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THE INTERACTION OF A SHOCK WAVE WITH A PERMEABLE LAYER: AN EXPERIMENTAL STUDY

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In the paper, the interaction of a shock wave with a granular layer of spherical particles has been experimentally studied in an atmospheric shock tube. A near-edge space of pure gas was located between the porous layer and the tube's end wall. Two problem statements were considered. In the first embodiment, the structure and position of the porous layer remained unchanged. In the second one, the granular layer was destroyed under the action of the incident shock wave and turned into a mobile cloud of particles. For both variants, wave structures that occur both in front of the porous layer of granular particles and in the gap between the granular layer and the end wall of the shock tube were derived and analyzed. The initial information was obtained by measuring and recording equipment, which included piezoelectric pressure sensors and a multichannel ADC board for data collection.

Keywords: shock wave, permeable material layer, nonstationary gas filtration, wave structure

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ВЗАИМОДЕЙСТВИЯ УДАРНОЙ ВОЛНЫ СО СЛОЕМ ПРОНИЦАЕМОГО МАТЕРИАЛА

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В работе экспериментально исследовано взаимодействие ударной волны с гранулированным слоем сферических частиц в атмосферной ударной трубе. Между пористым слоем и торцевой стенкой трубы располагалась приторцевая область чистого газа. Были рассмотрены две постановки задачи. В первом варианте структура и положение пористого слоя предполагались неизменными. Во втором – гранулированный слой разрушался под действием падающей ударной волны и превращался в подвижное облако частиц. Для обоих вариантов получены и проанализированы волновые структуры, которые возникают как перед пористым слоем гранулированных частиц, так и в приторцевой области между гранулированным слоем и торцевой стенкой ударной трубы. Исходная информация была получена при помощи измерительно-регистрирующей аппаратуры, которая включала пьезоэлектрические датчики давления и многоканальную плату АЦП для сбора информации.

Ключевые слова: ударная волна, проницаемый слой материала, нестационарная фильтрация газа, волновая структура

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Introduction

Determining aerodynamic loads on the surface is an important applied aspect in studies of transient processes such as shock waves or pulsed jets. The problem becomes increasingly complex assuming a gas-permeable barrier that can consist of perforated elements, gratings, woven meshes, spongy structures, layers of granular media, etc. As waves propagate through such barriers, their amplitude typically decreases and wave profiles transform. The barrier can be deformed by intense impacts, including irreversible ones. There is much interest towards lattice barriers that allow substantial deformations, enhancing the dynamic effects on the barrier in certain circumstances [1, 2]. The boundary case, for example, when the porous layer in granular media is destroyed and two-phase flow is generated, is no less significant [3, 4].

The primary data obtained in experimental studies are important for this type of problem, allowing to characterize the key phenomena and discover the main trends. Experimental data can be used to refine existing mathematical models and construct new ones, describing the processes with varying degrees of completeness.

Multifactor studies of unsteady seepage began in the 1950s; fairly systematic review of these studies is given, for example, in monograph [5]. The key issues of mechanics of heterogeneous media for destructible lattices are discussed in [6, 7]. Let us consider the experimental studies providing data on granular flows. In particular, [8, 9] generalized the experimental studies, allowing to modify the model based on the Stokes drag. The effect of the medium's compressibility and general unsteady behavior of the given phenomenon was described in [10].

Representative data were given in [3, 4], considering wide variation ranges of geometric factors and flow parameters. Refs. [11, 12] served as a basis for formulating the laws governing shock waves passing through layers of dense mixture taking into account several mechanisms of particle collision [13–15]. Additionally, [16, 17] used sensors located directly in the porous layer to study the pressure variation in gas and in a gas-particle mixture. It was found that the pressure amplitude of the transmitted wave depends on a number of parameters characterizing different properties of the porous layer: length (depth), diameter and shape of the elements, thermal characteristics of the material (density, heat capacity, etc.), potential compression and reordering of structural elements.

The focus of modern studies in this area is on numerical simulation [18, 19]. There are two main directions. On the one hand, efforts are made to provide more complete and detailed descriptions of the processes under consideration; on the other hand, algorithms for numerical integration of differential equations for the given range of problems are improved and new algorithms are developed.

