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NONSTATIONARY GAS DISCHARGE FROM A SEMICLOSED CAVITY

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A mechanism of formation of pressure fluctuations in a closed cylindrical cavity filled with compressed gas is studied. Pressure fluctuations occur with sudden rupture of the cavity over the entire section. Boundary conditions imposed on an open boundary in the case of quick interchange of discharge and inflow through it are suggested. A comparative analysis of the nonstationary process of intense gas discharge from cylindrical and conical cavities closed from one side is made.

It is known that with the sudden opening of a cut in a closed cylindrical cavity filled by compressed gas the discharge process is accompanied by pressure fluctuations relative to atmospheric pressure at the bottom of the cavity [1].

The aim of our paper is to study the mechanism of pressure fluctuations and of the effect of the cavity shape on the characteristics of an oscillating process.

Problem Formulation. Three semiclosed cavities of the same length and mean cross-section, viz., a cylinder (with a length equal to ten diameters), a diffusor and a convergent channel are considered (Fig. 1). The free end of the cavity is closed by a membrane, which at the initial time instant $t = 0$ breaks over the entire section and compressed gas begins to discharge from the cavity to the surrounding medium. The system of equations of gas dynamics describing this motion in an axisymmetric formulation has the form

$$\frac{\partial K_1}{\partial t} + \frac{\partial K_2}{\partial x} + \frac{\partial K_3}{\partial y} = K_4 ,$$

where

$$K_1 = y \begin{Bmatrix} \rho \\ \rho u \\ \rho v \\ E \end{Bmatrix}; \quad K_2 = y \begin{Bmatrix} \rho u \\ p + \rho u^2 \\ \rho u v \\ (e + p)\, u \end{Bmatrix}; \quad K_3 = y \begin{Bmatrix} \rho v \\ \rho u v \\ p + \rho v^2 \\ (e + p)\, v \end{Bmatrix}; \quad K_4 = \begin{Bmatrix} 0 \\ 0 \\ -p \\ 0 \end{Bmatrix};$$

$$E = \rho\,(e + (u^2 + v^2)/2) .$$

The system is closed by a thermal equation of the state of an ideal gas

$$p = \frac{\rho R T}{\mu} .$$

Boundary Conditions. Nonflow conditions were assigned as boundary conditions on solid surfaces and on the symmetry axis. At the open cut there is a difficulty in the choice of boundary parameters, since in this case the regimes of supersonic and subsonic discharge as well as of subsonic inflow caused by the motion of compression and rarefaction waves can be realized. In this case the use of ordinary conditions of the drift of parameters or

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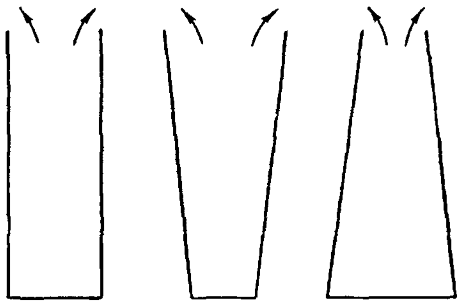


Fig. 1. Schematic diahrams of cavities: 1) cylindrical, 2) diffusor, 3) convergent channel.

assignment of surrounding parameters is impossible, since this will lead to nonphysical reflections of disturbances from the boundary [2]. Due to this fact it is suggested to calculate parameters at the boundary of the computational region on the basis of characteristic relations in the following manner.

If the regime of supersonic discharge $|u_0| > c_0$ and $u_0 > 0$ is realized at the cut, then the parameters in imaginary cells (the subscript 1) are determined from the simple drift of the parameters of the boundary cells (the subscript 0).

In the case of subsonic discharge $|u_0| < c_0$, $u_0 > 0$ the characteristics

$$\frac{dx}{dt} = u_0 + c_0 \quad \text{and} \quad \frac{dx}{dt} = u_0 .$$

are directed to an imaginary cell and "drift" into Riemann invariant and the total enthalpy

$$J_0^+ = u_0 + \frac{2c_0}{\gamma - 1}, \quad H_0 = \frac{u_0^2 + v_0^2}{2} + \frac{c_0^2}{\gamma - 1} .$$

Assuming the pressure in an imaginary cell to be equal to the surrounding pressure $p_1 = p_{un}$ [2], we obtain the following system for the determination of parameters in the imaginary cell

$$p_1 = p_{un}, \quad J_1 = J_0^+, \quad H_1 = H_0, \quad v_1 = v_0 . \tag{1}$$

We note that relations (1) are solved with respect to u_1 and c_1 and are in fact reduced to the condition of the drift of flow velocity and sound velocity from the boundary cell to the imaginary one:

