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NUMERICAL ANALYSIS OF BLAST WAVE PROPAGATION IN A GASEOUS MEDIUM SEPARATED BY A RIGID PARTITION

Abstract. The article considers numerical modelling of a blast disturbance in a compressible ideal gas within a closed two-dimensional domain separated by an internal partition. The aim of the study is to investigate the spatio-temporal redistribution of the main gas-dynamic parameters and to evaluate the response of a rigid partition, represented in the model as a rigid plate, under the action of a shock wave as a baseline case for subsequent comparison with a deformable partition. The mathematical model is based on solving the Euler equations, which describe the conservation laws of mass, momentum, and energy for a compressible ideal gas, using the ideal-gas equation of state. The numerical implementation is performed by the finite element method with Euler time integration and stabilization by the Lax-Friedrichs scheme. For the computational experiment, C# software was developed.

The simulation results showed that an absolutely rigid partition completely localizes the blast disturbance in the chamber containing the explosion source and does not allow the transfer of energy, gas motion, pressure changes, or density changes into the adjacent chamber. It is shown that, after the initial arrival of the shock wave at the partition, the pressure and energy maxima shift to its left face and then split into two symmetric branches propagating toward the upper and lower supports. The relative-density field additionally revealed the formation of compaction zones near the plate and rarefaction in the central part of the chamber, while the velocity field made it possible to trace the kinematics of the shock-wave front and its subsequent reflection from the outer boundary. The integral analysis showed that the maximum response of the partition itself occurs at the early stage of the primary impact, whereas the greatest total force response of all reflecting surfaces forms later, after the outer boundaries of the domain become involved in the wave process. The obtained results can be used as a baseline computational scenario for assessing blast loads on rigid protective and isolating structures, as well as a stage in the development of a software and computational framework for solving problems related to the assessment of blast-protection barriers and the propagation of impact loads in closed volumes.

Keywords: blast wave; wave reflection; impact loading; numerical modelling; finite element method.

1. Introduction

In general, an explosion is understood as the rapid release of a significant amount of energy within a limited volume over a very short time interval. As a result, a region with sharply increased pressure and temperature is formed in the gaseous medium and expands intensively. This expansion is accompanied by compression of the surrounding gas and the formation of a shock wave - a thin region within which the parameters of the medium (pressure, density, temperature, and velocity) change almost discontinuously. Unlike ordinary sound waves, a shock wave is a nonlinear phenomenon and carries considerable energy, which determines its decisive influence on surrounding objects [1, 2].

The propagation of a shock wave in a compressible gas is characterized by the fact that the gas ahead of the front is almost at rest, whereas behind the front it moves at high velocity and has elevated pressure. As the wave moves away from the explosion source, it gradually weakens and its front expands. The classical theoretical description of this process is the Taylor-von Neumann-Sedov self-similar solution, which is used for strong explosions in an ideal gas [3, 4].

The interaction of a shock wave with solid surfaces is of particular importance. When the wave reaches, for example, a plate, it cannot continue to propagate freely as it does in gas, and reflection occurs. In this case, the gas velocity in the direction

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normal to the surface decreases to zero, and part of the wave energy returns to the gaseous medium in the form of a reflected shock wave. A zone of increased pressure forms near the surface, and the post-reflection pressure may substantially exceed the pressure in the incident wave [1, 5]. Depending on the interaction conditions, different modes of wave reflection are possible.

The action of an explosion on a solid body manifests itself as a short-duration but intense impulse load. This load is characterized not only by the maximum pressure value, but also by the duration of its action and by an integral quantity - the impulse. It is the impulse that is one of the determining parameters in assessing the response of structures to blast loading [2, 6].

The problem of an explosion near a plate is characterized by the superposition of incident and reflected waves, which leads to a complex spatiotemporal flow pattern and local pressure amplification near the surface. The magnitude and nature of the load depend on the distance to the explosion source, the gas parameters, and the mechanical properties and stiffness of the plate. The complex and nonlinear nature of these processes necessitates the use of numerical methods for their detailed investigation [7–12].

The relevance of such studies is determined by a wide range of engineering and applied problems in which the action of blast loads on structures must be taken into account [8, 13, 14]. In particular, blast waves generate short-duration but extremely intense impulse loads that determine the stability and reliability of structures. Under modern conditions, there is an increasing need for the calculation of protective structures and shelters, for assessing the stability of critical infrastructure, and for analysing accidental and technological explosions. The results of numerical blast modelling that accounts for interaction with structures can be used in such fields as civil and military construction (design of protective structures, shelters, and blast-resistant structures); mining and underground construction (assessment of the effect of explosions on workings, tunnels, and supports); energy and critical infrastructure (analysis of accidental explosions and their consequences); and biomechanics and human safety (studies of the effects of shock waves on the human body and protective equipment). In addition, numerical models are widely used to optimize structures without conducting expensive full-scale tests [14].

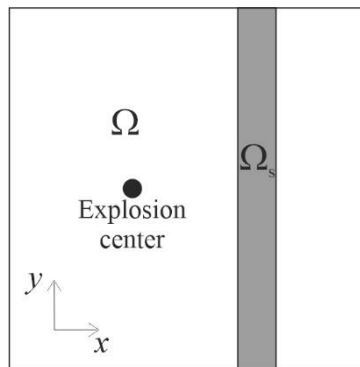
In this context, the aim of this study is to perform a numerical analysis of the processes occurring during an explosion in a gaseous medium separated by a rigid partition, taking wave reflection into account in order to determine the load on the partition.

To achieve this aim, the following tasks were formulated:

- to model an explosion in a gaseous medium and the interaction of the shock wave with a rigid partition represented as a rigid plate;
- to analyse changes in the fields of energy, gas pressure, density, and gas velocity in the investigated domain;
- to analyse the level of loading on the partition during the investigated time interval.

2. Methods

To investigate these processes, numerical modelling was performed, making it possible to reproduce the spatiotemporal evolution of the parameters of the gaseous medium while accounting for the nonlinear nature of shock waves and their interaction with solid boundaries. The problem statement is based on solving the gas-dynamics equations for a compressible ideal gas in a two-dimensional domain (Fig. 1) separated by a rigid partition. Reflection of waves from the domain boundaries and interaction with the partition are taken into account; the partition is represented in the computational model as an absolutely rigid, stationary, non-deformable plate.



Ω – gas domain; Ω_s – rigid partition

Figure 1 – Computational domain

The conservation equations of mass, momentum, and energy for an ideal gas (Euler equations) [15, 16]:

$$\begin{aligned}\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \vec{u}) &= 0; \\ \frac{\partial (\rho_f u)}{\partial t} + \nabla \cdot (\rho_f u \vec{u}) + \frac{\partial p}{\partial x} &= 0; \\ \frac{\partial (\rho_f v)}{\partial t} + \nabla \cdot (\rho_f v \vec{u}) + \frac{\partial p}{\partial y} &= 0; \\ \frac{\partial E}{\partial t} + \nabla \cdot ((E + p) \vec{u}) &= 0,\end{aligned}$$

where ρ_f is the gas density, kg/m³; t is time, s; $\vec{u}$ is the flow-velocity vector, m/s; u and v are the projections of the velocity vector on the x and y axes, m/s; p is the gas pressure, Pa; E is the specific energy, J/m³.