Reviewing the literature on the subject, we note that no studies so far have been carried out on direct comparison of flow regimes for retained and destructible porous layers under identical conditions. There are also no studies considering how the location of porous layers (retained and destroyed) relative to an impervious surface affects the instantaneous and integral characteristics of the attenuating dynamic response to this surface.

The subject of this study is the interaction of a shock wave with a layer of granular material in two problem statements.

The layer remains stationary in the first statement and the lattice structure of the porous layer is preserved; as the structure of the porous layer is destroyed, a mobile cloud of particles forms in the second statement. The size of the region free of granules between the porous layer and the impervious wall plays a certain role in the second case, with diverse effects on the integral characteristics [1]. The momentum transmitted to the particle cloud and the subsequent shock-wave interaction of this cloud with the 'gas cushion', which is a region filled with pure gas, is an important factor in this case.

Experimental test bed and experimental procedure

The experiments were carried out in an atmospheric shock tube 55 mm in diameter, placed horizontally. The tube is peculiar in that the initial level of air pressure in the high-pressure chamber coincides with the ambient pressure. The schematic of the shock tube with the locations of the holes for the pressure sensors is shown in Fig. 1 (linear dimensions in mm). The pressure sensors G1 and G2 were located opposite each other in the same cross-section of the tube to ensure that the processes and the obtained results were uniform in the circumferential direction.

Piezoelectric pressure sensors with a time constant of 10^{-4} s were used in the experiment. The signal from the sensors was amplified using cathode repeaters and fed to the ADC board, which worked as a multiplexer with a sampling frequency of 100 kHz per channel. The same regime of gas flow was maintained in the shock tube in all experiments by pumping the air out of the low pressure chamber (LPC) to a pressure lower than atmospheric by 10 times. The diaphragm separating the high pressure chamber (HPC) from the evacuated part of the shock tube was destroyed by a mechanical punch. The Mach number of the shock wave for the selected pressure ratio in the chambers of the shock tube was equal to 1.7.

Polyurethane particles of regular spherical shape were used to create a porous layer. The density of the material was 200 kg/m^3. Particles had different sizes, ranging from 2 to 3 mm. The thickness of the granular layer was 30 mm. The granular layer was located at equal distances from sensors G3 and G4 for the given series of experiments in the shock tube.

Different types of containers (depending on the purpose they were intended for) were constructed for holding the granular material in a horizontally arranged setup. To make the granulated layer indestructible, the container holding it consisted of a thin-walled metal support of a cylindrical shape and two meshes covering its end faces. To make the granular layer destructible, one of the meshes was replaced with tracing paper, which was easily destroyed by the shock wave. The longitudinal size of the container was 30 mm. The mesh was made of textile fabric and had a cell size of approximately 0.5×0.5 mm. The effect of the mesh and the paper on the wave structure was considered separately. Experiments were conducted in an empty tube and in a tube with empty containers, without a granular layer. We found that the influence of a container with two meshes does not exceed 15%, which is a small disturbance if the meshes are used to hold granular materials (see the section below).

The illustrations given below for the empty tube, the tube with an empty container, and different configurations with a granular layer correspond to one of the cases of initial data from the signals received from the sensors G1–G5 rather than an average value for the series of experiments. The trends observed in each series of experiments were fully reproducible and the results were obtained with the required repeatability.

Experiments without granular layer

The pressures here and in the graphs are given in relative units. The initial pressure in the low-pressure chamber was chosen for normalizing the function. Time was counted from the moment when the signal in the sensor G5 deviated from its initial level by a threshold value, i.e., when the sensor detected an incident shock wave.

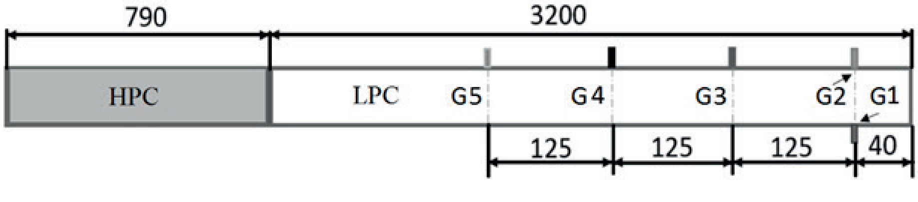

Fig. 1. Schematic of experimental shock tube:
Pressure sensors G1–G5; high and low pressure chambers HPC and LPC, respectively; linear dimensions are given in mm

