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NUMERICAL SIMULATION OF A NONSTATIONARY GAS JET GENERATED BY A PULSED-GAS GENERATOR

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The efflux of an axially symmetrical ideal-gas jet generated by a pulsed-gas generator has been mathematically simulated. The structure and parameters of nonstationary gas jets have been determined. The influence of the geometric parameters of a pulsed-gas generator and the initial pressure in its accumulation reservoir on the characteristics of the jet, determining the efficiency of its action on an obstacle, has been investigated. The calculation data were compared with the corresponding experimental data.

The problem of increasing the heat efficiency of high-temperature technological apparatus by increasing the use of the thermal and chemical energy of the waste gases has been pressing all along for various industries. The solution of this problem depends to a large extent on the efficiency of the methods of cleaning the heated surfaces of apparatus from the combustion products deposited on them. The estimations done in [1] for a hot-water boiler of heat capacity $1.16{\cdot}10^8$ W have shown that a significant economical effect is obtained when this boiler is cleaned carefully. The problem of removal of deposits arises also in other technological processes. For example, a rapid growth of the deposits of finely dispersed materials processed in apparatus used in the chemical industry can lead to a sharp decrease in their operative reliability and output. Pulsed, vibrating, and shot-blast cleaning systems are widely used in the metallurgy industry and heat power engineering. Ash deposits formed in the process of combustion of coals are removed by vapor or water with the use of blasting apparatus (the so-called "gun blasting"). Mechanical scrapers and vibration methods are used for removal of deposits in technological processes.

The gas-pulse and pneumopulse methods of cleaning surfaces by a short-time action of powerful air or gas jets are, in our opinion, the most universal and effective.

The gas-pulse methods of cleaning are explosion-proof and safe for the environment. They can be realized with the use of small-dimension apparatus and small amounts of gases. These methods allow one to automate the cleaning process and can be realized with the use of inexpensive equipment.

Pulsed-gas jets are generated by special apparatus — pulsed-gas generators. A pulsed-gas generator (see Fig. 1) represents a gas-dynamic apparatus in which a valve having a high speed of response forms a pulsed-gas jet flowing from an accumulation reservoir through the exit nozzle to the space treated [2].

After switching a pulsed-gas generator on, a leading shock wave begins to propagate from the nozzle in the undisturbed gas. The static pressure downstream of this wave increases sharply. In the wake of the leading shock wave, there arise alternating supersonic and subsonic zones separated by shocks. The shock wave and the gas wake perform the main cleaning action in the method considered; therefore, this method can be called the shock-wake method. The cleaning action of the leading shock wave is mainly determined by its intensity as well as the excess pressure and the impact-gas pressure in the wake of it. The main parameters determining the cleaning action of the gas wake are its pressure, velocity, and total momentum. The contributions of the leading shock wave and the gas jet to the process of decomposition of deposits depend on the initial pressure in the accumulation reservoir of the generator, the distance from the object treated, the method of energizing the apparatus (which determines the parameters of the leading shock wave), and the physicochemical properties of the material treated.

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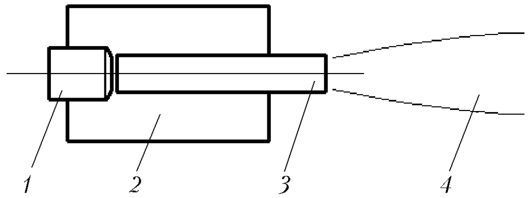

Fig. 1. Diagram of a pulsed-gas generator: 1) valve with a high speed of response; 2) accumulation reservoir; 3) exit nozzle; 4) pulsed jet.

At the moment, the dynamics of propagation of pulsed-gas jets to large distances from the output nozzle (as large as 100–150 nozzle diameters), which is of greatest practical interest, is poorly understood. Numerical solutions of this problem are absent in the literature. The experimental data presented in [3] were obtained for high-temperature jets flowing in shock tubes at a practically constant pressure. However, the pressure in the accumulation reservoir of pneumatic pulsed-gas generators varies significantly and the temperature of the gas in the jet is low (of the order of room temperature). The semiempirical dependence, obtained in [4] on the basis of experimental investigations of air jets generated by pneumatic generators with accumulation reservoirs of different volumes and exit nozzles of different radii, allows one to determine the trajectory of movement of the jet front in accordance with the geometry of the generator and the initial pressure in the accumulation reservoir. However, the method used in [4] gives no way of determining the structure of the jet and the leading shock wave.

