Experimental study of seismic action influence on gas permeability of coal and hydraulic fractures

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Abstract. Mine field development of coal deposits is currently associated with work at depths exceeding 400m. Under these conditions the gas content of promising horizons is one of the main factors constraining the pace of development. An integral part of gas-bearing coals’ extraction is their preliminary degassing. The methane recovery ratio affects the efficiency and safety of longwall work. Degassing is intensified in order to achieve the required values of methane content in coal seams. A well-known method employed to intensify filtration processes in fluid-saturated rocks is the elastic vibrations’ treatment. The laboratory tests and field work show the positive effect of elastic vibrations on the intensification of methane desorption from coal. Modern works in this field are devoted to investigation of connections between the parameters of vibration action and the degree of increase in the methane desorption. This paper provides the results of a series of experimental studies on seismic action’s effect on the permeability of coal and hydraulic fractures. The research has been carried out on a custom designed laboratory bench. The design of the stand provides the effect of elastic vibrations of small amplitude with independent regulation of the average and differential gas pressures, axial and lateral compression of the sample. The experiments have been carried out using solid coal cores, cores with single through longitudinal cracks simulating drainage hydraulic fractures and cores with the single fractures propped with a low-density proppant designed to intensify the degassing of coal seams. The patterns of the seismic impact on the gas permeability of coal under the conditions of all-round compression have been established in accordance with the results of experiments. Also, the experimental results reveal certain patterns of increase of the drainage cracks’ gas permeability observed when the cracks are propped with proppant and are under the low intensity seismic effect under the conditions of all-round compression. The studies show that the effectiveness of seismic action increases with an increase in the accumulated exposure time, followed by stabilization and persistence of the positive effect for at least 3 - 7 days after the cessation of exposure. The obtained results provide the opportunity to assess the possibility of using seismic action to intensify the degassing of non-propped hydraulic fractures in coal mines.

1. Introduction
Mine field development of coal deposits is associated with a constant risk of negative accidents due to methane gas captured in coal seams. An increase in the depth and pace of seam development with modern mining complexes imposes significant restrictions on the preparation time for promising horizons and contributes to an increase in the risks of unfavorable gas-dynamic manifestations, such as sudden coal and gas outbursts.
The research works dedicated to increasing the production of methane from coal beds are aimed at studying the adsorption and desorption of gas by coal. Papers on the effect of seismic action on the coal mass are currently focused on changes in the stress-strain state of rocks, the development of cracks, and an increase in gas recovery. Thus, authors [1] found that acoustic technologies can facilitate oil recovery and improve gas production efficiency. In works [2, 3] studied the mechanism of a sound wave that reduces the gas adsorption capacity of coal and increases the rate of gas desorption. Authors [4] studied the effect of pulsed hydraulic fracturing on gas desorption and found that pulsed fracturing would facilitate gas desorption with increasing pressure and pulsation frequency. The paper [5] provides the results of the study about the effect of seismic impact on the core permeability, characterizing the dependence of the impact efficiency on the frequency and intensity of vibrations when performing single sessions.

Currently, waterjet technology, hydraulic fracturing and pulse hydraulic fracturing technology can significantly improve the efficiency of extraction of coal seams [6, 7, 8]. It was found that mechanical vibration generated by the aforementioned technology can facilitate gas desorption. Promising for research appears to be the integration of hydraulic fracturing technology and subsequent treatment with mechanical vibration, for example, due to borehole vibration sources.

In this work we carried out a series of studies of the effect of mechanical vibration on coal cores containing a through crack filled with proppant during axial gas filtration in the frequency range of up to 360 Hz. The dependencies of the increase in the permeability of the core-fracture system with the proppant on the frequency and amplitude of vibrations were established. The obtained results provide a great reference value for the development of approaches to vibration treatment of coal seams.

2. Experimental technique and sample preparation

2.1. Sample preparation
Dense dry coal of grade "D" from the Permyakovsky open-cut coal mine of the Karakansky coal deposit (Kuznetsk basin) was used for the performed experiments. The density of the dry coal was 1350 kg/m³, in which the velocity of longitudinal waves was 1550-1650 m/s.

