An experimental study of the propagation of a shock wave in a granular medium

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Abstract. In this work, experimental study of propagation shock waves and pressure-waves in granular medium was performed. As a granular medium are used hollow glass microspheres and composite sorbent based on them. The special experimental setup was prepared, which uses the principle of a shock tube. The setup includes a high pressure section and low pressure section with stepwise change of its internal diameter. The pressure graphics were obtained for the various tube sections for different media. The tube filling time and pressure wave velocity in the medium were estimated.

Introduction
The propagation of a shock wave and a pressure wave through selectively sorbed granular media is a pressing problem. Such problems arise in the design of facilities operating on the principle of pressure swing adsorption. In such facilities, when the elements of shut-off and control valves are quickly opened, shock waves and pressure waves can occur and propagate further through the pipelines into the adsorber with a sorbent. The parameters of gas–sorbent interaction, wave propagation velocity, adsorber filling time are needed to simulate the operation of the facilities and their design.

One of the applied problems, where it is important to take into account the parameters of interaction and propagation of a shock wave and a pressure wave in granular media, is the design of facilities for the extraction of helium from a helium-containing mixture using the membrane-sorption method. This method is developed at the Institute of Theoretical and Applied Mechanics SB RAS and combines membrane technology and short-cycle adsorption [1]. One of the distinguishing features of the proposed method is the use of hollow microspherical particles of silicate materials as membrane elements, the wall of which is selectively permeable to helium and impermeable to other components of natural gas [2]. The use of fine particles in their original form presents some technological difficulties, one of the solutions to this problem is the creation of a granular composite sorbent with microparticles as a helium-permeable component [3].

Installation description
To study the propagation of a shock wave and a pressure wave in granular media, a special experimental setup was prepared, the schematic diagram of which is shown in figure 1.
Figure 1. Schematic diagram of the setup.

The experimental setup uses the principle of a shock tube and includes a high pressure section (1), a low pressure section (2), a membrane unit (3), elements of shut-off and control valves and pressure sensors (PS). The high pressure section is a pipe made of stainless steel with length of 1120 mm and internal diameter of 25 mm. The low pressure section consists of two pipes with different diameters: the first part has the same internal diameter of 25 mm as the high pressure section and length of 160 mm, the second one has internal diameter of 50 mm and length of 793 mm. A special flange connects these parts of the low-pressure section, so that the internal diameter of the channel is changed stepwise. In the narrow part of the pressure gauge there is a pressure sensor at distance of 100 mm from the installation site of the membrane. In the wide part of the low pressure switch along its generatrix, 10 pressure sensors are installed. The first one is installed at distance of 60 mm from the upper end of the wide part, followed by the sensors going with constant interval of 84 mm. At the lower end of the pressure section there is another pressure measurement sensor. To protect the pressure sensors from the ingress of solid particles of the medium, special filters made of non-woven material are installed.

Two types of materials were used as a granular medium: microspheres MS-V-2L and a composite sorbent based on microspheres.

Figure 2. Microspheres MS-V-2L from an electron scanning microscope.

Figure 3. The composite sorbent.
Microspheres are a light granular medium in the form of a white powder, consisting of individual hollow particles of a spherical shape with size of up to 90 microns and thickness of ~ 1 micron. The microspheres MS-V-2L are made of sodium borosilicate glass at JSC “NPO Stekloplastik”. Figure 2 shows the image of microspheres MS-V-2L obtained using an electron-scanning microscope. Particles have spherical form and a smooth surface. Bulk density is 0.23-0.27 g/cm³.

A composite sorbent is made using microspheres as a helium-permeable component and a gamma alumina binder as a highly porous, strong binder framework. The content of microspheres in the sorbent under consideration is 15% by weight. The granules are cylindrical in shape. The diameter of the granule is 3 mm, the length is about 10 mm. A photograph of the composite sorbent is shown in figure 3. The parameters of the media formed by such materials were considered in [4, 5].

The shock tube is positioned vertically to ensure uniform filling by filling the bottom of the low-pressure section. The backfill level is between the third and fourth pressure sensors. The experiments are carried out using air and helium as the working gas; the temperature in the experiments was ~ 20 C. A dried cellophane membrane is installed in the membrane block to provide brittle fracture. A needle detonated the membrane.

When conducting the experiment in air, the pressure in the low-pressure section is equal to atmospheric; in the high pressure section, it is let in by air to the pressure of 3.5 atm. During the experiment with helium, the shock tube is previously evacuated, after which the low and high pressure sections are filled with helium to values of approximately 1 atm, after which helium is additionally injected into the high pressure section with pressure of 3.5 atm. Then, the membrane is ruptured. The data from pressure sensors 2–11 are digitized using an ADC with frequency of 40 kHz, time series are 3 seconds for experiments with a composite sorbent, and 10 seconds for experiments with microspheres.

**Experimental background**

Previously, experiments were conducted in air and helium with an empty setup. Then, experiments were carried out with backfill of microspheres (backfill porosity 0.33) and a composite sorbent (backfill porosity 0.82). Figure 4 shows data from the pressure sensors for the empty low-pressure section.

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**Figure 4.** Graphics for empty tube.
Due to the relatively low reaction speed of pressure sensors, it is difficult to measure the speed of a shock wave in the empty tube. Near the connection of tubes of different diameters, next to pressure sensor 3, after the propagation of the shock wave, a toroidal vortex is formed, due to which the pressure measured by this sensor is lower than in the other sections of the tube. After the propagation of the shock wave, gas oscillations are observed in the tube, the period of which is shorter for helium due to its lower density and higher adiabatic index.

In the case of filling the low-pressure section with a composite sorbent, when the shock wave-pressure wave propagates, the experimental data are as follows in figure 5. As follows from the graphs, as the shock wave passes through the backfill, it is broken up and a pressure wave propagates further along the sorbent.

Figure 5. Graphics for composite sorbent backfill.

Figure 6 shows the pressure graphs in the tube with microspheres. At this time scale, the difference between pressure sensors 2 and 3 is not noticeable. Immediately after the collision of the shock wave with microspheres, all sensors demonstrate almost simultaneous slight stepwise increase in pressure. This phenomenon can be explained by shock wave propagation throw the system of glass microspheres, which can be regarded as a solid. Using the pressure curves from figure 6, it is possible to determine the pressure-wave velocity in the granular medium under study, which is changed from the shock wave propagation velocity up to 0.3 m/s towards the end of the tube.
Conclusion
In this work, an experimental study of propagation of shock waves and pressure-waves in granular medium was performed. The experiments were carried out in a tube with various fillings. The pressure graphics were obtained for the various tube sections for different media. The tube filling time and the pressure wave velocity in the medium were estimated.

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