In the present work, we carried out numerical investigations of the structure and parameters of nonstationary ideal-gas jets generated by pulsed-gas generators. The calculation data were compared with the corresponding experimental data [5].

Formulation of the Problem. The mathematical model of an axially symmetric jet is based on a system of nonstationary, divergent gas-dynamic equations for a gas with a constant adiabatic index γ

$$\partial\mathbf{U}/\partial t + \partial\mathbf{F}/\partial x + \partial\mathbf{G}/\partial r = -\,\mathbf{Q}/r\,,$$

$$\mathbf{U} = (\rho,\ \rho u,\ \rho v,\ e)\,,\quad \mathbf{F} = (\rho u,\ p + \rho u^2,\ \rho uv,\ u\,(p + e))\,,$$

$$\mathbf{G} = (\rho v,\ \rho uv,\ p + \rho v^2,\ v\,(p + e))\,,\quad \mathbf{Q} = (\rho v,\ \rho uv,\ \rho v^2\,,\ v\,(p + e))\,.$$

For the model considered,

$$p = (\gamma - 1)\,(e - \rho\,(u^2 + v^2)/2)\,,\quad a^2 = \gamma p/\rho\,.$$

The system of equations is supplemented with the conditions at the boundaries of the computational region Ω representing a rectangle. At $r < 1$, the parameters of the gas flowing from a hole are set at the left boundary (x = 0); at $r > 1$, gas flow through the left boundary is absent; at the upper boundary, the pressure and density correspond to those of an undisturbed gas and "soft conditions" are set for the velocity components; symmetry conditions are set at the symmetry axis ($x > 0$, r = 0); and gas flow through the right boundary (solid wall) is absent.

At x = 0 and $r < 1$, the gas-flow parameters are determined by the conditions realized in the accumulation reservoir. These parameters are initially critical:

$$\rho_* = \rho_0\,(1 + 0.5\,(\gamma - 1)\,(2/(\gamma + 1))^{0.5(\gamma+1)/(\gamma-1)}\,t/\tau)^{-2/(\gamma-1)}\,,$$

$$p_* = p_0\,(\rho_*/\rho_0)^{\gamma}\,,\quad u_* = a_* = a_0\,(\rho_*/\rho_0)^{(\gamma-1)/2}\,,\quad v = 0\,.$$

It is assumed that the initial temperature of the gas in the reservoir is equal to the temperature of the undisturbed gas in the environment. The parameters of the jet at its initial cross section are determined by the above expressions until the critical pressure becomes lower than the pressure of the undisturbed gas in the environment, $p_* < p_1$ = 1. To this instant of time, a supersonic jet flows from the reservoir. When the pressure at the initial cross section of the jet de-

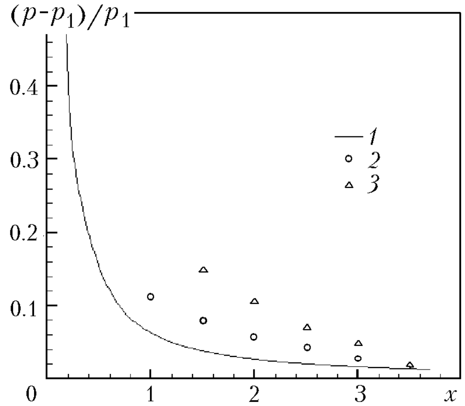

Fig. 2. Relative differential pressure in the shock wave propagating from the exit nozzle: 1) calculation; 2 and 3) experimental data obtained for a plane valve and a broken-down membrane.

creases to $p_1 < 1$, the jet becomes subsonic and the parameters of the jet at its initial cross section are determined from the equations

$$d\rho/dt = -\pi\rho_0 a_0/V\,(2/(\gamma-1))^{1/2}\,(p_1/p_0)^{0.5(\gamma+1)/\gamma}\,((p_0/p_1)^{(\gamma-1)/\gamma}\,(\rho/\rho_0)^{\gamma-1}-1)^{1/2}\,,\quad p = p_1 = 1\,,$$

$$u = (2/(\gamma-1))^{1/2}\,a_0\,((a/a_0)^2-(p_1/p_0)^{(\gamma-1)/\gamma})^{1/2}\,,\quad v = 0.$$

The boundary conditions set in the region of the outlet hole are approximate even in the case where the gas flows through a hole in the reservoir wall. In actual practice, gas jets flow usually through a nozzle. In the present work, a stationary solution in the "channel" approximation is used as the boundary condition for simulation of the jet efflux through a short nozzle at $x = 0$ and $r < 1$. It is assumed that all gas is undisturbed at the initial instant of time ($t = 0$): $p_1 = 1$, $\rho_1 = 1.4$, and $u_1 = v_1 = 0$.

