Experimental research on desorption characteristics of gas-bearing coal subjected to mechanical vibration

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Abstract
Mechanical vibration can induce coal and gas outburst accidents, and can also promote the exploitation of coalbed methane. In this paper, a vibration-adsorption-desorption experiment system was established, the effects of coal sample particle diameter, gas pressure, and vibration frequency on gas desorption were studied. Mechanical vibration can generate a shear force in the adsorbed gas and promote gas desorption, but there are appropriate vibration parameters. Within the range of experimental parameters, the larger the amplitude, the more favorable for gas desorption. The change rules of gas desorption rate and desorption quantity under different conditions are basically the same, showing a power function shape with time increase, and most of the desorption quantity was completed within the first 5 minutes. The gas desorption rate and desorption quantity were positively related to the gas adsorption pressure. The results have great reference value for preventing gas outbursts and promoting gas exploitation.

Keywords
Mechanical vibration, gas desorption, coalbed methane, gas drainage, desorption model

Introduction
Coal will remain a major energy source around the world for a long time because of the energy structure. Most coal seams in China have the characteristics of high gas and low

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permeability, and gas outburst accidents often happen. These accidents seriously threaten the safety and production efficiency of coal mines, and result in lots of personnel and property losses (Lau et al., 2017; Lu et al., 2016; Zhou et al., 2014). As the mining depth increases, the gas pressure becomes higher, the possibility of gas outburst accidents increases. It’s found that gas outburst accidents mostly occur during drilling or blasting. Some scholars (Fedorchenko and Fedorov, 2012; Nie and Li, 2012) believe that because vibration generates during drilling and blasting, and the vibration promotes gas desorption, which induces gas outbursts. Additionally, gas is a kind of clean energy that attracts more and more attention (Joubert et al., 1974; Qin et al., 2019; Zuo et al., 2020). The reserves of gas are much larger than conventional natural gas and worth further exploitation. The permeability of most coal seams is very low and gas is difficult to be extracted. At present, water jet slotting technology, hydraulic blasting technology, and pulse hydraulic fracturing technology can effectively enhance coal seam extraction efficiency (Hu et al., 2018; Zuo et al., 2019). It is found that the mechanical vibration generated by the above-mentioned technology can promote the desorption of gas.

To improve gas extraction efficiency and prevent gas outbursts, scholars have done many research about the influencing factors of gas adsorption and desorption, and most of the studies do not consider the impact of mechanical vibration. Ettinger et al. (1966) found that the gas adsorption ability of the vitrinite is greater than that of the inertinite. Reznik et al. (1984) found that gas components also affect the desorption ability of coal. For example, the adsorption ability of coal for CO₂ is stronger than that for CH₄, and gas production can be increased by 2 to 3 times by gas displacement. Levy et al. (1997) believed that the capacity of coal to adsorb coalbed methane is U-shaped with the increase of the metamorphic degree, and there is a minimum value in the high-volatile bituminous coal. Krooss et al. (2002), Busch and Gensterblu (2011), and Gensterblum et al. (2014) believed that the gas adsorption ability of coal gradually decreases as the moisture increase. But when the moisture exceeds the critical value, the adsorption capacity will no longer be affected. Dai et al. (2013) found that the adsorption ability and adsorption rate was a positive correlation with gas pressure. Dai (2016) and Yang et al. (2019) found that the adsorption ability of coal for CH₄ was a negative correlation with temperature, but there is still controversy about the change laws of the adsorption constants a and b in the Langmuir equation with temperature. According to Zhao et al. (2019), the influence of particle diameter on gas desorption is limited. In terms of mechanical vibration promoting gas desorption, Naderi and Babadagli (2010) and Ye et al. (2008) found that acoustic technology can promote oil recovery and improve gas extraction efficiency. Mohammadian et al. (2013) and Abramov et al. (2013) studied the mechanism of sound wave reducing the gas adsorption ability of coal and increasing the gas desorption rate. Wang et al. (2016) found that the vibration and thermal effect generated cavitation water jet can promote gas desorption. Ni et al. (2019) studied the effect of pulse hydraulic fracturing on gas desorption and found that pulse fracturing will promote gas desorption as pulse pressure and frequency increase. However, research on gas desorption by vibration is not comprehensive in the above literature.