Fig. 2,*a* shows the pressure variations over time for sensors G1–G5 in the empty low-pressure chamber without a container and a granular layer. Each of the sensors detects two shock wave in the given time interval: a compression wave and a rarefaction wave. In particular, two abrupt changes in pressure to a level of 30 kPa and then to a level of 70 kPa correspond to the sensors detecting an incident shock wave and a shock wave reflected from the end of the low-pressure chamber. The decrease in pressure observed starting from the fourth millisecond corresponds to the rarefaction wave detected. The smooth increase in pressure above the level of 70 kPa preceding the rarefaction wave corresponds to a compression wave appearing in the interaction of the reflected shock wave with fragments of the contact surface.

The term ‘contact surface’ should be further clarified. If we use a simplified description for the structure of gas flow in the shock tube, the contact surface is represented as a plane separating the high and low pressure gases starting from the initial time. However, when air enters the low-pressure chamber, the final velocities of diaphragm fracture generate intense gas flow in both axial and radial directions. This leads, in addition to front bending with a jump in density and temperature, to partial mixing of air from different chambers of the shock tube. The reflected shock wave actually interacts with the region consisting of fragments of the contact surface in this case.

The gas pressure behind the incident and reflected shock waves (readings from sensors G1–G5) is in good agreement with

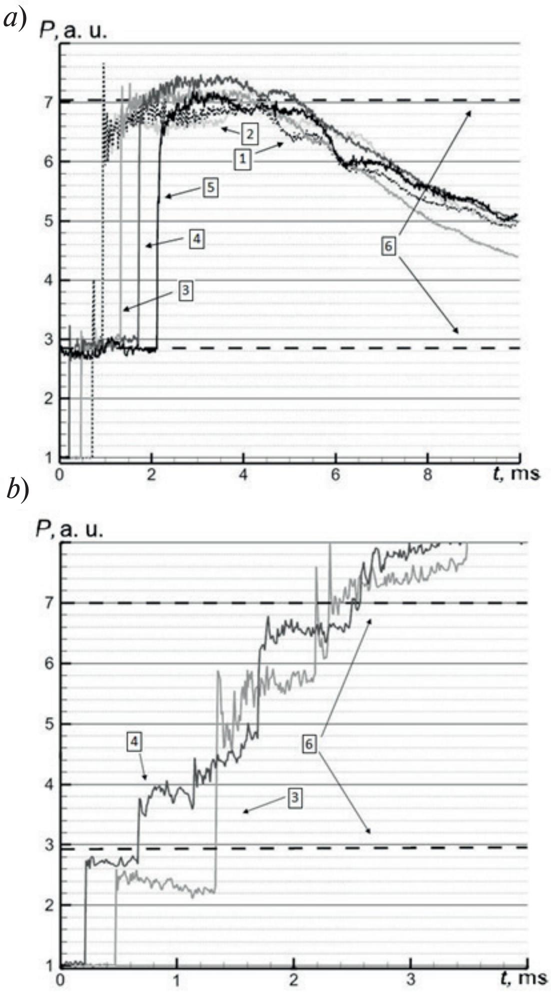

Fig. 2. Pressure variation over time in monitored points in low-pressure shock tube without container (*a*) and in same tube with empty container (*b*):
sensors *1*–*5*, analytical solutions *6*

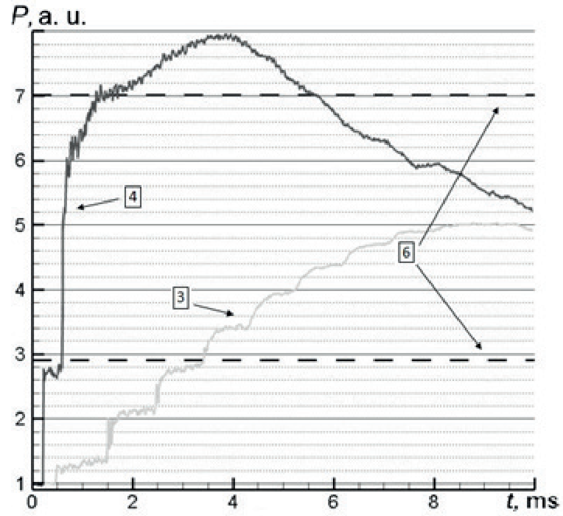

Fig. 3. Pressure variation over time in monitored points
for sensors G3 and G4 for configuration with indestructible granular layer:
sensors *3*, *4*, analytical solution *6*

