Influence of temperature on gas desorption-diffusion laws of coal particles

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ABSTRACT

With the continuous increase in coal mining depth in China, temperature has a more and more apparent effect on the coal seam gas adsorption, desorption-diffusion, and seepage. To investigate the effect of temperature on the gas desorption and flow law of coal, the coal gas desorption test system by independent research and development is used. The gas desorption diffusion process of coal particles was studied under the conditions of adsorption equilibrium pressure 1.1 MPa and desorption temperature (20℃, 30℃and 40℃). The variation law of the coal particle gas desorption-diffusion amount and the gas desorption-diffusion rate change with temperature are defined. Subsequently, the mathematical physics equations of coal particle gas desorption diffusion is established based on the third boundary condition, and the desorption-diffusion coefficient is solved by using the piecewise fitting method combined with the dynamic process characteristic of gas desorption-diffusion and the experimental data. The variation law of the gas diffusion coefficient change with temperature is found. The results show that: (1) the cumulative amount of coal particle gas diffusion desorption is a capped monotonically increasing function, and the higher the temperature, the faster the initial rate of gas desorption-diffusion. (2) in the short time (t<10min), the gas desorption-diffusion coefficient decreases as the temperature increases, and when t>10min, temperature change has little effect on the desorption-diffusion coefficient. This effect is mainly due to the fact that the rise in temperature accelerates the velocity of the gas molecules, therefore increasing the probability of collisions between the gas molecules. The diffusion length of gas molecules is reduced, followed by a decrease in the effective diffusion cross-sectional area. Finally, the gas desorption-diffusion coefficient is reduced. This provides theoretical guidance for the prevention of coal and gas outburst and the prediction of gas emission quantity and extraction.

KEYWORDS: coal particles; gas; desorption-diffusion; temperature

1. INTRODUCTION

More than 95% of China's coal resources are obtained from underground coal mines. Gas, water, fire, dust, ground pressure, heat damage and other disasters often influence the process of mining due to the complex condition of coal resources, the poor geological conditions, and the large depth of burial (Yu, 2011). Mining depth increases at an annual rate of 10 to 30 m deep (the deepest to 1501 m). Many shallow low gas mines gradually change into high gas mines, resulting in increases in stress, temperature, and pressure (Xie et al., 2015). According to data obtained from the observation of a coal field in China, temperature increased from 1.5 to 4.5 K/100m (Zeng et al., 2011). In China's state-owned mines, the average temperature of the original rock is 35.9℃ to 36.8℃ in 650 m production levels, and in mines more than 1000 m, the original rock temperatures reaches as high as 40 to 45 degrees. At present, there exist more than 80 mines showing the patterns of differing levels of heat. At the same time, the effect of downhole temperature on coal gas adsorption, desorption, diffusion, and percolation is becoming increasingly outstanding (Sun et al., 2003; Zeng et al., 2009; Li et al., 2003).

The process of gas desorption-diffusion in the coal seam is extremely complex, and much research has been conducted by domestic and international scientists. Winter et al. (1969) discovered that after adsorption equilibrium is reached, the amount of gas adsorption is determined by the gas content of the coal, time, temperature, adsorption equilibrium pressure, and the particle size of coal samples. Jaroniec et al.'s (1990) study on the process of gas desorption in coal showed that some deformation will occur when the coal body adsorbes gas. Yee et al. (1993) put forward the theory of diffusion, finding that the square root of desorption quantity and time does not show a simple linear relationship. Marecka (1995) found that the pores in coal and coal metamorphic degree play an important role in the process of gas desorption. Pokryszka et al. (2010) study the competitive adsorption of CH_4 and CO_2 diffusion behaviour, considering the influence of temperature on the effective diffusion coefficient. Sun (1983) studied coal seam gas solution

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desorption, desorption rate, and grain size of coal samples as factors influencing the desorption rate. Nie et al. (2000) studied the micro mechanism of coal bed methane diffusion in coal pores. Cao et al. (2007) studied gas desorption attenuation coefficients and desorption intensities as a function of coal granularity in different samples, and analyzed the influence of particle size on desorption intensity. Fu et al. (2008) analyzed the difference between tectonic coal and non-coal structures on the microstructure carried on by the structure of coal gas radiation, using mathematical models of micro and macro theory research. Liu et al. (2013) studied the quantitative relationship between diffusion flux and the temperature of coal particles with different coal rank, and the influence of temperature on the gas diffusion dynamic process of coal particles.