Therefore, a vibration-adsorption-desorption experiment system was established in this paper, the coal sample desorption experiments under different mechanical vibration conditions were conducted, and the influence law of coal sample particle diameter, vibration frequency, and adsorption gas pressure on gas desorption was studied. The results have important reference value for preventing gas outbursts and promoting gas exploitation.
Experimental methods and sample preparation

Sample preparation

The coal sample was lean coal and taken from Zhengzhou Coal Industry Group, Henan, China. In this experiment, the influence of coal particle diameter was considered. The raw coal is crushed by a crusher, and the raw coal with particle diameters of 1 ~ 3 mm and 0.25 ~ 0.3 mm screened out by standard sieve was used as the coal sample. The coal samples were dried at a temperature of 45 to 50 centigrade for 4 hours before the experiments.

According to the industrial analysis experiment, the moisture content of the coal sample was 0.53%, the ash content was 11.76%, and the volatile content was 11.76%. The maximum reflectivity of the coal vitrinite group $R_{\text{max}}^0$ was 2.28 ~ 2.40%, the apparent density was 1.45 t/m$^3$.

Equipment

The adsorption and desorption of coalbed methane are affected not only by the factors of the coal body itself, but also by the external environment such as temperature, pressure, and moisture. Therefore, the control variable method should be adopted to research the effect of mechanical vibration on gas desorption. The experimental device was designed as shown in Figure 1. The device includes the following subsystems: a gas supply subsystem, a mechanical vibration generation subsystem, a gas adsorption-desorption subsystem, and a data acquisition subsystem.

Gas supply subsystem. The gas supply subsystem consists of a vacuum pump, a gas cylinder, a pressure reducing valve and shut-off valves. The gas cylinder provides high-pressure gas for the adsorption of coal samples. By adjusting the pressure reducing valve can provide different gas pressures.

Mechanical vibration generation subsystem. The mechanical vibration generation subsystem is mainly composed of the YE1311 signal generator (USA), the YE5873A power amplifier

Figure 1. The principle diagram of the experimental apparatus.
(USA) and the JZK-20 electric vibration generator (USA). The signal generator has a power of 60 W and can generate signals from 2 Hz to 2 kHz. The signal can be amplified to 500 W by a power amplifier. Different vibration forms and vibration frequencies can be generated by connecting the vibration generator. The vibration generator has a maximum vibration amplitude of 10 mm, a maximum vibration force of 200 N, and a maximum acceleration of 25 g. The vibration generator is connected to the coal sample tank through a connecting rod, and the mechanical vibration has an impact on the coal sample.

Gas adsorption-desorption subsystem. The gas adsorption-desorption subsystem consists of a gas adsorption and desorption tester (China), a gas adsorption device (China), a coal sample tank and a thermostat. The tank was placed in the thermostat. By adjusting the shut-off valve, the device can realize functions such as vacuum pumping and gas adsorption. The gas desorption and desorption tester can measure the gas desorption data automatically.

Data acquisition subsystem. Besides, to obtain gas desorption data, an external data acquisition system was also connected to the device. The data acquisition system includes an acceleration sensor, a gas pressure sensor, a computer, a measuring cylinder, and other related equipment. The acceleration sensor is a CA-YD-186 piezoelectric acceleration sensor (USA), and the maximum transverse sensitivity is less than 5%. The accuracy of the gas pressure sensor is 0.1%.

Features of equipment. The characteristics of the device as follows: (a) Controlled temperature. The device can adjust and maintain the ambient temperature during adsorption and desorption of coal samples to eliminate the influence of temperature. (b) Adjustable vibration. The vibration frequency and the vibration amplitude can be controlled. (c) Automatic measurement. The measuring accuracy of the device is high.

Experimental design

The purpose of the experiments was to study the influence law of vibration frequency, vibration amplitude, particle size and equilibrium gas pressure on gas desorption. The experimental design is shown in Table 1.