the pressure calculated using the analytical dependence. The calculations were carried out based on elementary theory of a shock tube, using the solution of the Riemann problem on the decay of an arbitrary discontinuity [20]. Notably, the difference in the readings from the sensors G1 and G2 has the level of error of a single measurement for this problem statement when gas flow is known to be axially symmetric.

Fig. 2,*b* shows pressure variation over time for sensors G3 and G4 when an empty container is installed in the tube. It is somewhat difficult to interpret these results, since the wave structure is formed not only from the interaction of the shock wave with the end face of the low-pressure chamber and the contact surface but also from the effect of two meshes generating multiple wave reflections inside the empty container. However, it is still possible to determine the level of pressure in the incident shock wave and in the wave reflected from the end face of the LPC. The corresponding pressure levels in the empty tube act as reference values. The attenuation of the incident wave caused by the structural elements of the container can be assessed by the data for the first millisecond; comparing the values of the functions by the second millisecond, when the sensors G3 and G4 detect a shock wave reflected from the end face of the low-pressure chamber, the effect of the two meshes on pressure is no more than 15% of the measured quantity.

Experiments with stationary granular layer

Fig. 3 shows pressure variations over time for sensors G3 and G4, located on opposite sides of the granular layer that remained stationary during this experiment. The first pressure increase to a level of 30 kPa for sensor G4 corresponds to an incident shock wave. A reflected and transmitted shock wave appear in the interaction with the granular layer. Compared to reflection from the end face of the tube, the amplitude of the shock wave reflected from the surface of the granular layer is lower and detected by the sensor G4 at a level of 60–65 kPa. The same as in the tube without a granular layer, the reflected shock wave interacts with the elements of the contact surface. With the given position of the granular layer, the compression wave is reflected multiple times both from the contact surface and from the layer surface, leading to an increase in pressure to a higher level (80 kPa). The subsequent decrease in pressure for the sensor G4 is from a rarefaction wave passing.

Sensor G3 is located in the region between the porous layer and the end face of the low-pressure chamber. The readings from sensor G3 point to a wave structure in the form of a traveling wave reflected multiple times from both the surface of the granular layer and the end face of the low-pressure chamber. This is confirmed by the stepwise dependence of pressure on time. The intensity of the shock wave decays over time. The increase in pressure is associated with continuous flow of gas into the

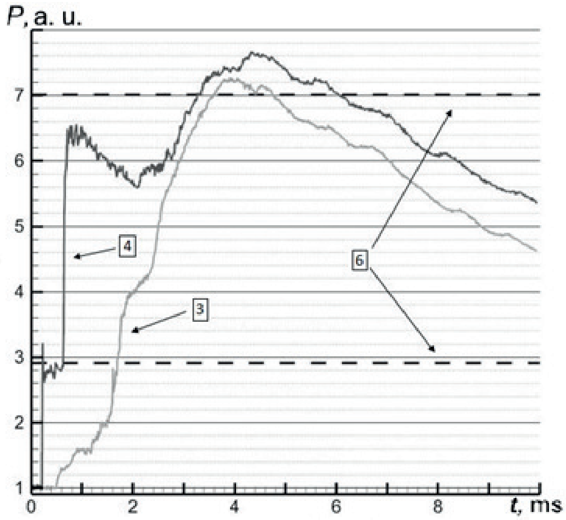

Fig. 4. Pressure variation over time
for sensors G3 and G4 for configuration with destructible granular layer:
sensors *3*, *4*, analytical solution *6*

near-edge region through the granular layer. The mechanism for supplying gas is based on seepage, i.e., mass flow of gas is a function of pressure drop across the thickness of the granular layer. As pressures on opposite sides of the granular layer are equalized and the pressure gradient is subsequently inverted, reverse seepage of gas occurs, that is, the gas in the granular layer changes the flow direction and moves away from the end face of the low-pressure chamber.