The problem formulated was numerically solved using the finite-volume scheme decreasing the total variation (TVD reconstruction). It is assumed that the grid points are crowded to the symmetry axis and the grid pitches are uniform along the x axis. The flows at the boundaries of meshes are calculated by the method of [6]. The integration with respect to time was carried out by the second-order Runge–Kutta method.

Results of Calculations. The calculation data obtained using the model described and the corresponding experimental data obtained in [2] are compared in Fig. 2. This figure presents the relative differential pressure in the shock wave propagating from the outlet hole (V_d = 7 dm^3, R = 20 mm, p_{0d} = 20 atm, p_1 = 1 atm, the distance x from the hole is measured in meters). It is seen that the influence of the model used in the calculations and the method of generation of a shock wave in the experiments on the data obtained decreases with increase in the distance from the hole.

In the experimental apparatus, the gas flowing out of the reservoir through a Laval nozzle (of length 90 mm) had a supersonic velocity at the output of it (the Mach number of the flow M = 2). The nozzle significantly influences the distribution of the jet parameters. This is demonstrated in Fig. 3, which shows the time change in the pressure at the axis of the jets with a Mach number M = 2 at the output (at a distance x_d = 1.15 m) flowing from a hole (Fig. 3a) and a nozzle (Fig. 3b). Here, the time t is a dimensionless quantity (to the interval Δt = 1 corresponds 0.0765 μsec under experimental conditions). The vibrational character of the change in the pressure and the large amplitude of these vibrations (Fig. 3a) point to the existence of "rolls" in the supersonic jet.

In the calculations, we modeled the inertia of the measuring apparatus; therefore, the time dependence of the pressure was somewhat flattened. The data presented in Fig. 3b were averaged over the interval Δt = 5 (frequencies higher than 250 Hz were filtered) (see Fig. 3c). For comparison, Fig. 3d presents the corresponding experimental time dependence of the pressure at the point x_d = 1.15 m, r = 0. It is seen that the calculation and experimental data agree fairly well ("rolls" are absent in the wake of the shock and the pressures are close).