Table 1. Experimental design.

| No. | Vibration frequency (Hz) | Vibration amplitude (mm) | Particle size (mm) | Gas pressure (MPa) |
|-----|--------------------------|--------------------------|--------------------|-------------------|
| 1   | 0                        | 6                        | 1 ~ 3              | 1                 |
| 2   | 30                       | 6                        | 1 ~ 3              | 1                 |
| 3   | 50                       | 6                        | 1 ~ 3              | 1                 |
| 4   | 100                      | 6                        | 1 ~ 3              | 1                 |
| 5   | 30                       | 2                        | 1 ~ 3              | 1                 |
| 6   | 30                       | 4                        | 1 ~ 3              | 1                 |
| 7   | 0                        | 6                        | 0.25 ~ 0.3         | 1                 |
| 8   | 30                       | 6                        | 0.25 ~ 0.3         | 1                 |
| 9   | 30                       | 6                        | 1 ~ 3              | 0.7               |
| 10  | 30                       | 6                        | 1 ~ 3              | 0.4               |
**Experimental procedures**

To eliminate the effect of moisture and air, the samples were poured in the tank and carried out adsorption-desorption several times before the experiment. First, the vacuum pump was turned on and the coal sample tank was evacuated for 4 hours. Then, the pressure reducing valve was adjusted and gas was injected into the tank. The coal sample fully adsorbs the gas for 48 hours. Then opened the shut-off valve and connected the cylinder to record the gas desorption quantity. At the same time, the connecting rod was connected to the vibration generator and the coal sample tank. The vibration generator was operated in advance for 30 minutes under the conditions of the test parameters. The experimental data were recorded in real-time in the experiment, and the data recording intervals were 1 minute.

**Results and discussion**

**Influence of vibration frequency**

The changes of gas desorption rate and desorption quantity of samples (particle diameter of 1 to 3 mm) under different vibration frequencies with time are shown in Figure 2. The change law of gas desorption quantity and desorption rate under different vibration frequencies is basically the same, and both show a power function shape with the increase of time. Both curves can be divided into two phases, the first phase (0 to 5 minutes) is the efficient desorption phase and the second phase (after 5 minutes) is the stable phase. The gas desorption rate is the highest in the beginning, and it sharply decreases as a power function with time during the efficient desorption phase and eventually tends to a fixed value. In the stable phase, the effect of vibration frequency on the desorption rate is small, which is basically the same as that of coal samples that are not affected by vibration. In the beginning, the tank was filled with unabsorbed free gas, and the free gas flowed out of the tank after opened the shut-off valve. Meanwhile, the gas pressure decreased sharply after opened the valve, the absorbed gas in the coal was largely desorbed. The desorbed gas at the first phase includes free gas and adsorbed gas, and adsorbed gas is the majority part. The high gas desorption rate in this phase is mainly due to the gas pressure decrease in the tank. The gas desorption quantity increases with time as a power function and finally tends to be

![Figure 2](image)

*Figure 2. The curves of gas desorption under different vibration frequencies. (a) The curves of gas desorption quantity. (b) The curves of gas desorption rate.*
stable. Additionally, it can be found that the coal sample completed most of the desorption quantity during the first phase.

In the stable phase, the gas pressure in the tank was also relatively stable, and the gas pressure in the tank was close to the atmosphere. The absorbed gas was desorbed and transported out of the tank steadily in this phase. Within the range of experimental data, the gas desorption rate changes very little and is close to stable. Finally, the gas desorption rate eventually approaches zero as time increases. And the gas desorption quantity also eventually reaches a stable value.

At the same time, it can be found that the vibration frequency affected the gas desorption rate greatly in the efficient desorption phase. The vibration frequency of 100 Hz has the largest impact on the desorption, followed by 30 Hz. The effect of 50 Hz has the smallest influence, and it is not much different from 0 Hz (unaffected by mechanical vibration). The gas desorption rate was calculated by measuring the gas desorption quantity, as shown in Figure 3(a). It is found that the vibration frequencies of 100 Hz and 30 Hz can increase the desorption percentage by 8.9 and 4.2 percentage points, respectively. Because the mechanical vibration causes the gas molecules to crush and collide with each other, which intensifies the thermal movement of the gas molecules. Meanwhile, the shear action generated by mechanical vibration can accelerate the gas peeling from coal seam and promote the gas desorption. With the increase of mechanical vibration frequency, the peeling effect of vibration on gas is weakened, and the thermal effect of the gas molecules is enhanced. Therefore, the 50 Hz vibration frequency has the least influence. Besides, the gas content in the initial desorption phase is high, which makes it easier for gas molecules to collide, and the desorption effect will be improved. The results show that the effective action time of the vibration is the efficient desorption phase, and there is an effective range of vibration frequency.