Total energy:

$$E = \frac{p}{\gamma - 1} + \frac{1}{2} \rho_f (u^2 + v^2),$$

where γ is the adiabatic index $\gamma = c_p/c_v$, for a monatomic gas, $\gamma \approx 1.67$, and for air, $\gamma \approx 1.4$; c_p and c_v are the specific heat capacities at constant pressure and constant volume, respectively.

Ideal-gas equation of state:

$$p = (\gamma - 1) \left(E - \frac{1}{2} \rho_f (u^2 + v^2) \right).$$

The transition to the variational form is performed by multiplying the equations by a test function and integrating over the domain:

$$\int_{\Omega} \frac{\partial \rho_f}{\partial t} \psi d\Omega - \int_{\Omega} (\rho_f \vec{u}) \cdot \nabla \psi d\Omega + \int_{\partial\Omega} \rho_f \vec{u} \cdot \vec{n} \psi dS = 0;$$

$$\int_{\Omega} \frac{\partial (\rho_f u)}{\partial t} \varphi_x d\Omega - \int_{\Omega} \rho_f u \vec{u} \cdot \nabla \varphi_x d\Omega - \int_{\Omega} p \frac{\partial \varphi_x}{\partial x} d\Omega + \int_{\partial\Omega} \rho_f u \vec{u} \cdot \vec{n} \varphi_x dS + \int_{\partial\Omega} p n_x \varphi_x dS = 0;$$

$$\int_{\Omega} \frac{\partial (\rho_f v)}{\partial t} \varphi_y d\Omega - \int_{\Omega} \rho_f v \vec{u} \cdot \nabla \varphi_y d\Omega - \int_{\Omega} p \frac{\partial \varphi_y}{\partial y} d\Omega + \int_{\partial\Omega} \rho_f v \vec{u} \cdot \vec{n} \varphi_y dS + \int_{\partial\Omega} p n_y \varphi_y dS = 0;$$

$$\int_{\Omega} \frac{\partial E}{\partial t} \chi d\Omega - \int_{\Omega} (E + p) \vec{u} \cdot \nabla \chi d\Omega + \int_{\partial\Omega} (E + p) \vec{u} \cdot \vec{n} \chi dS = 0,$$

where ψ , φ_x , φ_y , χ are test functions; S denotes the domain boundary.

The finite element method (FEM) [17] with triangular finite elements was used to solve the problem.

Time integration is performed by the Euler method. To suppress oscillations in shock-wave calculations, SUPG (Streamline Upwind Petrov-Galerkin) methods or artificial viscosity may be used. In this study, the required numerical dissipation is obtained by selecting the local Lax-Friedrichs scheme [18, 19]. When determining the numerical flux at the boundary between two states UL and UR, the following function is used:

$$F^* = \frac{1}{2} (F(U_L) + F(U_R)) - \frac{1}{2} \lambda (U_L - U_R),$$

where $\lambda = \max(|u| + c)$ is the maximum wave-propagation speed, m/s; c is the speed of sound, m/s; UL and UR are the vectors of conservative gas variables on the left and right sides of the computational boundary where the numerical flux is determined (for an internal boundary between adjacent elements, they correspond to the gas states on both sides of that boundary; on a reflective boundary or on the surface of a rigid plate, the external state is specified in accordance with the impermeability con-

dition, that is, with the zero normal component of gas velocity at the boundary taken into account).

Speed of sound:

$$c = \sqrt{\gamma \frac{p}{\rho_f}}.$$

The dissipative term $\frac{1}{2}\lambda(U_L - U_R)$ acts as numerical artificial viscosity, smoothing high-frequency oscillations and suppressing unstable “noise” at the shock-wave front. This approach effectively stabilizes hyperbolic discontinuities and ensures the symmetry and stability of the solution.

Initially, an undisturbed state was prescribed throughout the entire gas domain, including the left and right chambers, except for the local region of the blast energy disturbance:

$$\rho_f(x, y, 0) = \rho_{f0}; \quad p(x, y, 0) = p_0;$$

$$u(x, y, 0) = 0; \quad v(x, y, 0) = 0;$$

$$E(x_1, y_1, 0) = E_0,$$

where (x_1, y_1) are the explosion coordinates, m; ρ_{f0} is the initial gas density, kg/m³; p_0 is the initial gas pressure, Pa; E_0 is the explosion energy, J/m³.

Reflective boundary conditions corresponding to an absolutely rigid stationary boundary were used on the external boundaries of the computational domain and on the surface of the internal partition:

$$(\rho_f \vec{u}) \cdot \vec{n} = 0; \quad ((E + p)\vec{u}) \cdot \vec{n} = 0,$$

where $\vec{n}$ is the unit vector normal to the surface.

For numerical modelling of the explosion in the gaseous medium, C# software was developed to perform the computational experiment, visualize spatiotemporal distributions of gas parameters, and export results for further analysis [20]. Initial conditions: domain size – 80 × 80 m; plate coordinates $x = [47; 48]$; time step $\Delta t = 0,001$ s; simulation time – 0,2 s; explosion-centre coordinates (40.0; 40.0); explosion energy $E_0 = 300,0$ J/m³.

3. Results and discussion

3.1 Analysis of changes in the energy field

Figure 2 shows the distributions of energy values in the investigated domain.

In the case of an absolutely rigid partition, the energy process is completely localized in the left chamber, where the explosion source is located. The right chamber

remains in the background state throughout the entire computational interval, indicating complete blocking of energy transfer through the partition. Under these conditions, the rigid plate represents the limiting case of maximum reflecting capacity: it does not allow the disturbance to penetrate into the adjacent space, but only redistributes energy within the explosion chamber, forming a complex pattern of reflections and local concentrations near its supports.

At $t = 0.002$ s, the energy field is almost axisymmetric with respect to the explosion centre (40; 40). The global maximum $E \approx 288.3$ J/m³ is localized in the near-centre region, while the disturbance front has not yet lost the character of radial propagation. At the same time, an intensive increase in energy toward the plate is already observed at this stage: on its left face at $x = 47$ m, values reach approximately 159.9 J/m³, whereas immediately behind the plate, at $x = 48$ –49 m, the energy remains at the background level (Fig. 3). This means that, even at the early stage, the plate acts as an absolutely impermeable boundary at which the front is interrupted and partially accumulates before the obstacle.

