

## Numerical simulation of the formation of return reflected shock wave in semi-closed channel with gas-permeable highly porous barriers

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The article presents the results of a numerical study of the interaction of a shock wave (Mach number  $M = 1.39$ ) formed at the entrance to a semi-closed cylindrical channel with highly porous gas-permeable barriers located within it. Barriers with a non-uniform spatial structure preventing the formation of a return reflected shock wave near the channel entrance are considered. A method for controlling the formation of shock waves in the return flow of the exhaust duct of a pulsed wind tunnel is proposed.

**Keywords:** shock waves, semi-closed channel, gas-permeable highly porous barriers, control method, numerical simulation.

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Study of interaction between shock waves (SW) and barriers is of great practical importance for asset protection against SW and prevention of in-process detonation of combustible mixtures. More recently, these problems have been solved using an approach where gas flow is directly simulated in a porous barrier material skeleton, i. e. without using continuum models of heterogeneous media mechanics [1–7].

Processes of SW reflection from high-porous barriers installed in a semiclosed cylindrical channel were experimentally and numerically studied in [5–7] to prevent SW focusing and conversion into strong shock waves. This has shown that the processes of interaction between SW and gas-permeable high-porous materials could be used for flow control in pulsed gas dynamic facilities. When a pulsed wind tunnel is running, supersonic flow from the nozzle goes into a pre-evacuated exhaust duct, which has a form of semiclosed cylindrical channel. Aerodynamic measurements are carried out in a uniform flow region immediately adjacent to the nozzle cross-section (measurement domain). SWs reflected from the rear end of the exhaust duct are the main source of flow pattern distortion. These backward SWs interact with the main flow and disrupt the operating mode of the wind tunnel.

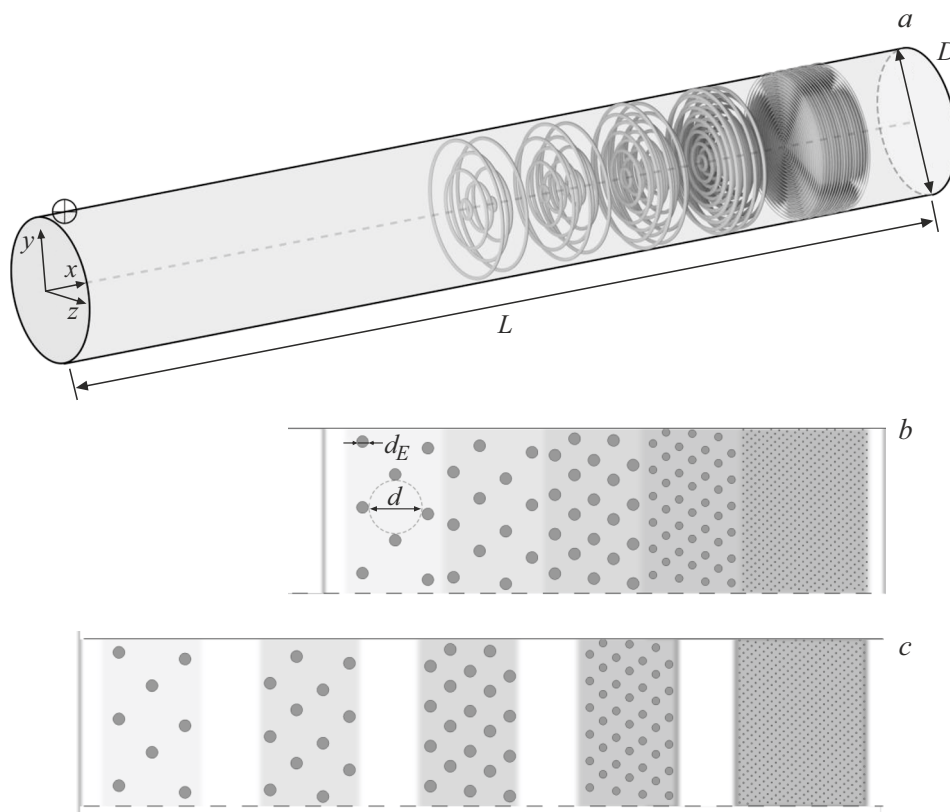
The objective of this study is to suppress backward shock waves by placing gas-permeable high-porous inserts into the model semiclosed cylindrical channel. The authors have earlier shown in [5–7] that the best barrier for minimizing the reflected wave intensity near the barrier in the semiclosed channel was a combined barrier consisting of four triangular grid layers with reducing porosity and one high-porous honeycomb layer. Successive grid layers ensure the minimum SW reflection from their structural elements and simultaneously provide a time delay for reflected waves induced inside the barrier. Having high drag for fluid flow,