To analyze desorption laws of gas-bearing coal under different vibration conditions, the experimental data were fitted with different models, including the diffusion model, the empirical formula, the percolation model, and the desorption-diffusion model (Crosdale et al., 1998; Jiang et al., 2015, 2008; Yang et al., 2016). Figure 4 is the fitted curves of experiment No. 2 (with the particle diameter of 1 ~ 3 mm). Table 2 is fitted functions and errors of different desorption models. In this condition, the desorption-diffusion model has the best fitting effect. This model is a suitable model to explain the desorption rule of
gas-bearing coal under vibration conditions. The desorption-diffusion model is expressed by equation (1):

\[ Q = Q_0 + Q_t = Q_0 + \sqrt{1 - e^{-Bt}} \]  

where \( Q \) is the total desorption quantity, ml/g; \( Q_0 \) is the desorption quantity of coal sample surface, ml/g; \( Q_t \) is the desorption quantity of internal pore surface, ml/g; \( B \) is a parameter, \( B = \pi^2 D / R^2 \); \( D \) is the diffusion coefficient, cm²/s; \( R \) is the coal particle radius; \( t \) is time, min.

The desorption-diffusion model was used to explain the desorption laws of gas-bearing coal under different vibration frequencies. As shown in Table 3, the fitting results indicated that the vibration frequency of 100 Hz and 30 Hz can significantly increase the \( Q_0 \) and \( Q_t \). It means that gas desorption quantity on the surface and inside of the coal can be increased with a suitable vibration frequency. The reason for the above phenomenon is that the gas molecular adsorbed on the surface of the coal body and pores were subjected to shear force. Under the action of mechanical vibration, the gas and coal body will vibrate together with the
mechanical waves. However, due to the different densities of solid and gas, the acceleration and amplitude generated during vibration are also different, which will cause the gas and coal particles to squeeze and collide with each other. At the same time, the vibration wave will be refracted and reflected during its propagation. The gas molecular on the coal surface were subjected to oblique shear stress during the vibration process (Figure 5). The shear stress would cause gas to fall off the coal surface and accelerate the gas desorption course.

**Table 3.** The fitting results of the desorption-diffusion model.

| Vibration frequency (Hz) | $Q_0$ (ml/g) | $Q_t$ (ml/g) | $B$ (min$^{-1}$) |
|--------------------------|--------------|--------------|-----------------|
| 0                        | 0.6005       | 6.8315       | 0.0989          |
| 30                       | 0.6120       | 7.3440       | 0.0941          |
| 50                       | 0.6061       | 6.8196       | 0.1029          |
| 100                      | 0.7137       | 7.6091       | 0.1077          |

**Figure 5.** The force diagram of gas molecules under the action of the mechanical vibration wave.

**Figure 6.** The curves of gas desorption under different vibration amplitudes. (a) The curves of gas desorption quantity. (b) The curves of gas desorption rate.

Influence of vibration amplitude

When the samples subjected to different amplitude conditions, the desorption also changed as the above-mentioned laws, and all of them show a power function shape with time (Figure 6). The gas was quickly desorbed in the first phase (0 to 5 min) and most of the
desorption quantity was completed. And the desorption was performed at a stable rate in the second phase (after 5 min). The vibration amplitude had little influence on the desorption rate and had almost no influence in the desorption process. In the second phase, when the vibration frequency is fixed, the larger the vibration amplitude, the greater the total quantity of gas desorption and the higher the desorption speed. The increase in vibration amplitude can promote the desorption of gas-bearing coal.

When the vibration frequency was the same, the desorption rates were similar to different amplitudes. The desorption quantity in the initial stage are basically the same, and then little differences will occur. As shown in Figure 3(b), the larger the amplitude, the greater the desorption quantity in the later stage. After 40 minutes, the desorption percentage of the samples with an amplitude of 6 mm was 3.3 percentage points higher than that with an amplitude of 2 mm. The main reason is that when the particle diameter is the same, the paths of gas desorption and diffusion of samples are basically the same. And the larger the amplitude, the more movement the gas can be promoted, and the more favorable for gas desorption and diffusion out of samples. Additionally, according to the desorption-diffusion model, $Q_0$ and $Q$, increased, and $B$ decreased with the increase of vibration amplitude. It means that the desorbed gas from the inside and surface of the coal sample increases after the amplitude increased, and the attenuation coefficient decreases.