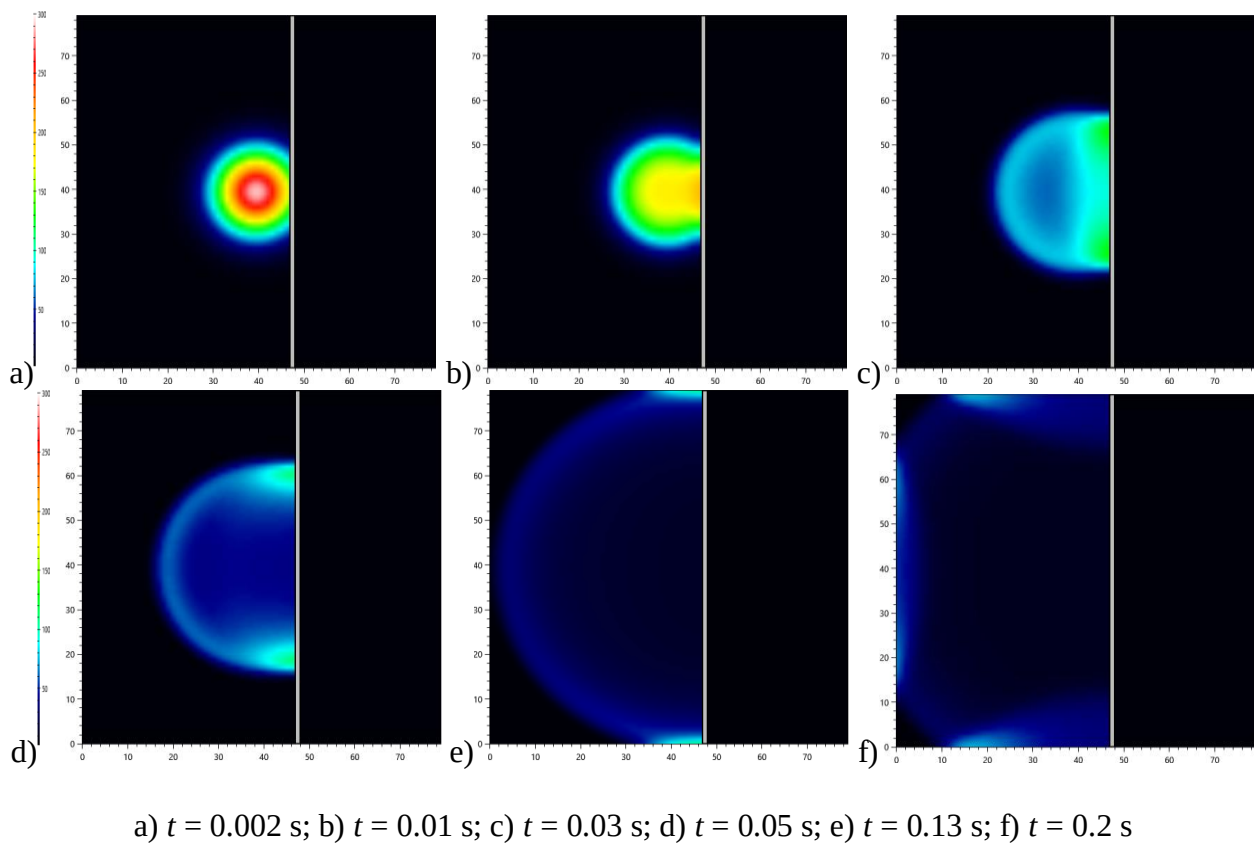


Figure 2 – Distributions of energy E in the investigated domain

At $t = 0.01$ s, the energy maximum shifts directly to the left face of the plate and reaches $E \approx 204.6$ J/m³ at the point (47; 39), Figs. 2b and 3. This is the clearest manifestation of the primary energy build-up in front of the rigid partition. Compared with the previous moment, the maximum is no longer associated with the explosion centre itself but is localized in the contact zone between the wave and the obstacle. Thus, at this stage, not merely the approach of the front to the plate occurs, but the actual for-

mation of the main energy-concentration zone in front of it. The sharp jump from high values at $x = 47$ m to the background level at $x = 48$ – 49 m (Fig. 3) directly indicates complete blocking of energy transfer into the adjacent chamber.

At $t = 0.03$ s, a qualitative restructuring of the energy field becomes characteristic (Fig. 2c). The continuous central maximum zone in front of the plate splits into two symmetric regions located along its left face above and below the explosion axis. Global maxima of $E \approx 128.7$ J/m³ are recorded near the points (47; 26) and, symmetrically, (47; 53). This means that, after the primary impact on the rigid obstacle, energy no longer concentrates in the central part but is redirected along the plate toward the upper and lower supports. This stage best demonstrates that the rigid partition acts not only as a screen but also as a guiding surface for the redistribution of wave energy.

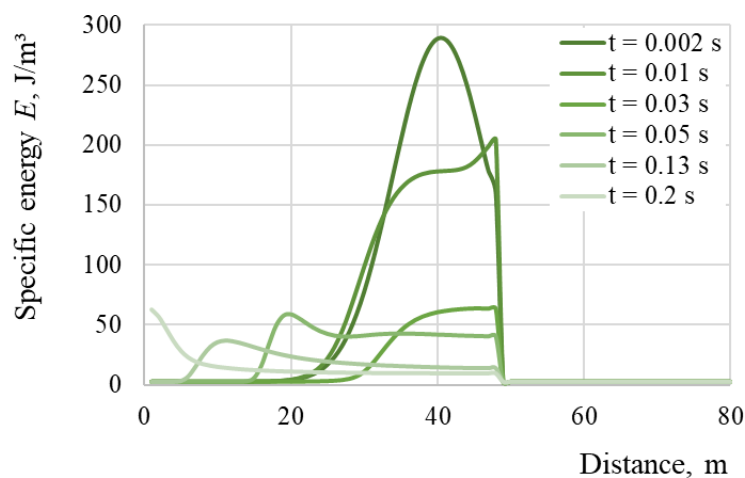


Figure 3 – Energy-wave shape at different time moments

At $t = 0.05$ s, the local maxima shift further toward the ends of the plate. The highest values, $E \approx 107.0$ J/m³, are observed near the points (47; 19) and (47; 60). This indicates the further development of two reflected energy branches propagating along the partition toward the upper and lower boundaries of the domain. The central part in front of the plate has already lost its dominant role, and the main concentration zones become the regions approaching its supports. Thus, energy in the left chamber begins to concentrate not in front of the entire plate but mainly in its end zones.

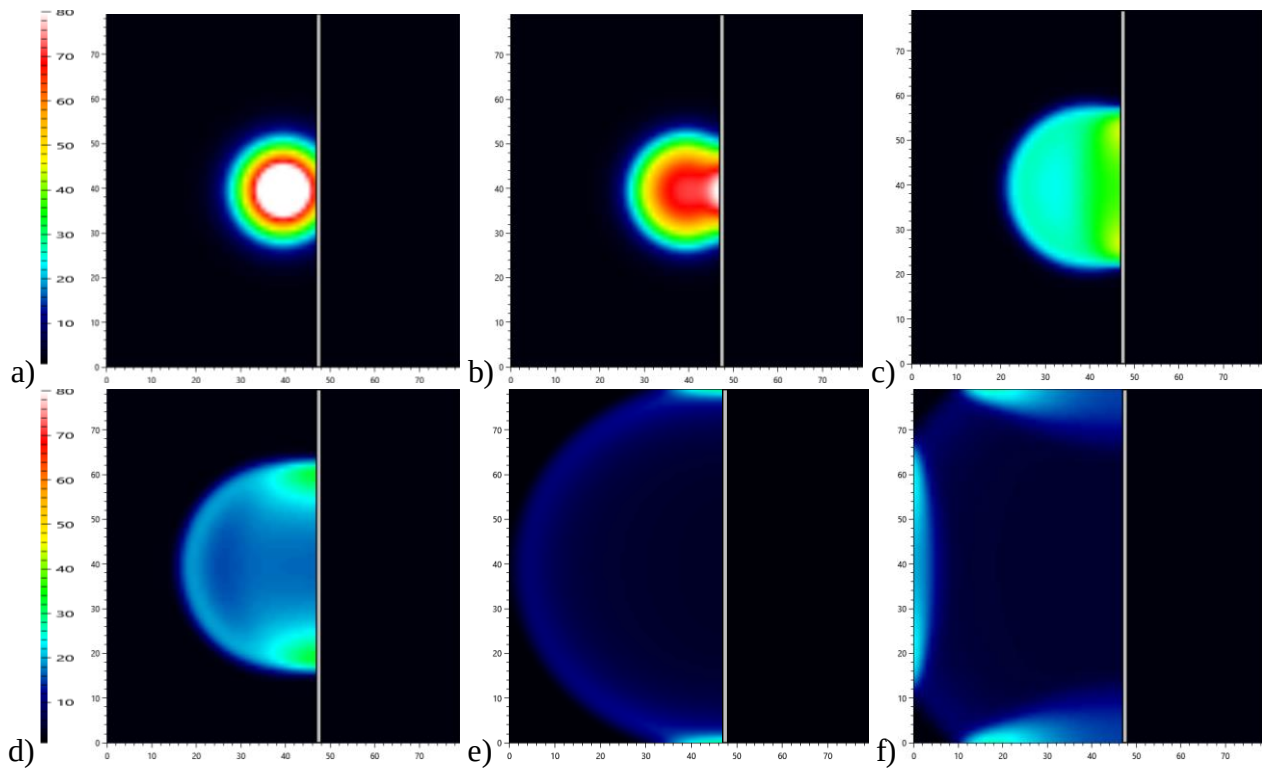
At $t = 0.13$ s (Fig. 2e), the stage of energy focusing at the junctions between the plate and the upper and lower boundaries of the domain occurs. Global maxima of $E \approx 101.3$ J/m³ are localized directly at the points (47; 0) and (47; 79). This means that the reflected waves, which had previously slid along the plate, reached the rigidly fixed ends of the partition and formed zones of the highest energy concentration there. Physically, this corresponds to the superposition of two factors: directed energy transfer along the plate and its subsequent reflection in geometrically closed junctions. These points should therefore be regarded as the most heavily loaded in the energy sense for the case of an absolutely rigid partition.