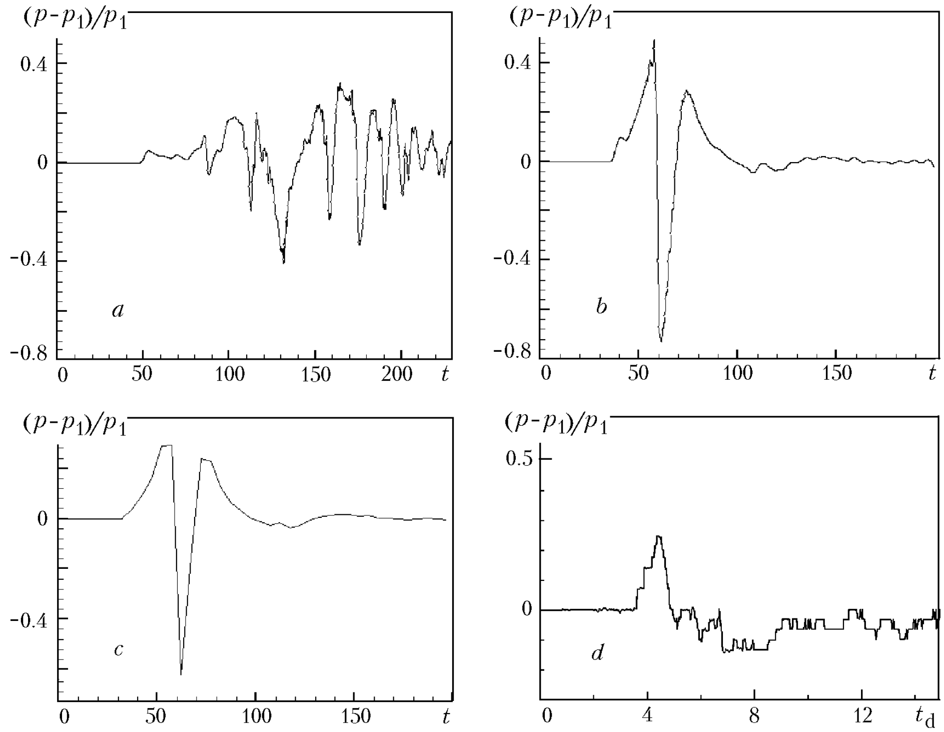

Fig. 3. Time change in the pressure at the axis of jets at a distance x_d = 1.15 m: a) jet flowing from the hole in the reservoir wall (calculation); b) jet flowing from the nozzle (calculation); c) pressure in the jet flowing from the nozzle is averaged over the interval Δt = 5; d) jet flowing from the nozzle (experiment). t, μsec.

The gas-jet efflux through the hole was mainly calculated at V_d = 7.5 and 30 dm^3, R = 25 and 50 mm, p_{0d} = 4 and 8 atm, and p_1 = 1 atm.

Figure 4 shows the dynamics of the jet. The pressure fields and the Mach numbers at the initial stage of the jet efflux ($t_d \approx 3$ μsec) at V_d = 30 dm^3, R = 50 mm, and p_{0d} = 8 atm are presented in Fig. 4a and b. The intensity on the color of the patterns presented in this figure changes with change in the pressure from 0.2 to 2.5 and change in the Mach number from 0.01 to 3.0. The velocity of the gas flow sharply increases near the hole (to M $\approx$ 3 in the end). The compression waves propagating from the edge of the hole are closed by a compression shock near the symmetry axis. Then the velocity of the gas flow increases once again and a low-pressure ($p \approx 0.2$) region (shaped as a torus) is formed around the symmetry axis, after which an oblique shock wave propagates. The pressure in the wake of this wave is only slightly higher than the atmospheric pressure ($p \approx 1.3$). The oblique wave is transformed into a practically spherical shock wave.

A series of "rolls" is formed at the exit of the hole. This is seen from Fig. 4c and d, where the pressure fields and the Mach numbers, determined at $t_d \approx 6$ μsec, are shown. The intensity of the color on the patterns presented in this figure changes with change in the pressure from 0.4 to 2.2 and change in the Mach number from 0.005 to 2.5. These "rolls" are formed because the pressure at the outlet of the hole is higher than the ambient pressure (unsprayed jet). However, as the gas flows out of the reservoir, the pressure in it decreases and the structure of the jet becomes less cellular in character. This is seen from the patterns in Fig. 4e and f, detected at $t_d \approx 15$ μsec. The intensity of the color on these patterns changes with change in the pressure from 0.6 to 1.3 and change in the Mach number from 0.002 to 2.0. The Mach number at the jet core changes only sightly along the symmetry axis (as compared to the initial instants of time). In this case, the differential pressure in the jet decreases. It should be noted that the possible force action of the jet considered on the wall is narrow-directional in character. Figure 4 shows the initial stage of reflection of the leading shock wave from the wall positioned at a distance x = 100.