a high-porous honeycomb layer suppresses waves coming from the buffer volume and resulting from reflections between the buffer volume end and the barrier. Reduction of the reflected wave intensity was achieved immediately before the combined barrier.

However, as the suppressed pressure waves move to the front end of the long channel, they are transformed into SW. The aim of this work is to build a combined barrier preventing SW formation in the backflow near the front end of the model channel.

Numerical simulation of the problem of interaction between SW and barriers in the semiclosed cylindrical channel was performed by solving Reynolds-averaged unsteady Navier–Stokes equations in two-dimensional (axially symmetric) formulation using the  $k-\omega$  SST turbulence model in ANSYS Fluent package provided there are high Reynolds numbers  $Re$  (here,  $Re = \rho U D / \mu = 9 \cdot 10^6$ , where  $\rho$ ,  $U$ ,  $\mu$  are the flow density, velocity and dynamic viscosity behind SW). Explicit fourth-order Runge–Kutta scheme for time approximation, second-order upwind scheme for space approximation, and flux vector splitting method, Roe-FDS, with a TVD-limiter to maintain solution monotonicity near discontinuities and local flow extrema were used to solve the problem. Flow in high-porous barrier was studied using an approach where gas flow is directly simulated in the porous barrier material skeleton, i. e. with resolution of porous insert skeleton elements.

Computational domain was a long semiclosed cylinder with the length  $L$  and diameter  $D$  (Figure 1, *a*). Then, all dimensions were assigned to the channel diameter  $D$ . Model nonuniform five-layer barriers were placed within the cylindrical channel at the distance  $L/D = 1.2$  from the rear end of the channel (Figure 1, *b, c*). Porous barrier simulation used a toroidal skeleton model developed by the



**Figure 1.** Schematic general view of the computational domain with toroidal model of the gas-permeable barrier skeleton and indicated position ( $\oplus$ ) of the pressure detection point (*a*) and five-layer barrier skeleton model (axial cross-section of the channel) with adjacent layers (*b*) and spaced-apart layers (*c*).

authors [8] that consisted of a set of tori, i.e. coaxial ring elements with circular cross-section (Figure 1, *a*). Thus, in the axial cross-section plane (Figure 1, *b*), this model is a set of staggered impermeable round elements with the diameter  $d_E$ .  $d_E$  of round elements (tori), number of round elements  $N$  and distance between round elements  $d$  were chosen according to the layer porosity setting. Material porosity was calculated using equation  $k = (1 - V_E/V_c)$ , where  $V_E$  is the volume of skeleton elements in the barrier layer taking into account tori diameters,  $V_c$  is the full volume of the barrier layer.