At the late stage, $t = 0.2$ s, the global maximum has already left the plate itself and shifts toward the upper-left and lower-left parts of the chamber. The highest value,

$E \approx 73.1 \text{ J/m}^3$, is observed near (17; 0) and symmetrically in the lower part of the domain (Fig. 2f). This means that, after focusing at the support points, the waves are reflected from the upper and lower boundaries; at the same time, reflection of the primary wave already appears near the left boundary because it reaches the outer wall at $t \approx 0.14 \text{ s}$. At this moment, the energy on the plate itself is already lower than during the phase of local accumulation near its ends; therefore, the active role of the partition as a zone of maxima gradually changes into the role of a source of secondary reflections in the closed domain.

3.2 Analysis of changes in the relative gas-pressure field

In the case of a rigid partition, the relative pressure field p/p_0 is the basic reference scenario of maximum reflecting capacity. At the early stage $t = 0.002 \text{ s}$ (Fig. 4a), an almost axisymmetric shock front forms with a maximum $p/p_0 \approx 115.3$ in the near-centre region around (39–40; 39–40). At the same time, a strong pressure increase toward the plate is already visible at this stage: on its left face at $x = 47 \text{ m}$ along the central section, the value reaches approximately 63.9, whereas farther to the right the pressure is already equal to the background level (Fig. 5). This means that the front rapidly approaches the obstacle and begins to form a pressure build-up zone in front of it.



a) $t = 0.002 \text{ s}$; b) $t = 0.01 \text{ s}$; c) $t = 0.03 \text{ s}$; d) $t = 0.05 \text{ s}$; e) $t = 0.13 \text{ s}$; f) $t = 0.2 \text{ s}$

Figure 4 – Distributions of relative gas pressure p/p_0 in the investigated domain

At $t = 0.01 \text{ s}$, the pressure maximum shifts directly to the left face of the plate and reaches $p/p_0 \approx 81.8$ at the points (47; 39–40), Figs. 4b and 5. This moment corresponds to the primary reflection of the shock wave from the rigid partition. A local

compression zone forms in front of the plate, where the normal component of gas motion is blocked and transformed into an increase in pressure. Behind the plate, the pressure does not change, which confirms the complete separation of the right chamber from the wave process.

At $t = 0.03$ s, the continuous zone of maximum compression in the central part in front of the plate splits into two symmetric regions (Fig. 4c). Global maxima of $p/p_0 \approx 44.0$ are localized near the points (47; 27) and (47; 52). This means that, after the primary impact, the wave energy no longer concentrates in the centre in front of the partition (Fig. 5), but is redistributed along its surface into two reflected branches directed toward the upper and lower supports. Thus, the plate acts not only as a rigid screen but also as a guiding boundary along which the wave field is restructured.

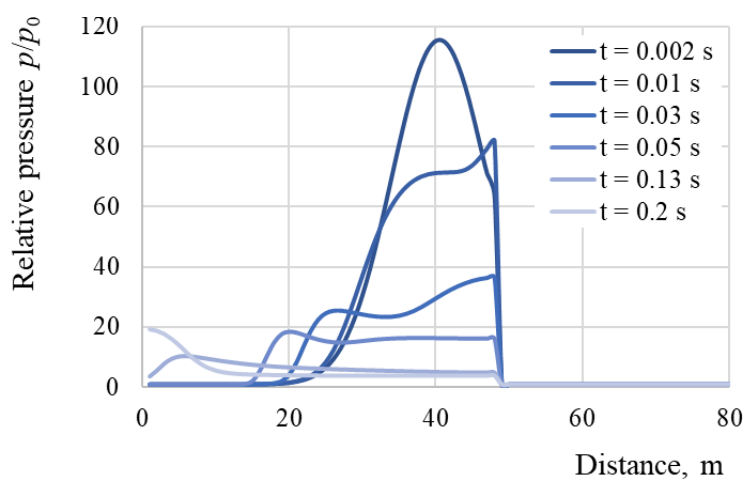


Figure 5 – Change in relative gas pressure p/p_0 over time

At $t = 0.05$ s, this tendency intensifies (Fig. 4d). The pressure maxima $p/p_0 \approx 32.6$ shift even farther along the plate – toward the regions (47; 19) and (47; 60). The central zone in front of the plate has already lost the role of the main compression region. This indicates further movement of the two reflected waves toward the upper and lower boundaries of the domain. Thus, at the intermediate stage of the process, the rigid plate not only reflects the front but effectively redirects the wave action toward its own support nodes.

At $t = 0.13$ s, the most representative stage of local pressure concentration occurs. Global maxima of $p/p_0 \approx 40.1$ arise directly at the junctions between the plate and the upper and lower boundaries of the domain (Fig. 4e), that is, near (47; 0) and (47; 79). This means that the reflected waves, which had previously propagated along the partition, reached its rigidly fixed ends and focused in geometrically constrained nodes. These points prove to be the most highly loaded in terms of pressure in the case of an absolutely rigid plate. Also, at $t = 0.13$ s, the annular zone of increased pressure approaches the left boundary of the chamber (Fig. 4e).

At the late stage, $t = 0.2$ s, the maximum $p/p_0 \approx 25.5$ shifts toward the upper-left and lower-left parts of the domain, approximately around $x \approx 18$ m. At the same time, reflection of the primary wave already appears near the left boundary because it reaches the outer wall at $t \approx 0.14$ s. Thus, at this stage the plate is no longer the im-

mediate location of the global maximum, but its previous role in redirecting the waves determines the entire subsequent pattern.