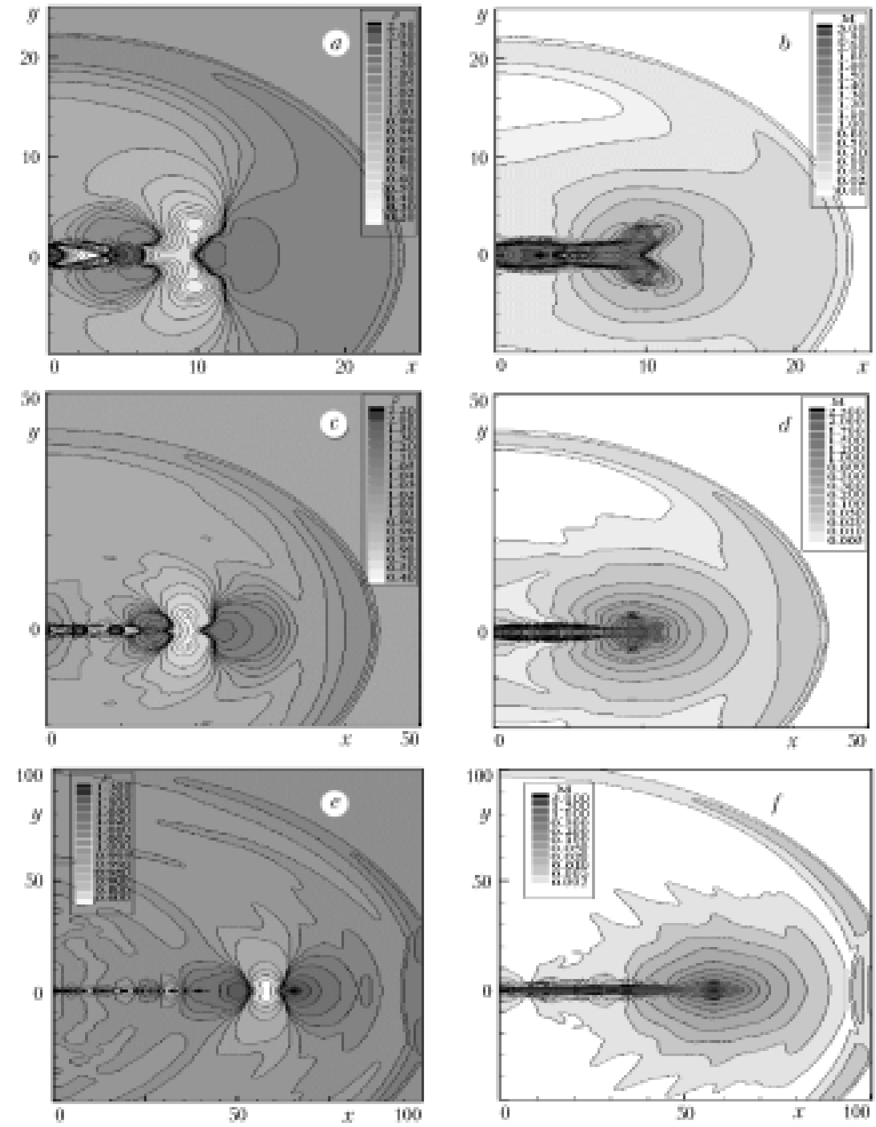

Fig. 4. Distribution of the static pressure and the Mach number of a gas flow at different instants of time: $t_d \approx 3$ μsec (a, b), $t_d \approx 6$ μsec (c, d), $t_d \approx 5$ μsec (e, f).

Figure 5 presents the change in the maximum relative static pressure at points on the axis of the jet for the calculation time. Curve 1 was obtained at V_d = 30 dm^3, R = 50 mm, and p_{0d} = 8 atm; curve 2 was obtained at V_d = 30 dm^3, R = 50 mm, and p_{0d} = 4 atm; curve 3 was obtained at V_d = 7.5 dm^3, R = 25 mm, and p_{0d} = 8 atm; and curve 4 was obtained at V_d = 7.5 dm^3, R = 25 mm, and p_{0d} = 4 atm. Curves 1 and 3, obtained at a high initial pressure in the reservoir p_{0d} = 8 atm, oscillate at a certain distance from the hole (x_d = 1 m), which points to the fact that the jet has a quasistationary cellular structure at least until the pressure in the reservoir decreases significantly. The distance between the maxima, determined for different pneumatic generators, correlates well with the radius of the outlet hole (for curves 1 and 3, these distances differ by a factor of two). At $x_d < 1.1$ m, the maximum pressure in the jet flowing from a generator outlet hole of radius R = 50 mm substantially exceeds the corresponding pressure in the jet flowing from a hole of radius R = 25 mm. At a lower initial pressure in the accumulation reservoir of a generator (≈4 atm), this effect is observed at smaller distances from the outlet hole ($x_d < 0.2$ m). At $x_d > 1.1$ m, the curves correspond to approximately equal maximum pressures that are independent of the geometric parameters of the generator and are determined by the initial pressure in the reservoir.

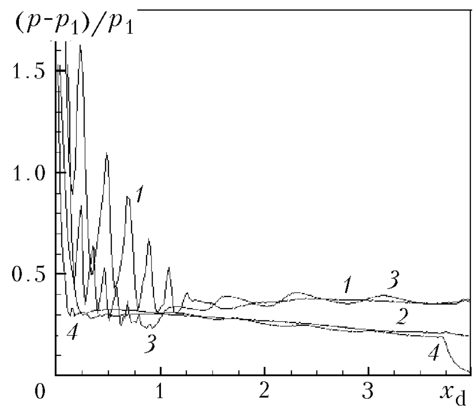

Fig. 5. Change in the maximum relative static pressure at points on the axis of a jet for the calculation time. x_d, m.