At present, these theoretical and experimental studies of coal particles gas desorption-diffusion are mostly carried out under isothermal conditions. However, the changes in and mechanism of the coal particle gas desorption-diffusion flux, the gas desorption-diffusion rate and the diffusion coefficient still lack in-depth study. Therefore, based on previous research, and in order to further investigate the effect of temperature on the gas desorption and flow law of coal, the coal gas desorption test system by independent research and development is used to study the variation law of the coal particles gas desorption-diffusion under different temperatures. The present study has practical significance on the prediction of coal and gas outburst, as well as coal seam gas content prediction.

2. EXPERIMENTAL SYSTEM AND METHODS

2.1 Experimental system

To achieve the law of coal particles gas desorption-diffusion under different temperature, the experimental system was independently designed and assembled. The system mainly consisted of the temperature control system, the adsorption-desorption system, the data acquisition and processing system, the desorption-diffusion gas gathering system, the gas supply and control system, and other auxiliary devices. A schematic diagram of the experimental system is as shown in Figure 1.
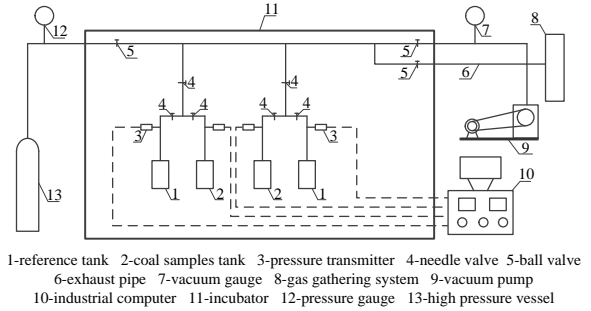

1-reference tank 2-coal samples tank 3-pressure transmitter 4-needle valve 5-ball valve 6-exhaust pipe 7-vacuum gauge 8-gas gathering system 9-vacuum pump 10-industrial computer 11-incubator 12-pressure gauge 13-high pressure vessel

Figure 1: The schematic diagram of the experimental system.

2.2 Experimental coal sample

Samples of Shanxi Jincheng Phoenix Mountain coal seam face 9# were collected. The coal sample industry analysis data is shown in Table 1.A balance was used to weigh the coal sample of 50 g (weighing accuracy 0.001 g), with the bottle containing the coal sample being pre-numbered and weighed. In order to exclude the impact of moisture, the weighed coal sample was placed in a vacuum oven, and heated to 100~105℃ for 4~6 hours. The vacuum degree of the oven was at least 700 mmHg. The coal sample was then dried and placed in a desiccator to cool and save.

Table 1: Experimental coal industry analysis.

Sample	Moisture content %	Volatile content %	Ash content %	Fixed carbon %
Jincheng Phoenix Mountain 9#	3.17	7.09	8.32	81.42

2.3 Experimental procedure

The purpose of this experiment is to study the dynamic rule of coal particles gas desorption-diffusion under different temperatures (20, 30 and 40 ℃) with pressure held constant (1.1 MPa).

Using coal particles of 40~60 mesh at a temperature of 20℃ as an example, the specific experimental procedure is as follows:

(1) Weigh the prepared coal sample of 50 g, and load it into the sample tank. Connect with the experimental system.

(2) Open the temperature control system and keep the temperature at 20℃.

(3) Access the methane gas cylinders to the experimental system, open the vacuum pump, and perform vacuuming tanks and piping systems for about 1 hour.

(4) Fill the reference tank with the methane gas to keep it at a stable pressure, and adjust the valve to

connect the reference tank with the sample tank. Collect the pressure values of the reference tank with the sample tank.

(5) After the adsorption equilibrium is reached, adjust the valve to connect the sample tank with the atmosphere.

(6) Once the sample tank pressure drops below atmospheric pressure (0.1 MPa), access it using the desorption gas gathering system quickly. Meanwhile, open the gas desorption acquisition software to record the gas desorption change varying with time, until the end of the desorption experiments. Lastly save the experimental data.

