 4 is compressed and heated most intensely and in addition has a high velocity of motion along the bisectrix of the angle ϕ. The parameters of the plasma obtained by this process are completely defined by the values of v and ϕ. It is desirable that toward the end of generator operation the velocity v increase and the angle ϕ decrease [1].

Three methods of producing plasma with colliding solid surfaces can be distinguished: 1) gas compression in the vicinity of the acute angle with increase in plate flight velocity and decrease in the angle between the plates [1]; 2) compression in the acute angle region with subsequent shock braking of the gas on a fixed or moving obstacle; 3) gas compression in the acute angle region with subsequent shock compression of the plasma by organizing symmetric converging flows in a space with a decreasing volume [1].

The temperature, pressure, density, speed of sound, and enthalpy of the plasma obtained by methods 2 and 3 can be evaluated with Eqs. (3)-(6). To do this, in place of P_0, ρ_0, a_0, T_0, v, we must substitute P_4, ρ_4, a_4, T_4, v_p. In these cases shock compression of the gas occurs similarly to shock compression of a gas between parallel plates. After a number of reflections defined by the expression

$$n = \left(1 + \frac{a_4^2}{v_p^2}\right)\frac{2k}{k-1},$$

the speed of sound in the plasma reaches the value v_p and the compression process becomes subsonic. The expressions for the temperature T and the speed of sound a take on the form:

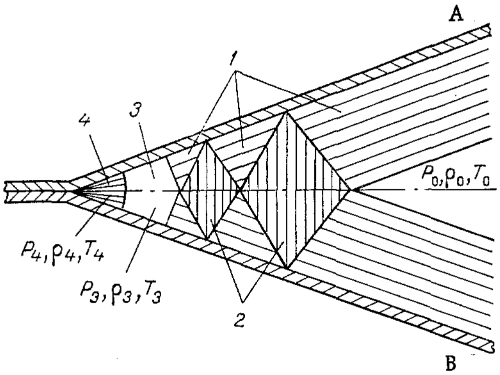

Fig. 1

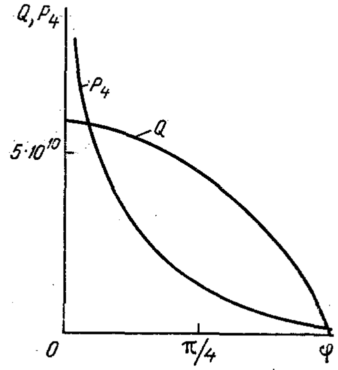

Fig. 2

Fig. 1. Distribution of gas compression zones in acute angle region between plates.

Fig. 2. Plate material braking pressure on contact line and gas pressure on same line vs angle between plates. Q, P, Pa.

$$T = T_4 + n\frac{v_{\mathrm{p}}^2}{2C_p};$$

$$a^2 = a_4^2 + n\,\frac{k-1}{2k}\,v_{\mathrm{p}}^2.$$

The above statements were made with the assumption that the energy of plate motion is infinitely large. In reality the upper limit of the velocity of a plate accelerated by an explosion does not exceed 10 km/sec. Under these conditions the parameters determining the possibility of plasma generation and the maximum possible temperature, pressure, and density thereof are the pressure Q of plate braking on their collision line and the gas pressure P_4 in the acute angle region. If $Q > P_4$, then plasma generation is possible, and if the reverse is true, plasma generation is impossible. Figure 2 shows curves of Q and P_4. For simplicity Q is defined approximately by the expression

$$Q = 2\rho_{\mathrm{a}} C v \cos \varphi/2.$$

The point of intersection of the curves in Fig. 2 corresponds to equality of the pressures Q and P_4. The phase velocity v_{p} corresponding to this equality is the maximum phase velocity at which production of a directed plasma flux is possible. At higher phase velocities, i.e., at $Q < P_4$ the plates do not contact and the acute angle geometry is not formed. Thus the condition

$$Q > P_4 \tag{8}$$

is a necessary condition for realization of the process of directed plasma flow generation. The other necessary condition is continuity of the colliding plate surfaces.

Considering the above, the technique of designing explosive plasma generators can be reduced to the following sequence:

1) analysis of available explosive materials and detonation wave forms which can be realized easily;

2) selection of charge detonation methods which realize detonation waves which will not destroy the drive plates as they are accelerated within the limits of the required displacements:

3) determination of plate flight velocity, and with consideration of condition (8), determination of the maximum admissible phase velocity;

4) determination of the generator dimensions and form of the colliding surfaces such that at the end of operation the phase velocity does not reach the limiting angle;

5) selection of the law for change of the acute angle geometry and generator dimensions such that the plasma generation time does not exceed, for example, 1/8 of its energy deexcitation time.

This technique encompasses all explosive plasma generator constructions which can be achieved using acute angle geometry . Such generators can be classified by the form of the plasma jet, the method by which the acute angle geometry is realized (number of movable and fixed surfaces and their relative locations), relative orientation of the phase velocity and the direction of detonation wave propagation in the charge, the form of the detonation wave, and its variation during generator operation. It would be desirable to introduce such a classification, since it groups together generators not only by their construction features, but also by their defining technical parameters such as quantity of plasma produced, temperature thereof, jet form, etc.

NOTATION

T, temperature; i, gas enthalpy; P, gas pressure; a, sound velocity in gas; ρ, gas velocity; v, plate velocity; k, adiabatic exponent; t, time; H, thickness of compressed gas layer; d, distance between plates; n, number of pressure wave reflections; C_p, gas specific heat at constant pressure; ϕ, angle between plates; v_p, velocity of plate contact line displacement along bisectrix of angle ϕ; Q, braking pressure of plate material at contact line; C, speed of sound in plate material; ρ_a, density of plate material. Subscripts: m, intermediate gas compression.

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