The absence in the calculations of a pronounced rarefaction phase with pressure below the initial level is associated with the adopted problem statement. The explosion is modelled as a positive local energy disturbance in a closed two-dimensional domain, and all boundaries, including the internal partition, are specified as rigid reflecting surfaces. Under these conditions, compression and wave-reflection processes dominate in the computational domain, whereas a rarefaction phase below the background pressure does not appear within the implemented model.

3.3 Analysis of changes in relative gas density

For the relative density field (Fig. 6), the pattern differs from that of the pressure field. If pressure within the implemented model remained nowhere below the background level, density demonstrates both compression zones $\rho/\rho_0 > 1$ and pronounced rarefaction zones $\rho/\rho_0 < 1$. This does not contradict the previous results: the density field reflects redistribution of gas mass, whereas pressure in this formulation is largely maintained by the positive energy disturbance and by multiple reflections of compression waves. Therefore, for the case of a rigid plate, the ρ/ρ_0 field is especially informative for identifying where gas accumulates and where, from the computational standpoint, a mass-depleted region forms.

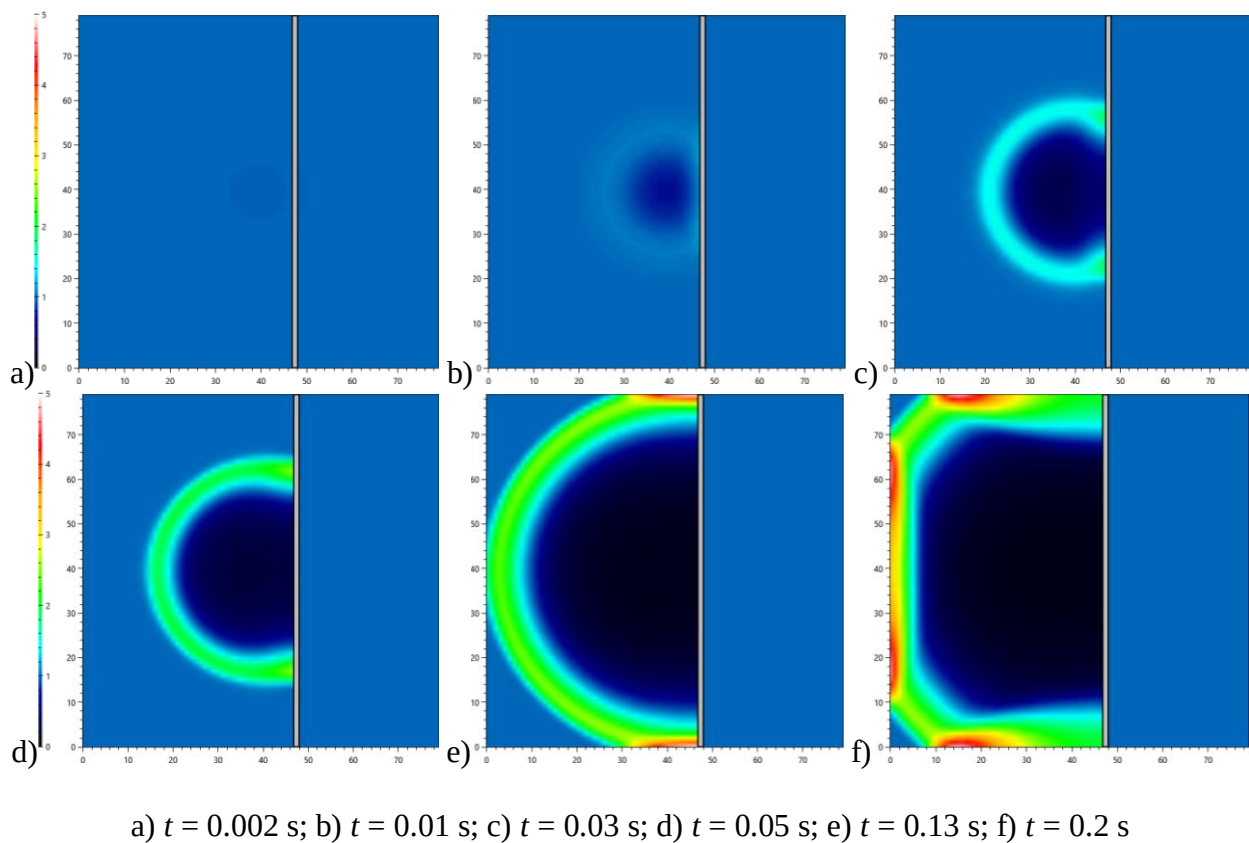


Figure 6 – Distributions of relative gas density ρ/ρ_0

At the initial stage, $t = 0.002$ s, density changes are still insignificant (Fig. 6a): the global maximum is only $\rho/\rho_0 \approx 1.013$, and the minimum is $\rho/\rho_0 \approx 0.988$. Even at this

stage, an important feature is observed: a slight increase in density is concentrated near the left face of the plate, with a maximum near (47; 39–40), whereas a weak density-decrease zone appears around the explosion center. Thus, even at the early stage, the model shows not merely axisymmetric compression but the onset of mass transfer from the central region toward the rigid obstacle, in front of which primary gas accumulation forms.

At $t = 0.01$ s, this tendency becomes much more pronounced. The maxima $\rho/\rho_0 \approx 1.173$ are no longer localized at the centre but at two symmetric points on the left face of the plate, approximately at $y \approx 31$ m and $y \approx 48$ m. At the same time, a distinct rarefaction zone forms in the near-centre region, with a minimum $\rho/\rho_0 \approx 0.743$ (Fig. 7). This means that, as the blast process develops, the gas mass does not accumulate at the source centre but is displaced from it toward the plate, where local compaction regions arise because normal motion is blocked. It is precisely at $t = 0.01$ s that the density field clearly loses axisymmetry and begins to show division into a central depleted region and two accumulation zones near the rigid partition (Fig. 6b).

At $t = 0.03$ s, the density distribution acquires an even more pronounced two-lobed structure (Fig. 6c). Global maxima of $\rho/\rho_0 \approx 1.905$ are observed near (47; 23) and (47; 56), that is, they shift upward and downward along the plate relative to the explosion axis. At the same time, a deep rarefaction zone develops in the left-central part of the domain, with a minimum $\rho/\rho_0 \approx 0.400$ (Fig. 7), localized near (35; 39–40). This is a highly indicative result: after the primary reflection, the wave not only forms increased density in front of the plate but redistributes the gas mass into two symmetric flows along the partition, whereas behind these moving fronts a sharply density-depleted zone remains in the inner part of the left chamber.