3. RESULTS

The variation law of the coal particles gas desorption-diffusion amount and the gas desorption-diffusion rates of change with temperature were measured, as shown in Figures 2 and 3.
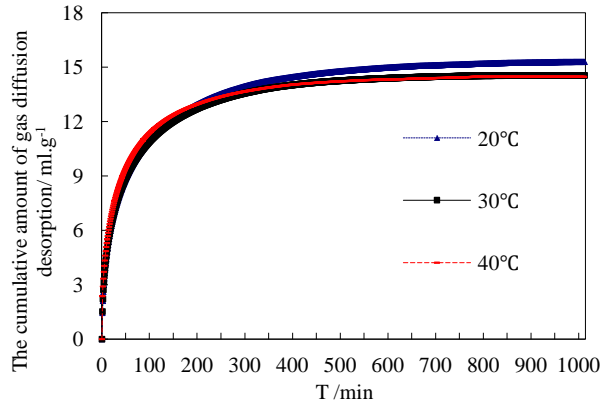

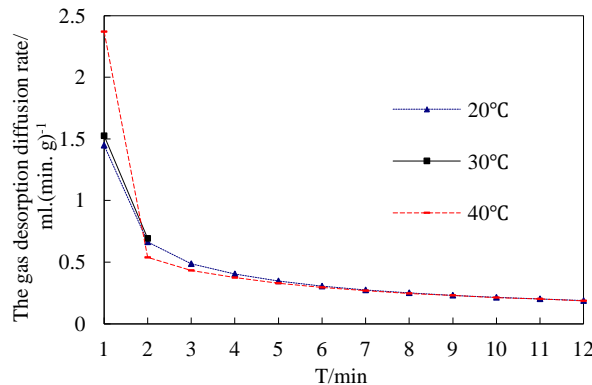Figure 2: The gas desorption diffusion amount curve.

Figure 3: The gas desorption diffusion rate curve.

Figures 2 and 3 show that: (1) the cumulative amount of coal particles gas diffusion desorption is a capped monotonically increasing function. (2) The limit cumulative amount of coal particles gas diffusion desorption decreases when the temperature increases. (3) The higher the temperature, the faster the initial rate of gas desorption diffusion. Meanwhile, the rate of gas desorption diffusion gradually decreases and finally stabilizes with time.

This is because of two main reasons: (1) The kinetic energy of gas molecules will increase due to the increase in temperature, giving a greater chance of surpassing the higher adsorption barrier energy, shortening the residence time on the coal pore surfaces. This reduction in the adsorption capacity leads to a reduction in the amount of gas adsorption. Finally, the amount of desorption will decrease, so the limit cumulative amount of coal particles gas diffusion desorption also decreases. (2) Under the same size and adsorption equilibrium pressure in the same coal sample, the thermal motion of gas molecules will be increased because of the increase in temperature. Thus the desorption diffusion capacity is enhanced, and the desorption-diffusion rate also accelerates.

4. EFFECT OF TEMPERATURE ON THE GAS DIFFUSION COEFFICIENT

Most scholars (Charriere et al., 2010; Yang et al., 1986; Zhou, 1990; Gives, 1992; Li, 2005) find that the process of coal particle gas irradiation is the desorption-diffusion process, and the methane adsorption (desorption) on the coal surface is physical adsorption (desorption). In principle, it can be completed in an instant ($10^{-10} \sim 10^{-5}$ s) and be negligible, therefore, the process can be described using Fick's second law and the driving force is the concentration gradient. In the complex system of coal, gas adsorption in the pore system follows Fick's diffusion law and free gas in the fractures follows the Darcy law. Most studies research the kinetics of coal particles gas desorption-diffusion.