Experiments with destructible granular layer

Fig. 4 shows the pressure variations over time for sensors G3 and G4, located on different sides of the granular layer at the initial time. Let us point out some important aspects explaining the behavior of the curves given by in this figure. The granular layer is destroyed and turns into a cloud of particles as a result of interaction with the incident shock wave. There are two stages of particle dispersal in the cloud:

'instantaneous', associated with the front of the shock wave, when the particle gains momentum due to a shock wave passing a spherical particle;

'slow', associated with different velocities of the particle and the medium, that is, primarily with the Stokes drag.

The boundaries of the mobile porous layer have different velocities, i.e., the cloud not only moves toward the end face of the low-pressure chamber but also increases in size. As the cloud grows, the permeability of the mobile porous layer increases. Shock waves or rarefaction waves can still be reflected until the cloud has significantly increased in size from the boundaries of the porous layer.

Sensor G4, located in front of the granular layer, detects several processes. The scenario with sensor G4 detecting the incident and reflected shock waves completely coincides with the case of an indestructible granular layer at the initial stages. Sensor G4 detects a rarefaction wave at subsequent times. The intensity of the rarefaction wave depends on two processes. Firstly, the mass of gas passing through the granular layer increases. Secondly, the displaced boundary of the porous layer generates a rarefaction wave, similar to that behind a moving piston.

Readings from sensor G3 can be used to assess the pressure variations in the near-edge region. This process is more intense for the case when the granular layer is destroyed. Firstly, more gas enters the near-edge region due to increased permeability of the granular layer. Secondly, the size of the near-edge region with pure gas decreases as the particle cloud shifts. In this case, the boundary of the porous layer acts as a piston pushed into the region. A linear slope is observed on the pressure versus time curve after the second millisecond. At this point in time, sensor G3 is surrounded by a cloud of particles, i.e., is located in the region of two-phase flow. Both sensors G3 and G4 are located on one side of the particle cloud after two and a half milliseconds, and their readings reach the same level.

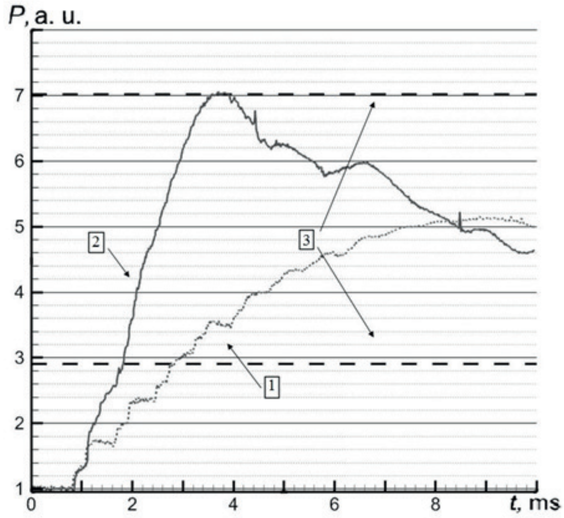

Fig. 5. Pressure variations over time for sensor G2 for both types of granular layer:
1, *2* correspond to indestructible and destructible layers, respectively;
3 is the analytical solution

Fig. 5 shows pressure variations over time for the two types of granular layer from the readings of sensor G2, which is closest to the end face of the tube.

The following patterns were observed for the waves. As follows from the behavior of the functions, the pressure in the near-edge region increases according to the same pattern in the first moments. This means that seepage laws differ little for the retained and destructible granular layers until the granules have gained a certain level of velocities. As noted above, the reason for subsequent discrepancies in the behavior of the pressure at the end face of the tube is that gas in the near-edge region is compressed by a cloud of particles in case of a destructible granular layer, in addition to an increase in pressure due to unsteady seepage. Using integral estimates, we can observe a decrease in the momentum of the impact on the end face of the shock tube in both cases, compared with the empty tube, and a decrease in absolute pressure in case of an indestructible granular layer.

Conclusion

We have carried out experiments on the interaction of a shock wave with a granular layer. We have established the main patterns in the behavior of unsteady seepage of gas through destructible granular layers and those preserving their structure. We have obtained the dependences of the dynamic effect of a passing shock wave on an impervious surface for two cases of porous layers.

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