Additional studies of polished sections using an electron microscope showed that the tested coal has a structure typical of coal with microblocks of 2.9 - 6.2 mm in size, between which there are cracks with an average opening in the unloaded state of 47 μm. Gas filtration in such coal goes along the existing fractures [8], and the permeability decreases exponentially with increasing compression. The experiments were carried out using a core with a through longitudinal fracture filled with a low-density proppant developed for intensifying the degassing of coal seams by hydraulic fracturing [9].

2.2. Equipment
Coal permeability depends on many parameters, such as compression of the core in mutually orthogonal directions, the differential pressure of the filtered gas, as well as the structural features of the rock from which the core was drilled. Additionally, it is necessary to integrate the method of measuring permeability and the method of applying controlled vibration exposure to obtain reliable and respectable results. A special laboratory bench was developed to implement these approaches.

The layout of the bench is shown in Figure 1. The developed bench is designed to study the permeability of coal and hydraulic fractures during stationary filtration of a linear gas flow and exposure to seismic vibrations. The bench consists of a small-sized test chamber, a vibration platform with a system for measuring vibrations of the test chamber, a gas preparation unit, a pneumatic system for lateral compression and a hydraulic system for axial compression of a cylindrical sample by external pressure, and a system for measuring the filtration time of a fixed volume of gas. The bench
provides automatic maintenance of a given pressure gradient and measurement of gas filtration time without restrictions on filtration rate.

![Figure 1. The layout of the bench: 1 – crate with moduli DI, DO; 2 – master oscillator (G); 3 – vibrating table (VT) with power amplifier; 4 – test chamber; 5 – gas-meter (C1); 6 – fluid outflow container (C2); 7 – cylinders with compressed nitrogen; 8 – gear boxes (K1, K2); 9 – gear box (K3)](image)

2.3. Plan of Experiment

During the experimental series the axial and radial pressures exerted on the core were changed in stages from 1 to 5 MPa and, then, decreased with a step of 1 MPa. The differential gas pressure was 0.1, 0.2, 0.3 MPa at each stage of measurement.

Two series of measurements of fracture permeability with proppant in coal core were carried out: the first – the fracture was exposed to vibrations that are equal to 160, 240, 320 Hz; the second – to vibrations that are equal to 40, 80, 120, 200, 280 Hz. At each of the indicated frequencies, the impact was carried out at signal amplitudes at the output of the vertical seismic receiver in the range from 2 mV to 100 mV. The diagram in Figure 2 shows time sequence of the seismic action, measurements of the time of nitrogen filtration through the sample before and during the action in one experiment (at one of the frequencies). The action of seismic vibrations was carried out in sessions lasting 5 minutes, each, the measurements of gas filtration through the sample took 2-3 minutes.

![Figure 2. A sequence of test in the experiment (at one of the frequencies) on seismic impact on a coal core with a through fracture with proppant.](image)

The permeability coefficient was calculated using the well-known formula for a linear gas flow and a stationary nature of filtration [10]:
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\[ k = \frac{2 \cdot 10^4 V \mu_a P_3}{L} \frac{1}{P_3^{1/2} - P_3^{1/2}} \]

where \( k \) – permeability coefficient, \( mD \); \( P_1 = P_3 + \Delta P \) - test chamber inlet pressure, bar \( (10^{-1} \text{ MPa}) \); \( P_3 \) – test chamber outlet pressure, bar; \( V \) – gas volume at pressure \( P_3 \), that went through the sample, \( \text{cm}^3 \); \( \mu_a \) – nitrogen viscosity, \( \text{mPa} \cdot \text{s} \) \( (\text{sPa}) \); \( S \) – cross-sectional area of samples, \( \text{cm}^2 \); \( L \) – length of the sample, \( \text{cm} \); \( t \) — time of gas filtration through the sample, \( s \).

3. Results and discussion

To observe the change in the filtration times after each processing session, a series of filtration through the core at rest was carried out with a certain frequency, hereinafter in the text such measurements are simply referred to as "background". In Figure 3 the dependencies of the filtration time without vibration on the lateral compression are shown according to the averaged background measurements in experiments at all frequencies.

Filtration time increases with increasing lateral compression of the core. The graph in Figure 3 shows that the dependence between these values is close to linear with no visible hysteresis (the ascending and descending branches of the graph are almost identical). The indicator of the reliability of approximating the dependence by a linear trend is \( R^2 = 0.9763 \).

