An experimental study of the effect of a shock wave front on a permeable material

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Abstract. The interaction of shock wave with granulated layer of spherical particles was experimentally investigated in the atmospheric shock tube. There was a gap between porous layer and the end wall of tube. Two different cases were considered. In the first the structure and position of porous layer remained unchanged. In the second case, after the impact of the incident shock wave on the granular layer, the structure was destroyed and it turned into a moving particle cloud. For both cases, wave structures that occur both in front of porous layer of granular particles and in the gap between the layer and the end wall of the shock tube are obtained and analyzed.

1. Introduction

When considering non-stationary processes in the form of shock waves or impulse jets, one of the important applied aspects is the determination of aerodynamic loads on the surface. The complexity of the problem under consideration increases many times under the assumption of gas permeability of the barrier. These can be structures in the form of perforated elements, grids, woven mesh packets, spongy structures, layers of granular media, etc. When waves propagate through such barriers their amplitude tends to decrease and wave profiles are transformed. At intensive influences the barrier can undergo deformations, including irreversible ones. The interest in frames that allows significant deformation was dictated by the fact that under certain circumstances, there is an effect of increasing dynamic impact on the barrier. It is also possible that, for example, in the case of bulk media, the structure of the porous layer is destroyed and a two-phase flow occurs.

For this type of problem, the primary information that arises during experimental research is important. It allows us to characterize the main range of phenomena and to detect important patterns. Based on experimental data it is possible to specify the existing mathematical models and build new ones, which have different completeness of description process.

The subject of this study is the interaction of shock wave with layer of bulk (granulated) material in two cases. In the first case, layer remains stationary and frame structure of porous layer is preserved; in the second case, when the structure of porous layer is destroyed, a mobile cloud of particles is formed. In the latter case, a certain role is played by the size of the gap between porous layer and impermeable wall; its value may have multidirectional effect on the integral characteristics. In this case, the momentum that is transmitted to the particle cloud becomes an important factor and the subsequent
shock wave interaction of cloud with the "gas cushion", which was in the form of gap between porous layer and impermeable surface.

Multifactorial study of non-stationary filtration began in the 1950s and has been systematized. For the destroyed frames the nodal issues of heterogeneous media mechanics are presented in the monograph [1]. The focus of modern research in this area is shifted to the field of numerical modeling and is developing in two directions: clarification of the completeness of the description and detailing of the processes under consideration and the creation or improvement of existing algorithms for solving that problem, i.e. methods of numerical integration of differential equations for the range of problems under consideration.

Specifically, in [2, 3] with the help of sensors located directly in the porous layer, the pressure changes of both a separate gas and the pressure in a gas-particle mixture are studied. It is shown that the pressure amplitude of the passing wave depends on a number of parameters transmitting different properties of porous layer: length (depth), diameter and shape of elements, thermophysical characteristics of the material (density, heat capacity, etc.), the possibility of compaction and reorder of structural elements.

Let's distinguish works [4-6], where attempts to carry out modeling of gas filtration problem at the microlevel are made. At some assumption about the form and arrangement of elements of granular layer the calculation of gas flow in space not occupied by a frame is carried out. More popular approach within the nested continua is the Euler-Euler statement, which allows both the case of a fixed frame and a situation of motion of a two-phase medium [7, 8].

2. Experimental stand and research method
The experiments were carried out in a 55 mm diameter horizontally positioned atmospheric shock tube. Its scheme, linear dimensions, and location of the pressure sensor holes are shown in figure 1. To control the homogeneity of the processes under consideration and the results obtained in the circular direction, the sensors No. 1 and No. 2 were located in the same pipe section.

![Figure 1. Schematic diagram of the experimental shock tube](image)

In the experiment, electric piezoelectric pressure sensors were used with a time constant of $10^{-4}$ s. The signal from the sensors was amplified with the help of cathode repeaters and got on the ADC board, which worked in the multiplexer mode with a sampling frequency of 100 kHz per channel. In order to provide all experiments with a constant mode of gas flow in the shock tube from the low pressure chamber (LPC) the air was pumped out to the value of 10 times less than the atmospheric pressure. The diaphragm separating the high-pressure chamber (HPC) from the evacuated part of the shock tube was destroyed by a mechanical puncher. For the selected pressure ratio in the chambers of the shock tube, the Mach number of the shock wave was 1.7.