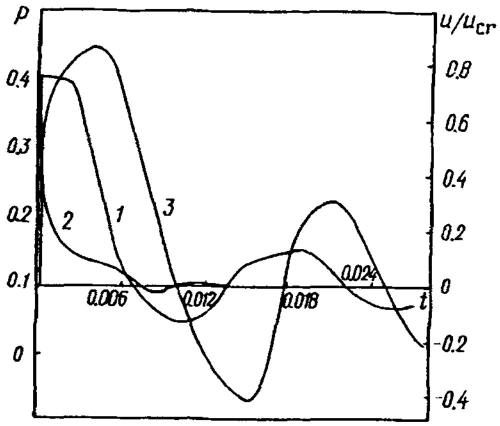
$$p_1 = p_{un}, \quad u_1 = u_0, \quad v_1 = v_0, \quad \rho_1 = \gamma \frac{p_{un}}{c_0^2} .$$

If $u_0 < 0$, $|u_0| > c_0$, i.e., there takes place a subsonic inflow, then only one characteristic is directed to the imaginary cell

$$\frac{dx}{dt} = u_0 - c_0$$

with the known Riemann invariant and thus there is only one equation for determining parameters in the imaginary cell. The remaining parameters are suggested to be determined from the condition of the equality of enthalpy and entropy to their values in the boundary cells at the cut that are borne in mind at the moment of the change of the discharge regime by the inflow regime

$$H_1 = H_{1t}, \quad \sigma_1 = \sigma_{1t}, \quad v_1 = 0 . \tag{2}$$



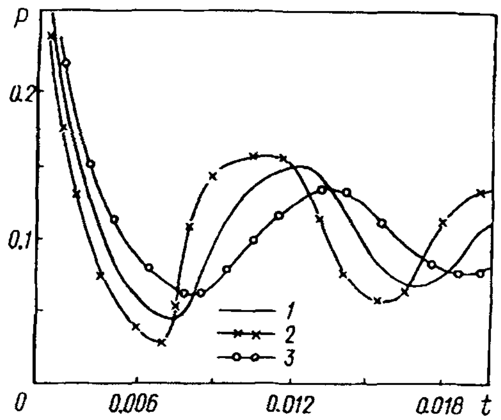


Fig. 2. Time-variation of pressure and longitudinal velocity component in the cavity: 1) pressure at the bottom, 2) pressure at the cut, 3) velocity at the cut. p, MPa; t, sec.

Fig. 3. Pressure at the cavity bottom as a function of the cavity shape: 1-3), see Fig. 1.

The correctness of boundary conditions (2) at the cut was checked by comparing with the calculation allowing for a gas flow in a large volume around the cavity. The volume has a rectangular section with area $(2L) \times L$. The grid was constructed in a geometrical progression with the coefficient 1.2 over all four directions from the cut. On the upper boundary of the computational region (above the cut) the suggested boundary conditions were set. On the remaining boundaries the nonflow conditions were set to avoid the appearance of parasitic flows through open boundaries. The deviation from the values of pressure at the bottom of the cavity for these two calculations was 1%.

The results were obtained at the following initial data: pressure in the cavity $p = 0.4$ MPa, temperature $T = 2100$ K, molecular weight $\mu = 23.55$ kg/mole, adiabatic index $\gamma = 1.25$, surrounding pressure $p_{un} = 0.1$ MPa, sound velocity in surrounding medium $c_{un} = 300$ m/sec.

The problems were solved numerically in an axisymmetric formulation within the framework of the model of a one component gas by the Godunov method [3].

Results of Calculations. The mechanism of the formation of pressure fluctuations was studied in a cylindrical cavity with the length-to-radius ratio of the cavity equal to 3 (Fig. 3). From the time instant $t = 0$ a rarefaction wave is directed into the cavity, which in time $t = 0.003$ sec will reach its bottom (curve 1). The wave front will be reflected and the reflection wave will move to the cut, thus reaching the cut in about the same time. Then reflected-wave-type flow will be observed in the cavity [1]; a specific feature of this flow is a weak dependence of pressure on the longitudinal coordinate (the period from $t = 0.006$ to $t = 0.007$). The dependence $p(t)$ will uniformly decrease over the entire cavity, approaching the value of the surrounding pressure.

The velocity of gas discharge at the cut during this period increases (Fig. 2, curve 3) and reaches a maximum at $t = 0.004$ sec, and then decreases with a decrease in the pressure gradient at the cut. However, at the time instant when the pressure in the cavity becomes equal to the surrounding pressure, the discharge velocity remains high ($t = 0.007$ sec, $u/u_{cr} = 0.58$), thus resulting in continuation of the discharge process due to inertia and leading to a decrease in pressure in the cavity (the period from $t = 0.007$ to $t = 0.0098$ sec) and, in particular, at the cavity bottom the value of pressure is much smaller than the surrounding pressure ($p = 0.056$ MPa at $t = 0.011$ sec). Thus, counterpressure will arise at the open cut, which first retards the discharging gas to its full stop, $t = 0.0098$ sec and then changes the discharge mode to the inflow mode (it is assumed, that a gas with the same adiabatic index enters the cavity). The pressure at the cut will quickly grow up to atmospheric (curve 2) and the pressure at the bottom will continue to decrease until the compression wave produced at the cut reaches the bottom ($t = 0.011$ sec). The velocity of inflowing gas increases and begins to decrease when counterpressure arises at the bottom. Then the process will repeat due to the same reasons. It is as if the cavity breathes, inhaling and exhaling