**Influence of particle size**

To research the effect of particle diameter on desorption, experiments were carried out on coal samples of 1~3 mm and 0.25~0.3 mm with 30 Hz vibration or without vibration. When the particle diameter is different, the gas desorption changes also conform to the law of power functions (Figure 7), and most of the gas was desorbed in the first 5 minutes. It was found that under the same conditions, the smaller the diameter, the larger the desorption quantity. In the early stage of desorption, the particle diameter had a notable influence on the desorption rate. After that, the desorption rates remained stable and are basically the same under different vibration frequencies.

As shown in Figure 8(a), after desorption for 40 minutes without vibration, the desorption percentage of coal with the particle diameter of 0.25~0.3 mm was 1.9 percentage points
higher than that with a particle diameter of $1 \sim 3 \text{mm}$. The increment was 4.5 percentage points after applying 30 Hz mechanical vibration. According to the desorption-diffusion model, under the same desorption conditions, the desorption quantity from the sample surface is a negative correlation with the particle diameter. The main reason is that the specific surface area increases as the decrease of the particle diameter. Additionally, at the same temperature, as the decreases of particle diameter, the diffusion path for gas diffused out the coal sample decreases, the diffusion resistance decreases, the activation energy required for gas diffusion decreases, and the kinetic diffusion parameter increases. Therefore, the gas will be desorbed and diffused out of coal samples easily.

**Influence of adsorption gas pressure**

Desorption experiments were carried out under three different gas adsorption equilibrium pressure gradients. As shown in Figure 9, there is a big difference between the desorption rate and desorption quantity with different gas pressures, mainly because the gas adsorption quantity under different gas pressure is different. As we know, the higher the

![Figure 8](image_url)

**Figure 8.** The gas desorption percentages under different conditions. (a) The gas desorption percentages of different particle sizes. (b) The gas desorption percentages of different adsorption gas pressure.

![Figure 9](image_url)

**Figure 9.** The curves of gas desorption under different adsorption gas pressure. (a) The curves of gas desorption quantity. (b) The curves of gas desorption rate.
gas adsorption pressure, the stronger the gas adsorption capacity, and the higher the desorption rate and quantity. The change laws of coal with different gas pressure were also consistent with the law of power functions. As shown in Figure 8(b), the gas desorption rate was positively correlated with gas pressure. The desorbed gas includes free gas and adsorbed gas. The free gas will directly flow out of the tank, and the adsorbed gas needs to be desorbed before diffusing out of the tank. The higher the gas adsorption pressure, the more favorable for the adsorbed gas desorption after pressure relief. However, the adsorbed gas in the coal was difficult to be completely desorbed and diffused out of the coal sample in a short time. The residual gas accounted for a small proportion of coal samples at high gas pressure, but a large proportion of coal samples with low gas pressure. Therefore, the gas desorption rate was positively related to the gas adsorption pressure.

**Conclusion**

In this paper, a vibration-adsorption-desorption experiment system was established, the influence laws of coal sample particle diameter, vibration frequency, vibration amplitude, and adsorption gas pressure on gas desorption were studied.

The change rules of gas desorption rate and desorption quantity under different conditions are basically the same, showing a power function shape with time increase, and most of the desorption quantity was completed within the first 5 minutes. And the desorption-diffusion model can relevantly describe the desorption laws of gas-bearing coal. Within the range of experimental parameters, the larger the amplitude, the more favorable for gas desorption. However, there is a suitable range for the vibration frequency, and the vibration frequency of 100 Hz has the best desorption effect. As the decreases of particle diameter, the specific surface area of the sample increases, the diffusion resistance for gas diffused out the coal sample decreases, and the gas desorbed from coal increases. The gas desorption rate and desorption quantity were positively related to the gas adsorption pressure. The results have important reference value for preventing gas outbursts and promoting gas exploitation.

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