To create of a porous layer, polyurethane particles of correct spherical form were used. The material density is 1200 kg/m$^3$. The particle size was not unified and was in the range of 2 to 3 mm. The thickness of granular layer was 30 mm. For the series of experiments under consideration, granulated layer in the shock tube was equidistant from sensors 3 and 4.

For the location and retention of the porous layer in a horizontally located installation, containers of various types were developed depending on the desired functionality. To create an indestructible granular layer, the container holding it consisted of a thin-walled cylindrical support and two nets covering its end parts. To create destructible granular layer, one of the nets was replaced by papyrus paper, which was easily destructed by the shock wave. The net was made of textile fabric and had the
size of cells $h \approx 0.5 \times 0.5$ mm. The influence of the net and papyrus paper on the wave structure was studied separately. Experiments were conducted with empty containers without granular layer and it was established that the influence of the container with two grids does not exceed 15%, which is a small perturbation when used together with granulated materials.

2.1. Experiments without a granular layer

Hereinafter all pressures are presented in relative values. The value of the initial pressure level in the low-pressure chamber has been selected as the number to normalize the function. Figure 2 shows pressure versus time for all sensors No. 1-5 in an empty low-pressure chamber without container and granulated layer. During the considered time interval, each of the sensors recorded two shock waves, a compression wave and a rarefaction wave. In particular, two pressure rises to a level of 30 kPa and then to a level of 70 kPa correspond to the registration of the shock wave incident and reflected from the end of the low-pressure chamber. The pressure drop observed from the 4th ms onwards corresponds to the recording of the rarefaction wave. The smooth pressure increase preceding it above the level of 70 kPa corresponds to a compression wave that arose during the interaction of the reflected shock wave with fragments of the contact surface.

The readings of the sensors are in good agreement with the analytical results of the pressure values for the incident and reflected shock waves. The calculations were made on the basis of the elementary theory of the shock tube, based on the solution of the Riemann problem on the decay of an arbitrary discontinuity.

![Graph of pressure versus time at monitoring points](image)

**Figure 2.** Graph of pressure versus time at monitoring points in an empty shock tube without granules and a holding container

2.2. Experiments with a fixed granular layer

In fig. 3, pressure dependences on time are presented for sensors No. 3 and No. 4 located on different sides of a granular layer that is stationary during this experiment. For the sensor No.4 the first pressure rise up to the level of 30 kPa corresponds to the falling shock wave. When interacting with a granular layer, reflected and transmitted shock waves arise. Compared with the option of reflection from the end of the tube, the amplitude of the reflected shock wave from the surface of the granular layer is lower and recorded by the sensor No. 4 at the level of 60-65 kPa. As in a tube without granular layer, the reflected shock wave interacts with the elements of contact surface. For the position of the granular layer under consideration, a multiple reflection of the compression wave occurs from both the contact surface and
the surface of granular layer, which leads to an increase in pressure to a higher level (80 kPa). Subsequent pressure drop at sensor 4 is caused by the registration of a rarefaction wave. Sensor 3 is located in the gap between porous layer and the end of the low pressure chamber. Sensor 3 shows formation of a wave structure in the form of a traveling wave with multiple reflections, both from the surface of granular layer and the end of the low pressure chamber. This is evidenced by the stepwise structure of the pressure dependence on time. Over time, the shock intensity decays. The pressure increase is related to the continuous flow of gas into the gap through granular layer. The gas supply mechanism is based on the phenomenon of filtration, i.e. gas mass flow is a function of the pressure drop across the thickness of the granular layer. When equalizing the pressures on the different sides of granular layer there is a "reverse gas filtration", i.e. the gas in the granular layer changes the direction of flow and moves away from the end of the low pressure chamber.