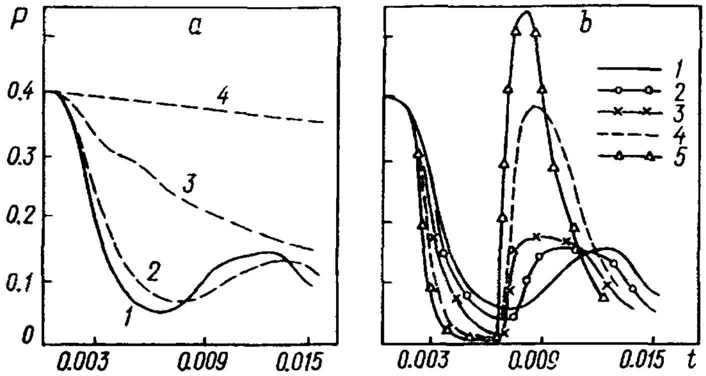


Fig. 4. Pressure at the bottom of a convergent channel (a) and a diffusor (b) for different values of s: a) 1, $s = 1$, 2) 0.9, 3) 0.33, 4) 0.11, b) 1, $s = 1$, 2) 1.1, 3) 1.5, 4) 3, 5) 5.

gas. Fluctuations of velocity and pressure in the cavity have a decaying character. The frequency of fluctuations depends on the rate L/c_c, where c_c is the sound velocity in the cavity at $t = 0$.

Thus, the delay in the arrival of information about the state of gasdynamic parameters from the cut to the bottom and inversely is the main reason for the considerable nonstationarity of the process and for the oscillatory character of gas discharge.

The laws governing the behavior of the medium in discharge from a cylindrical cavity are repeated for the case of conical cavities, though with a number of considerable differences.

Figure 3 presents the change in pressure at the bottom for different cavities at $L/d = 10$. We note that the presence of convergence leads to attenuation of pressure oscillations, whereas a diffusive character facilitates their intensification. It is convenient to characterize the degree of conicity by the relation

$$s = d_{\text{cut}}/d_{\text{b}}\,.$$

Figure 4a shows the dependence of pressure variation at the bottom for different values of the ratio s. It is seen from the figure that as s decreases fluctuations begin later and their intensity falls ($s = 1$ and $s = 0.9$). At $s = 0.33$ (not shown in the figure) fluctuations begin at $t = 0.25$ sec and their intensity over the amplitude is small (0.005 MPa), and at $s = 0.11$ a fluctuationless regime of gas discharge from the cavity is observed.

Figure 4b shows the same dependence $p(t)$ for a diffusor. It is interesting to note that as s grows pressure accumulates at the bottom till shock momentum loading of the bottom with the value of pressure for $s > 3.5$ exceeding an initial pressure in the cavity and it can reach great values. Thus, for example, for $s = 5$ the value of the $p(t)$ maximum grew to 0.546 MPa with the initial pressure in the cavity $p = 0.4$ MPa, and for $s = 7$ $p_{\max}(t)$ it was 0.622 with the same initial pressure. We also note that maximum pressure increases monotonically with s.

The reliability of the obtained results was confirmed by a calculation made on a doubly crowded grid. Morereover, the integral of mass conservation in the cavity was controlled during calculation by comparing the quantity of gas mass in the cavity before the onset of discharge with the quantity of gas mass in the cavity at the current moment plus or minus gas flows that passed through the open cut by this time instant. In this case the deviation of the integral did not exceed 10^{-6} of the initial mass.

Conclusion. The described specific physical features of the process should be taken into account in possible breakages of gas-filled cavities of the mentioned shapes.

NOTATION

ρ, density; p, pressure; u and v, longitudinal and transverse velocity components; $E = \rho(e + (u^2 + v^2)/2)$, total energy; e, internal energy of gas; T, temperature; R, universal gas constant; μ, molecular weight of gas; H_{1t} and σ_{1t}, enthalpy and entropy in boundary cell (with the subscript 1) at the moment of the change of the discharge regime to the inflow regime; c_c, sound velocity at the moment when pressure in the cavity is equal to surrounding pressure; c_{cr}, critical velocity of sound; L, cavity length; d, diameter of mean section of the cavity; d_{cut}, cut diameter; d_b, bottom diameter. Subscripts: un, undisturbed parameters of the medium into which gas discharges; t, current value; c, cavity.

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