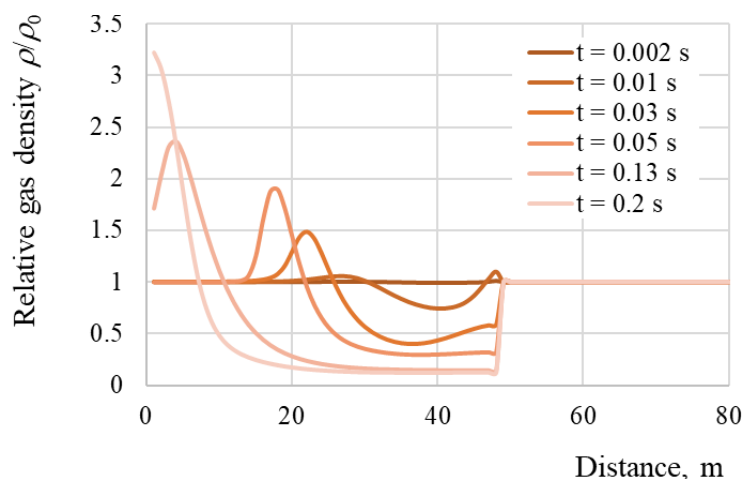


Figure 7 – Change in relative gas density ρ/ρ_0 over time

At $t = 0.05$ s, this process becomes even more intense. The maxima $\rho/\rho_0 \approx 2.516$ shift toward the regions (47; 17) and (47; 62), that is, even closer to the upper and lower supports of the plate, Fig. 6d. The minimum decreases to $\rho/\rho_0 \approx 0.298$ (Fig. 7) and remains in the central-left part of the domain. Physically, this means that the gas

mass flows increasingly actively toward the zones where the wave process “rests against” geometric constraints. In this case, the rigid plate not only screens the adjacent chamber but also determines the direction of mass transfer toward its own ends, forming two regions of intensive compaction near the upper and lower parts of its left face.

At $t = 0.13$ s, the most pronounced stage of density concentration occurs. Global maxima of $\rho/\rho_0 \approx 4.881$ arise directly at the junctions between the plate and the upper and lower boundaries of the domain, that is, near (47; 0) and (47; 79), Fig. 6e. The annular compression zone with a maximum $\rho/\rho_0 = 2.365$ reaches the left boundary of the chamber (Fig. 7). At the same time, the deepest rarefaction zone forms on the plate itself in its middle part, near (47; 39–40), where $\rho/\rho_0 \approx 0.140$ (Fig. 7). This means that, by this moment, the gas mass has been displaced as much as possible from the central part of the left chamber and concentrated in the nodes of geometric confinement. These points are the most loaded in terms of local compaction of the gaseous medium. Unlike the pressure field, where focusing at the supports was also observed at this stage, the density field additionally very clearly shows the “depletion” of the central region in front of the plate.

At the late stage, $t = 0.2$ s, the global density maxima have already shifted from the plate-support nodes toward the upper-left and lower-left parts of the domain (Fig. 6f). The highest values, $\rho/\rho_0 \approx 4.781$, are observed near (15; 0) and (15; 79). At the same time, reflection of the primary wave is already visible near the left boundary (Fig. 6f), since it reaches the outer wall at $t \approx 0.14$ s. Because, at this stage, reflection from the left boundary has not yet interacted with reflections from the upper and lower boundaries, the pattern has no interference character. Meanwhile, the central part of the left chamber remains sharply rarefied: the minimum is $\rho/\rho_0 \approx 0.121$ near (36; 39–40). Thus, at the late stage, the model already demonstrates a stable spatial division into peripheral mass-accumulation zones and an internal depleted region.

3.4 Analysis of gas velocity

For $|V|$, the pattern differs fundamentally from the pressure, energy, and density fields. If p/p_0 , E and ρ/ρ_0 best indicate zones of accumulation, compression, and local concentration, the velocity magnitude primarily reflects moving gas fronts. Therefore, the maxima of $|V|$ do not coincide with the pressure maxima on the plate or at its supports. On the contrary, in zones of direct abutment against the rigid boundary, the velocity decreases because kinetic motion is converted into compression. For this reason, the $|V|$ field should be interpreted as an indicator of disturbance transfer rather than as a map of the greatest loading.

At $t = 0.002$ s, the velocity field has an almost axisymmetric character (Fig. 8a). The maximum $|V| \approx 0.891$ m/s forms not at the explosion point itself but on an annular front around it, approximately within $x, y \approx 33$ –46 m. This corresponds to the initial radial acceleration of the gas away from the explosion source. The velocity already increases toward the plate, but to the right of it there is no motion.

At $t = 0.01$ s, the maximum increases to $|V| \approx 3.46$ m/s (Fig. 9); however, it is still localized not on the plate but in the moving frontal zone of the left chamber (Fig. 8b),

approximately near the points (36; 32), (32; 36), and the points symmetric to them. In front of the left face of the plate, the velocity is already substantial, but directly in the impact zone it does not reach the highest values. This is an important physical observation: at the stage of primary contact with the rigid obstacle, the gas motion begins to decelerate, which is why the $|V|$ maxima do not coincide with the pressure maxima that are already forming on the plate at this moment.