Computational domain beyond the gas-permeable barrier was covered with a regular rectangular computational grid with condensation towards the barrier. Porous barrier zone was covered with an irregular quadrilateral grid. Computational grids were matched with the channel walls and skeleton elements in the porous zone. Convergent grid method was used to choose the optimum computational grids with a number of computational cells of 230,000 for the channel without a porous barrier and 360,000 for the channels with porous barriers (197,000 in the porous zone and 163,000 beyond the porous zone). Whilst 250 cells fell on  $1/2$  of  $D$  of the channel, and from 920 to 1440 cells fell on the channel length depending on the absence/presence of barriers. From 19 to 8 computational grid cells fell on the perimeter of toroidal elements depending on the

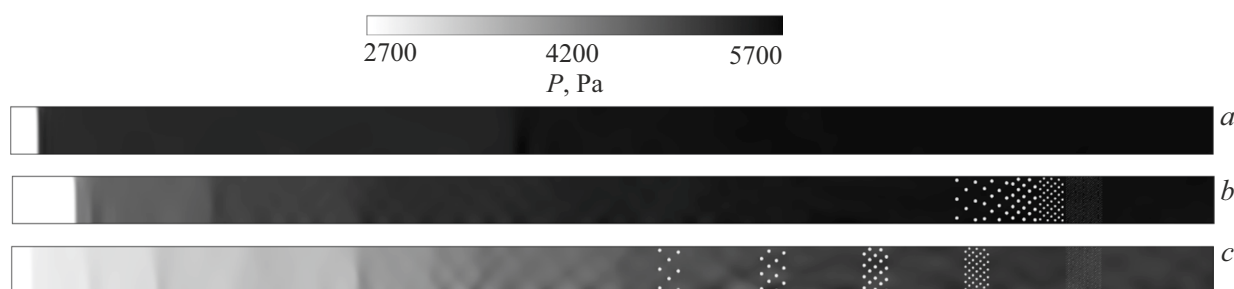
element diameter. Further grid refinement didn't result in any significant change of pressure in reflected waves (difference  $< 2\%$ ).

The problem addressed barriers with different thicknesses: 1 — a barrier consisting of five adjacent high-porous layers (Figure 1, *b*), whose properties are shown in the table; 2 — the same barrier, but with four front layers spaced apart at the triple thickness of each layer along the channel (Figure 1, *c*) without displacement of the last layer. Normalized thickness of the first four layers was equal to 0.3, and of the last layer was equal to 0.4. It should be noted that layer thickness and porosity  $k$  details of each layer correspond to those selected in [7] and providing the slowest pressure growth in all reflected waves near the porous barrier. The data on the layer-to-layer spacing was obtained via parametric numerical study: increase/decrease in the layer-to-layer spacing with respect to that specified in the work induced, accordingly, the growth of pressure wave variation amplitudes or formation of a backward SW at the pressure detection point (i.e. near the channel inlet).

Pressure was detected in a point on the model channel surface at  $L/D = 0.25$  from the front end. Total pressure and temperature were set at the left inlet boundary, no-slip conditions and adiabatic surface temperature were set on the model channel walls, including the rear end, and barrier skeleton elements. SW is formed at the model channel inlet

High-porous barrier layer properties

| Description                     | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 |
|---------------------------------|---------|---------|---------|---------|---------|
| Number of the skeleton elements | 8       | 12      | 20      | 42      | 651     |
| $d_E/D$                         | 0.036   | 0.036   | 0.036   | 0.024   | 0.005   |
| $d/D$                           | 0.2     | 0.16    | 0.12    | 0.08    | 0.024   |
| $k$                             | 0.95    | 0.92    | 0.88    | 0.87    | 0.95    |



**Figure 2.** Computational pressure field in the axial cross-section plane of the model channel for different times. *a* — without a porous barrier at  $t/t^* = 1$ ; *b* — with barrier 1 at  $t/t^* = 0.96$ ; *c* — with barrier 2 at  $t/t^* = 0.74$ .