Figure 3. Graph of pressure versus time for sensors No. 3 and No. 4 for the variant with indestructible granular layer

2.3. Experiments with a destructible granular layer
The Figure 4 shows time dependences of pressure for the sensors No. 3 and No. 4, located at the initial moment of time on different sides of granulated layer. We will point out the important points that explain the behavior of the curves shown in the figure. As a result of the interaction with the incident shock wave, granular layer is destroyed and transformed into a cloud of particles. There are two stages of particle acceleration in the cloud. "Instant", associated with the shock front when a particle receives a momentum by passing the shock wave past a spherical particle. “Slow”, which is associated with different speeds of the particle and the environment, i.e. primarily with the Stokes force. At the same time, the movement speed of the mobile porous layer borders is different, i.e. the cloud not only shifts towards the end of the low pressure chamber, but also increases in size. As a result of the increased size of the cloud, the permeability of the mobile porous layer increases. As long as the cloud does not increase significantly in size from the porous layer boundaries, it is still possible to reflect shock waves or rarefaction waves.
Sensor No. 3 in front of the granular layer detects several processes. In the initial stages, the scenario with sensor 3 recording of the incident and reflected shock waves is identical to the case of an indestructible granular layer. At the following time instants, sensor 3 detects the rarefaction wave. The rarefaction wave intensity is due to two processes. First, the mass of gas passing through the granular
layer increases. Second, the displacement of the porous layer boundary produces rarefaction wave as if it were behind a moving piston.

Sensor No. 4 indicates a change in the law of increasing the pressure in the gap. For the variant with destruction of granular layer, this process occurs more intensively. Firstly, due to the increased permeability of granular layer, more gas enters the gap. Second, the gap size itself is reduced by the particle cloud shift. In this case, the porous layer boundary acts as a piston that can be pushed into the area. After the 2nd ms, gentle linear section is observed on the time dependent graph of the pressure. At this point in time, sensor No. 3 is in the particle cloud, i.e. in the two-phase flow region. After 2.5 ms both sensors - No.3 and No.4 are on the one side of the particle cloud and their readings are aligned. The rarefaction wave observed after 4 ms causes the reverse movement of gas and granules, i.e. away from the end of the low pressure chamber.

3. Conclusion

Experiments on the interaction of shock wave with granulated layer of spherical particles are carried out in this paper. Non-destructive and destructible porous structure is considered. For both variants, wave structures that occur both in front of the porous layer of granular particles and in the gap between the layer and the end wall of shock tube are obtained and analyzed. In both cases, in comparison with the "empty" pipe, there is a decrease in the impact pulse on the end surface of the impact pipe, and in the case of an indestructible granular layer, there is a decrease in the absolute pressure level.

References

[1] Nigmatulin R I 1991 *Dynamics of multiphase media* vol 1 (New York: Hemisphere) p 244
[2] Ben-Dor G, Britan A, Elperin T, Igra O and Jiang J P 1997 Experimental investigation of the interaction between weak shock waves and granular layers *Experiments in Fluids* 22 432-43
[3] Britan A, Ben-Dor G, Elperin T, Igra O and Jiang J P 1997 Mechanism of compressive stress formation during weak shock waves impact with granular materials *Experiments in Fluids* 22 507-18
[4] Mehta Y, Neal C, Jackson T L, Balachandar S and Thakur S 2016 Shock interaction with
three-dimensional face centered cubic array of particles \textit{Phys. Rev. Fluids} \textbf{1} 27

[5] Sidorenko D A and Utkin P S 2018 Two-dimensional gas-dynamic modeling of the interaction of a shock wave with beds of granular media \textit{Russian Journal of Physical Chemistry B} \textbf{12} 869-74

[6] Osnes A N, Vartdal M, Omang M G and Reif B A P 2019 Computational analysis of shock-induced flow through stationary particle clouds \textit{International Journal of Multiphase Flow} \textbf{114} 268-86

[7] Gubaidullin A A, Boldyreva O Y and Dudko D N 2009 Interaction of acoustic waves with a porous layer \textit{Thermophysics and Aeromechanics} \textbf{16} 429

[8] Vivek P and Sitharam T G 2017 Shock wave attenuation by geotextile encapsulated sand barrier systems \textit{Geotextiles and Geomembranes} \textbf{45} 149–60