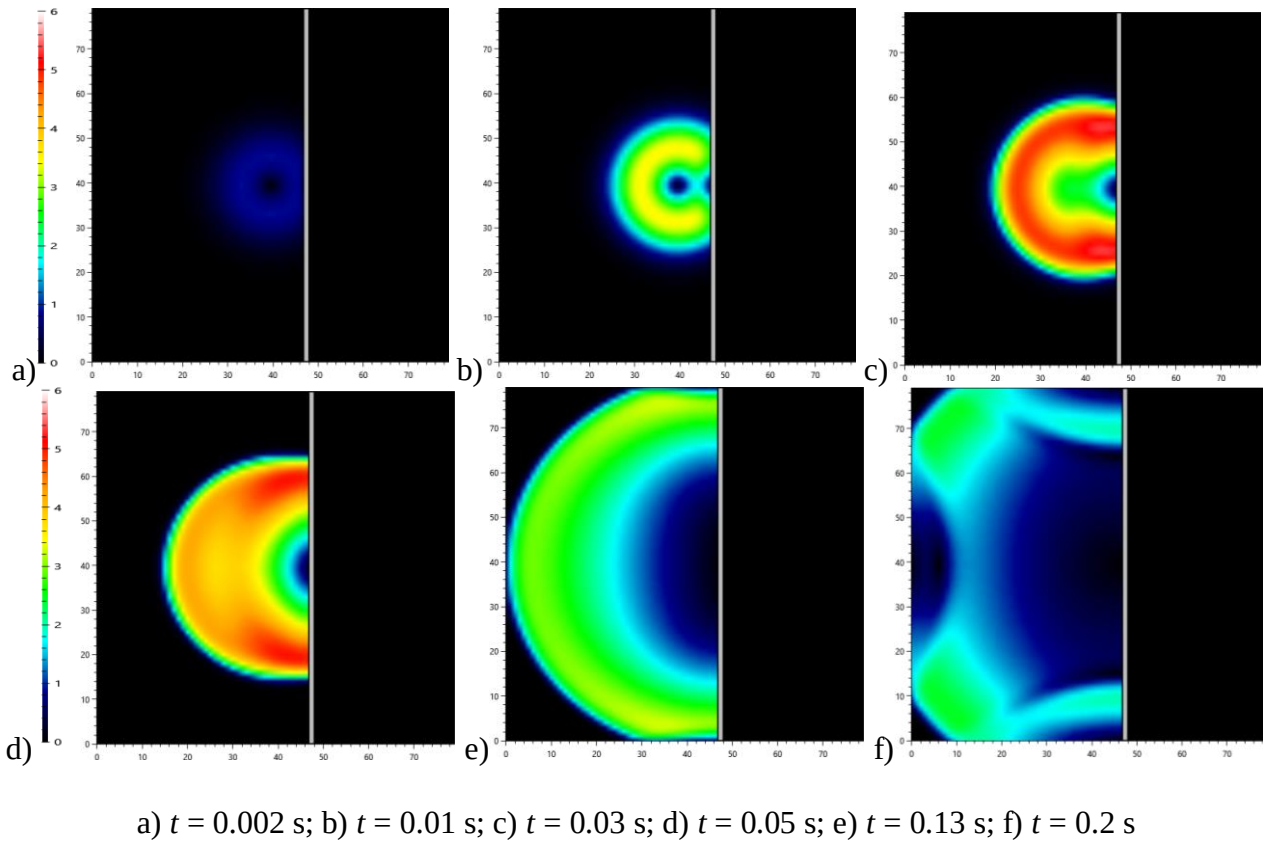


Figure 8 – Distributions of gas-velocity magnitude $|V|$

At $t = 0.03$ s, the pattern acquires a clear two-lobed shape (Fig. 8c). Global maxima of $|V| \approx 5.33$ m/s are localized immediately to the left of the plate, but not in its middle; rather, they occur in two symmetric zones approximately near (44; 26) and (44; 53). This means that, after the primary impact on the rigid obstacle, the most intense gas motion is concentrated in two reflected branches that slide along the plate toward the upper and lower supports. The central zone in front of the partition is no longer the region of the highest velocity, because the motion there is partly decelerated and transformed into compression.

At $t = 0.05$ s, these two maximum zones shift farther along the plate (Fig. 8d) – approximately to (42; 20) and (42; 59), while the maximum velocity is $|V| \approx 5.06$ m/s. This corresponds to further movement of the two high-velocity fronts toward the upper and lower support nodes. Thus, the rigid plate not only blocks the normal displacement of gas but also redirects the motion into two symmetric flows along its own surface (Fig. 8d).

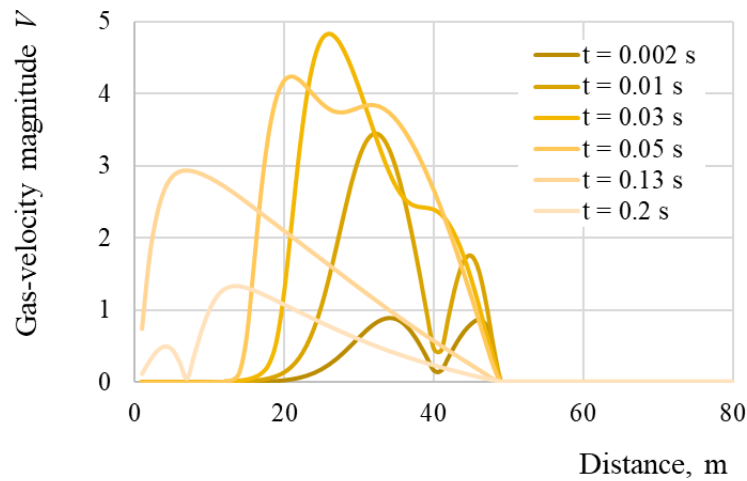


Figure 9 – Change in gas-velocity magnitude $|V|$ over time

At $t = 0.13$ s, the velocity maximum has already left the immediate vicinity of the plate. The highest values, $|V| \approx 3.28$ m/s, are observed near the points (33; 4) and (33; 75), that is, in the upper and lower parts of the left chamber. This means that, after the wave process focuses near the plate supports, the velocity fronts continue to propagate along the upper and lower parts of the domain toward the left boundary. At $t = 0.13$ s, the annular zone of maximum velocities corresponding to the propagating shock-wave front touches the left boundary of the chamber. The maximum velocity values at the level $y = 40$ m are slightly lower, $|V| \approx 2.93$ m/s (Fig. 9). In the central part directly in front of the plate, the velocity at this stage is already much lower, which agrees well with the previous conclusions for pressure and density: accumulation and redistribution of compression dominate here rather than intense motion.

At $t = 0.2$ s, the global maxima $|V| \approx 2.47$ m/s are localized in the upper-left and lower-left parts of the chamber near (10; 5) and (10; 74), Fig. 8f. This corresponds to further propagation of the primary velocity fronts after they have been redirected from the plate toward the upper and lower boundaries. At the same time, reflection is already observed near the left boundary, but at this stage interference with other reflections has not yet occurred. Thus, for the interval up to 0.2 s, the $|V|$ field reflects the sequential development of individual stages of the wave process: radial propagation, reflection from the plate, redirection of motion toward its supports, further propagation along the upper and lower parts of the chamber, and reflection from the left boundary.

3.5 Analysis of the loading level on the partition

The fields E , p/p_0 , ρ/ρ_0 and $|V|$ show the spatial pattern of the process, whereas the reflection force $F_{\text{partition}}$ characterizes the integral force response of the rigid partition over time:

$$F_{\text{partition}} = \int_{\Gamma_p} (p - p_0) dS,$$

where Γ_p is the surface (face) of the plate representing the partition.

This indicator makes it possible to quantitatively assess the overall load level on the partition. In addition to $F_{\text{partition}}$, the total reflection force from all faces of the domain, F_{total} , will also be considered:

$$F_{\text{total}} = \int_{\Gamma_{\text{side}} + \Gamma_p} (p - p_0) dS,$$

where Γ_{side} denotes the upper and lower reflecting faces of the chamber.

The change in $F_{\text{partition}}$ and F_{total} over time is shown in Fig. 10.

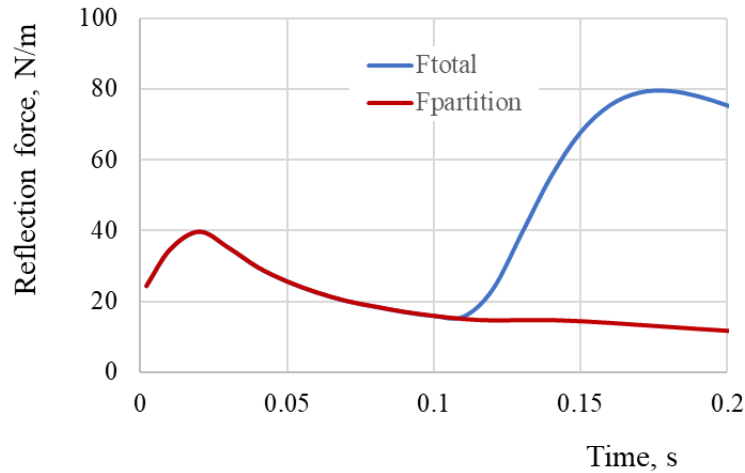


Figure 10 – Change in reflection force over time

Up to $t \approx 0.10$ – 0.11 s, almost the entire force response of the system is concentrated on the partition, since $F_{\text{total}} \approx F_{\text{partition}}$. This means that, at the early stage, the partition is the main reflecting surface that receives the integral wave load. Beginning approximately at $t = 0.11$ – 0.12 s (Fig. 10), the curves diverge sharply: the partition reaction no longer increases but instead slowly decreases, whereas the total reaction of all reflecting surfaces increases rapidly. This directly indicates that the wave process enters a stage in which the decisive contribution to the force response is already provided by the external boundaries of the left chamber rather than by the internal partition itself.