According to the literature (Dai, 2012; Nie et al., 2001), the mathematical physics equations of coal particle gas desorption-diffusion were established based on the third boundary condition. The meaning of symbols is as shown in the literature.

$$\begin{cases} \dfrac{\partial C}{\partial t} = D\left(\dfrac{\partial^2 C}{\partial r^2} + \dfrac{2}{r}\dfrac{\partial C}{\partial r} \right) \\ 0 < r < r_0, C|_{t=0} = C_0 \\ t > 0, \dfrac{\partial C}{\partial r}\Big|_{r=0} = 0 \\ -D\dfrac{\partial C}{\partial r}\Big|_{r=r_0} = \alpha(C|_{r=r_0} - C_f) \end{cases} \quad (1)$$

The approximate solution is obtained by using the variable separation method.

$$\ln(1-\frac{Q_t}{Q_\infty}) = \ln A - \lambda t \qquad (2)$$

Where: $A = \dfrac{6(\sin\beta_1 - \beta_1\cos\beta_1)^2}{\beta_1^2(\beta_1^2 - \beta_1\sin\beta_1\cos\beta_1)}, \lambda = \dfrac{\beta_1^2 D}{r_0^2}$,

Q_t is the cumulative amount of gas diffusion at any time. Q_∞ is the limit cumulative amount of gas diffusion desorption. D is the desorption-diffusion coefficient in m^2/s.

According to the obtained approximate analytical solution, the desorption-diffusion coefficient was solved by using the piecewise fitting method combined with the dynamic process characteristic of gas desorption-diffusion and the experimental data. The results are shown in Table 2 and Figure 4.

Table 2: The solution results of desorption-diffusion coefficients under different temperature.

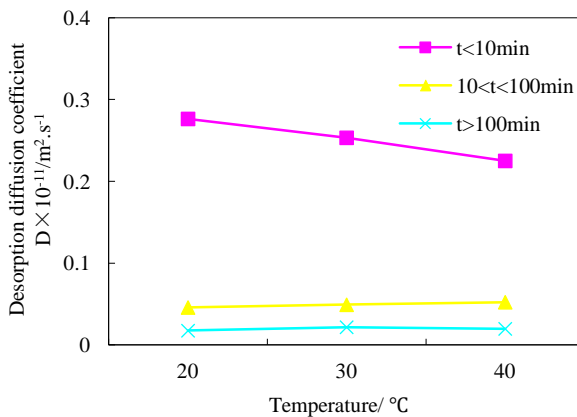| Temperature	Time (min)	Fitting formula	R^2	$D \times 10^{-11}$ (m^2/s)
20℃	t<10	y=-0.028x-0.0672	0.9802	0.2765
	10<t<100	y=-0.0094x-0.453	0.9875	0.0460
	t>100	y=-0.0051x-1.3544	0.9987	0.0176
30℃	t<10	y=-0.0308x-0.1067	0.9794	0.2534
	10<t<100	y=-0.0104x-0.4978	0.9882	0.0493
	t>100	y=-0.0064x-1.4028	0.9971	0.0218
40℃	t<10	y=-0.0301x-0.1369	0.9889	0.2251
	10<t<100	y=-0.0115x-0.561	0.9888	0.0524
	t>100	y=-0.0061x-1.6426	0.9986	0.0198

Figure 4: The segment fitting results under different temperature.

Figure 4 shows that temperature has a greater impact on the gas desorption-diffusion coefficient when t<10 min, but is less affected when 10<t<100 min and t>100 min. For short times (t<10 min), the gas desorption-diffusion coefficient decreases as temperature increases, and when t>10 min, temperature changes have little effect on the desorption-diffusion coefficient. This is mainly because the rise in temperature accelerates the velocity of the gas molecules, and increases the probability of collisions between the gas molecules, decreasing the diffusion length of gas molecules. The effective diffusion cross-sectional area decreases, and finally the gas desorption-diffusion coefficient are reduced.

5. CONCLUSION

The coal gas desorption test system by independent research and development was used and the gas desorption-diffusion process of coal particles was studied under conditions of adsorption equilibrium pressure of 1.1 MPa at desorption temperatures of 20℃, 30℃ and 40℃. The variation law of the coal particles gas desorption-diffusion amount and the gas desorption-diffusion rate of change with temperature were defined.

The mathematical physics equations of coal particle gas desorption-diffusion were established based on the third boundary condition, and the desorption-diffusion coefficients were found by using the piecewise fitting method combined with the dynamic process characteristic of gas desorption-diffusion and the experimental data. The variation law of the gas diffusion coefficient change with temperature was found.

Studying the influence of temperature on gas desorption-diffusion laws of coal particles is practically significant for use in coal and gas outburst prediction, as well as coal seam gas content prediction.

6. ACKNOWLEDGEMENTS

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