The force action of a jet on deposits should be estimated taking into account not only the change in the scalar value of the static pressure but also the vector value of the dynamic velocity pressure at a corresponding space point. For example, the stagnation pressure calculated as the sum of the static pressure and the dynamic velocity pressure along the axis of a jet at V_d = 30 dm^3, R = 50 mm, and p_{0d} = 8 atm varies from 2 to 4 atm at $t_d \approx 15$ μsec and reach 6 atm in certain regions, while the absolute value of the static pressure does not exceed 1.3 atm.

The main objective of the present work is to investigate the processes of formation and propagation of nonstationary gas jets. For simplicity, we did not include the viscosity of the gas into the mathematical model at the initial stage of the investigations. There is no question that the viscosity plays an important role in the processes of propagation of actual gas jets; nonetheless, the good agreement between the calculation and experimental data allows the conclusion that the pattern of a flow at small distances from the outlet hole does not change significantly when the viscosity is taken into account and, therefore, simplified mathematical models in which the viscosity is not taken into account can be used for the problems considered.

The maximum temperature of the gas in a jet used in the calculations and experiments was only slightly higher than the room temperature. Therefore, the gas jets considered can be mathematically simulated with the use of a constant value of the adiabatic index.

CONCLUSIONS

1. An algorithm of numerical simulation of an axially symmetrical ideal-gas jet generated by a pulsed-gas generator has been proposed. The calculation data obtained with the use of this algorithm are in good agreement with the corresponding experimental data. A narrow sound jet flowing from the outlet hole of a pulsed-gas generator has a complex cellular structure near its axis, and this structure is retained until x_d = 4 m. The existence of alternating zones of acceleration and stagnation of the gas flow in a jet leads to substantial variations in its pressure. A high-pressure region is formed at the front of the jet, and the transverse dimension of this region increases substantially with distance from the outlet hole. The intensity of the leading shock wave rapidly decreases with distance from the hole.

2. The influence of the geometric parameters of a pulsed-gas generator and the initial pressure in the storage reservoir on the parameters of the jet, determining the efficiency of its action, has been numerically investigated. It has been shown that, at a constant rate of efflux of a jet, its force action near the outlet hole of a generator ($x_d < 1$ m) increases substantially with increase in the size of this hole and the initial pressure in the accumulation reservoir. At distances from the outlet hole of 1 m < x_d < 4 m, the static pressure is practically independent of the size of the outlet hole and is determined by the initial pressure in the accumulation reservoir of the generator.

NOTATION

a_1, dimensional velocity of sound in the environment, m/sec; a, velocity of sound; a_0, initial velocity of sound in the reservoir; a_*, velocity of sound in the critical cross section related to a_1; e, total energy of a unit gas volume transformed into dimensionless form with the use of $\rho_1 a_1^2$; M, Mach number of the flow; u, v, velocity components of the gas in the jet; u_1, v_1, velocity components of the gas in the environment related to a_1; R, radius of the hole through which the gas flows, mm; r, cylindrical coordinate related to R; p_1, dimensional pressure in the environment, atm; p_{0d}, initial dimensional pressure in the reservoir, atm; p, pressure; p_0, initial pressure; p_*, critical pressure in the reservoir, related to $\rho_1 a_1^2$; x, cylindrical coordinate related to R; x_d, dimensional coordinate, m; t, time related to R/a_1; t_d, dimensional time, μsec; **F**, **G**, **Q**, **U**, vectors in standard gas-dynamic equations; V_d, dimensional volume of the reservoir, dm^3; V, volume of the reservoir related to R^3; γ, adiabatic index; $\tau = V/(\pi a_0)$; Ω, computational region; Δt, time interval; ρ_1, density of the gas in the environment (kg/m^3) determined from the relation $p_1 = \rho_1 a_1^2$; ρ, density; ρ_0 and ρ_*, initial and critical densities in the reservoir related to ρ_1. Subscripts: 0, initial parameters of the gas in the reservoir; 1, parameters of the gas in the environment; *, parameters of the gas in the critical cross section; d, dimensional.

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