With an increase in the accumulated impact time, the background (without vibration) filtration time decreases, which indicates the presence of the aftereffect of vibration treatments (shown in more detail below in Figure 6).

The effectiveness of the impact was evaluated by us in relation to the background value of the filtration time to its value during vibration. The graph of the change in the filtration time under seismic action, depending on the lateral compression, built according to the average measurement values of the 1st and 2nd series of experiments is shown in Figure 4.

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**Figure 3.** Dependencies of the filtration time without vibration on the lateral compression.

Average values for background measurements of 1 and 2 series of experiments
The graph in Figure 4 illustrates that the impact efficiency does not depend on lateral core compression (the accuracy of approximating the experimental data by linear, exponential, logarithmic and degree trends is $R^2 = 0.1$, which indicates that there is no connection between the analyzed parameters). Therefore, to assess the effectiveness of the impact, we used the average values of the efficiency at different values of the lateral compression.

Figure 5 shows the dependence of the average (over the lateral compression) decrease in the filtration time under seismic action on the vibration frequency.

Figure 5 shows that at the same frequency the seismic impact on the tested coal sample with a through crack propped with proppant increases the permeability (reduces the filtration time) at frequencies $\leq 260 \pm 20$ Hz 3 times stronger than at higher frequencies.

To study the effect of the intensity of impact on the permeability of the tested sample, the 3rd series of experiments was carried out, in which the amplitude of vibrations at the output of the master seismic receiver was 2, 5, 10, 20, and 30 mV, the frequency was 40, 120, 200 Hz, and the lateral...
Compression was 1, 3, 5 MPa, differential gas pressure - 0.01 MPa. On the first day of the third series of experiments, the impact was performed at a frequency of 40 Hz, on the second - 120 Hz, on the third – 200 Hz; the total time of exposure to seismic vibrations on the test sample was 125 minutes per day, for the entire series - 6 hours 15 minutes.

Figure 6 shows the graphs of the decrease in the time of nitrogen filtration through the tested sample (an indicator of the effectiveness of seismic action) from the amplitude and frequency of vibrations.

It can be seen that in the studied ranges of values, the effectiveness of the action increases with an increase in the amplitude of vibrations and is practically independent of their frequency.

Figure 7 shows a graph of the multiplicity of the decrease in the filtration time (averaged over the lateral compression) in both series of experiments relative to the initial background value (before the start of the first exposure session with a frequency of 160 Hz).
The aftereffect of seismic vibrations on the permeability of a fracture with a proppant in coal and an increase in efficiency (the ratio of the modulus of the filtration time change to the initial value) is clearly visible with an increase in the accumulated exposure time from 8-10% to 26-28%. The indicator of the reliability of the approximation of the dependence by the logarithmic trend is $R^2 = 0.93$.

Figure 8 shows a graph of the decrease in the filtration time (averaged over the lateral compression) from the accumulated time of the seismic action.

![Dependencies of filtration time decrease on accumulated seismic impact time](image)

It can be seen that with the impact mode adopted in the experiments (the duration of the seismic impact session is 5 min, the interval between sessions is 5 min, the number of sessions per day is 9 with a total impact time per day of 45 min.) 28% with an accumulated impact time of 225 - 270 min.

4. Conclusion

An increase in the filtration pressure gradient reduces the effect of seismic action on the permeability of coal. In the studied range of values, with an increase in the pressure gradient from 1.6-1.7 MPa/m to 3.2-5.1 MPa/s, the impact decreases by 2 times.

The permeability of drainage cracks in coal, propped with proppant, increases with seismic action with intensity which is more than 0.4 mW/m². The permeability increases in proportion to the logarithm of intensity, the maximum effect is reached, when the frequencies are below $260 \pm 20$ Hz. The effectiveness of the seismic impact increases with an increase in the accumulated impact time up to 4-3.5 hours, followed by stabilization.

The influence of seismic vibrations on the gas permeability of coal and proppant-propped fractures is traced for at least 3 and 7 days, respectively, after the cessation of impact.

The field of application of the results obtained in the work is associated with the increase of the efficiency of seams’ degassing and the safety of underground coal mining. The recommended areas of research are filtration processes in rocks and their stimulation by elastic vibrations of low intensity.
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