For $F_{\text{partition}}$, an early maximum is clearly visible. The integral reaction of the partition increases from 24.423 N/m at $t = 0.002$ s to a maximum of 39.819 N/m at $t = 0.02$ s (Fig. 10). This peak should be associated with the initial arrival of the shock wave at the plate and the most intense stage of its direct reflection. Then $F_{\text{partition}}$ decreases monotonically: to 15.971 N/m at $t = 0.1$ s and to 11.726 N/m at $t = 0.2$ s. Thus, after the initial impact, the total load on the partition itself does not increase again but gradually weakens. This agrees well with the previous spatial analysis: the pressure and density maxima first form in front of the plate and shift along it toward the supports, but later the leading role in the total reflecting response passes from the partition to the external boundaries of the chamber.

For F_{total} , by contrast, a two-stage evolution is observed. Initially, this quantity increases to the same early maximum of 39.819 N/m at $t = 0.02$ s, then decreases to a minimum of 15.786 N/m at $t = 0.11$ s, and subsequently begins to increase rapidly again, reaching the global maximum of 79.638 N/m at $t = 0.18$ s. Therefore, the greatest total force response of the system is formed not at the moment of the primary impact on the partition but later, when the wave, after redistribution near the plate, reaches the external reflecting boundaries of the chamber. This is an important conclusion: for the entire system of reflecting surfaces, the most dangerous moment does not coincide with the maximum load on the plate itself.

If the difference $F_{\text{total}} - F_{\text{partition}}$ is considered, it effectively shows the contribution of the external boundaries. Up to $t = 0.1$ s, this contribution is practically zero. At $t = 0.12$ s it is already approximately 8.78 N/m, at $t = 0.14$ s it is 40.79 N/m, and at $t = 0.18$ s it is 66.82 N/m. Thus, after $t \approx 0.12$ s, the external faces become the dominant source of the integral reaction. The share of the partition in the total force response decreases very sharply: from almost 100% at the early stage to approximately 37.4% at $t = 0.13$ s, 21.3% at $t = 0.15$ s, and only 15.5% at $t = 0.2$ s.

From the physical point of view, the pattern can be interpreted as follows. At the first stage, the wave initiated by the explosion reaches the partition, and it is the partition that forms the integral force response of the system. At the second stage, the wave process reflected from the plate is redistributed within the left chamber and then reaches the external reflecting faces. At this moment, the total reaction of the entire system increases sharply, although the force acting only on the partition no longer increases. Thus, the partition is the main reflecting surface at the early stage, but it does not determine the global maximum of the total system reaction at the later stage.

The presence of two maxima on the $F_{\text{total}}(t)$ curve indicates the two-stage nature of the formation of the total force response. The first maximum ($t \approx 0.02$ s) reflects the stage of direct interaction between the shock wave and the internal partition, when the partition contribution to the total reaction of the system is decisive. The second maximum ($t \approx 0.18$ s) forms at a later stage, when the wave process covers the external reflecting boundaries, as a result of which the total reaction of all surfaces substantially exceeds the reaction of the partition itself. Thus, the time history of F_{total} reflects the sequential transition from local reflection at the internal obstacle to the dominance of the response of the outer contour of the computational domain.

4. Conclusions

A mathematical model of blast-disturbance propagation in a compressible ideal gas within a closed two-dimensional domain with an internal rigid partition was developed. The model is based on solving the Euler equations by the finite element method with numerical stabilization using the Lax-Friedrichs scheme and makes it possible to account for wave reflection from external boundaries and the interaction of the gaseous medium with an absolutely rigid, stationary, and non-deformable partition. The proposed formulation is suitable for studying the spatiotemporal redistribution of the main gas-dynamic parameters and can be used as a baseline model for subsequent comparison between rigid and deformable partition cases.

The analysis of the energy, relative pressure, relative density, and velocity-magnitude fields showed that the rigid partition not only performs a shielding function but also determines the character of wave-process redistribution in the domain: after the primary impact of the front on the partition, the energy and pressure maxima shift to its left face, then split into two symmetric branches and move toward the upper and lower supports. The density field additionally showed the formation of compaction zones near the plate and simultaneous rarefaction in the central part of the left chamber, while the velocity field confirmed that the highest velocity values are associated with moving frontal zones rather than with regions of maximum compression.

The integral analysis showed that the greatest response of the partition itself occurs at the early stage of the primary impact, whereas the maximum total force response of all reflecting surfaces forms later, when the wave process reaches the external boundaries of the computational domain. Therefore, the rigid partition is the determining element of the early reflection stage, but it is not the only factor forming the late total force response of the closed system.

The obtained results can be used as a baseline computational scenario for assessing blast loads on rigid protective and isolating structures. In the mining industry, they are suitable for assessing the influence of blasting operations on supports, isolating stoppings, and protective barriers, as well as for predicting the loads on and effectiveness of such structures. The obtained dependencies should be used in the design of blast-protection structures while accounting for the trade-off between their rigidity and their ability to reduce peak loads. The developed software application can be extended to solve problems related to the assessment of blast-protection barriers and the propagation of impact loads in closed volumes.

Conflict of interest

Authors state no conflict of interest.

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ЧИСЕЛЬНИЙ АНАЛІЗ ПОШИРЕННЯ ВИБУХОВОЇ ХВИЛІ В ГАЗОВОМУ СЕРЕДОВИЩІ, РОЗДІЛЕНОМУ ЖОРСТКОЮ ПЕРЕГОРОДКОЮ

Круковський Д.О.

Анотація. У статті розглянуто чисельне моделювання вибухового збурення в стисливому ідеальному газі в замкненій двовимірній області, розділеній внутрішньою перегородкою. Метою роботи є дослідження просторово-часового перерозподілу основних газодинамічних параметрів і оцінка реакції жорсткої пластини під дією ударної хвилі як базового випадку для подальшого порівняння з перегородкою, що деформується. Математична модель ґрунтується на розв'язанні рівнянь Ейлера, що описують закони збереження маси, імпульсу та енергії для стисливого ідеального газу, із використанням рівняння стану ідеального газу. Чисельна реалізація виконана методом скінченних елементів на трикутній сітці з інтегруванням у часі методом Ейлера та стабілізацією за схемою Лакса–Фрідрікса. Для проведення обчислювального експерименту розроблено програмне забезпечення мовою C# з графічним інтерфейсом, візуалізацією результатів та експортом даних.

За результатами моделювання встановлено, що абсолютно жорстка пластина повністю локалізує вибухове збурення в камері з джерелом вибуху та не допускає передачі енергії, руху газу, змін тиску і густини в сусідню камеру. Показано, що після первинного приходу ударної хвилі до перегородки максимуми тиску й енергії зміщуються на її ліву грань, а далі розщеплюються на дві симетричні гілки, які поширюються до верхнього та нижнього закріплень. Поле відносної щільності додатково виявило формування зон ущільнення біля пластини та розущільнення в центральній частині камери, а поле швидкості дало змогу простежити кінематику фронту ударної хвилі та його подальше відбиття від зовнішньої межі. Інтегральний аналіз показав, що максимальна реакція самої пластини реалізується на ранній стадії первинного удару, тоді як найбільший сумарний силовий відгук усіх відбивних поверхонь формується пізніше, після залучення зовнішніх меж області у хвильовий процес. Отримані результати можуть бути використані при оцінці вибухових навантажень на захисні та ізолюючі конструкції. Розроблений програмний застосунок може бути розширений для розв'язання задач оцінки вибухозахисних бар'єрів і поширення ударних навантажень у замкнених об'ємах.

Ключові слова: вибухова хвиля; відбиття хвиль; ударне навантаження; чисельне моделювання; метод скінченних елементів.