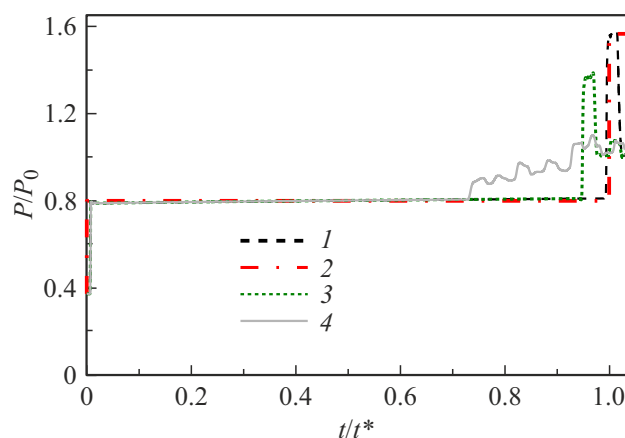
due to the difference between the total pressure  $P_0$  at the inlet boundary and initial static pressure in the channel such that SW with the Mach number  $M = 1.39$  is formed.

For these conditions, numerical simulation of interaction between SW and model nonuniform five-layer barriers 1 and 2 was performed. Figure 2 shows pressure field for the model channel without a porous barrier and the model channel with both barriers at times  $t/t^*$  when leading edges of the backflow arrive at the pressure detection point ( $t^*$  — backward SW arrival time in the case without a porous barrier). It can be seen that in the case without a barrier, a backward SW with large pressure surge arrives at the channel inlet. In the case with barrier 1, a backward SW also arrives at the detection point because the pressure wave fronts reflected from individual layers of barrier 1 and travelling along the channel catch up with each other and thus form a single reflected backward SW, but with a smaller pressure surge. In the case with barrier 2, the fronts of pressure waves reflected from single barrier layers are not able to catch up with each other because these layers are spaced apart along the channel and therefore a single reflected backward SW is not formed. Due to this, Figure 2, *c* shows that there are several low-amplitude pressure waves spaced along the channel.

Figure 3 shows calculation results in the form of time dependences of the static pressure  $P$  normalized to the total pressure at the pressure detection point for the model channel without a porous barrier and for the model channel with both barriers. It should be noted above all that calculation results for the model channel without a porous barrier show coincidence of the pressure surge amplitude and time  $t^*$  of SW arrival at the detection point with data obtained for a plane SW within a single-dimension perfect gas flow [9].

For the case with barrier 1 at the pressure detection point, as for the model channel without a porous barrier, formation of intense pressure surge is observed due to transformation of pressure waves reflected from elements of each barrier layer into a single backward shock wave when the pressure waves travel from the barrier to the channel inlet. However, it can be seen that the pressure surge amplitude is lower in the case with barrier 1 than in the case without a barrier due to frictional pressure loss on the barrier elements.

In the case with barrier 2, a time stretched pressure growth (shock-free pressure profile) is observed at pressure detection point instead of an intense pressure surge. This pressure growth has an amplitude, which is 1.5 times lower



**Figure 3.** Dependences of static pressure on time at the pressure detection point. *1* — calculation for the model channel without a porous barrier; *2* — calculation using equations for plane SW; *3* — calculation for the model channel with barrier 1; *4* — calculation for the model channel with barrier 2.

than that of the pressure surge in SW formed both in the flow without a barrier and in the flow with barrier 1. The effect was achieved by spacing apart the combined barrier layers with different porosity and number of elements per layer along the model channel.

A method for control of shock wave formation in backflow in the semiclosed channel, which simulates a pulsed wind tunnel exhaust duct, follows from the process fluid dynamics described above. This backflow reduction method can substantially increase the steady-state operating time of a pulsed tube and a uniform flow section.

Thus, the results of this study make it possible to design gas-permeable high-porous barriers, which are inserted into a semiclosed cylindrical channel and influence the backward flow properties. Barriers preventing backward shock wave formation near the channel inlet shall consist of several gas-permeable high-porous layers with increasing number of skeleton layers spaced along the channel. These results were used to propose a method for control of shock wave formation in backflows in a pulsed wind tunnel exhaust duct using multilayer high-porous barriers.

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## Conflict of interest

The authors declare no conflict of interest.

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