

Research Article

Coal Temperature Variation Mechanism during Gas Desorption Process

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To further reveal the mechanism of coal gas migration, the reasons for coal temperature changes during the methane desorption process were analyzed from the aspect of molecular motion and the thermodynamic theory. The temperature change mechanism was investigated, and the mathematical equation was established to describe the variation of temperature change during the methane desorption and diffusion process. The established equation was applied for the calculation of temperature change for two types of coal samples, and the measured and theoretical values of temperature changes were obtained. The results show that the temperature changes in the coal gas desorption process are mainly caused by the heat adsorption. The heat adsorption phenomenon was also caused by free gas expansion during the pressure relief process. The gas diffusion and work done for gas seepage also need heat adsorption. The temperature change is positively correlated to the coal gas pressure, quantity, and limit value of gas desorption volume. Due to the poor insulation in the test system, the difference between the theoretical and the measured temperature change values increase with the adsorption equilibrium pressure. It is helpful to further reveal the mechanism of coal and gas outburst. It also has an important reference value for controlling gas dynamic disasters in coal mines.

1. Introduction

Gas desorption is a dynamic process that changes over time. The adsorption and desorption of gas in coal is considered to be a reversible physical process that happens with thermal effects. A large number of studies showed that the coal temperature is closely related to coal gas desorption. The higher the temperature, the larger the desorption rate [1–11]. Temperature changes during gas adsorption and desorption were tested using a gas outburst simulator [12, 13]. It was found that the coal gas adsorption process is an exothermic process, whereas the gas desorption process is an endothermic process. The hot-dip galvanizing high-sensitivity infrared temperature measurement technology was also applied in studying the temperature change law in the process of coal gas desorption [14].

Desorption heat can be reflected by the temperature changes in the system. The temperature variation during

coal and gas outburst is studied by Guo and Jiang [15]. A decrease in the temperature of working face and coal wall was observed before the outburst. Workers can even feel the cold currents of gas flow that spray and escape to the roadway, chamber, and working space during gas outburst.

But coal and gas outburst is not only related to gas desorption. The gas outburst process includes three stages: inoculation, development, and occurrence. In each process, besides desorption and seepage of methane, the coal reservoir is also subjected to the surrounding ground stress and the erosion of the pore gas on the coal body. The coal body is squeezed and deformed and the internal energy is thus increased [16]. Although the desorption process is a complex energy exchange process, the total energy of the desorption process is constant, following the law of conservation of energy.

At present, there is no unified understanding of the causes of temperature change in the process of gas

desorption. Studying the mechanism of temperature change during coal gas desorption is of great significance for analyzing the mechanism of energy migration and transformation in coal mining. It is helpful to further reveal the mechanism of coal and gas outburst; therefore, it has important reference value in the prevention and control of gas dynamic disasters in coal mines.

2. Analysis for Heat Generation Mechanism during Coal Gas Desorption Process

2.1. Microprocess of Gas Desorption. The process of interaction between coal and gas is an integrated process of seepage-diffusion and adsorption-desorption. As we know, coal is a dual pore structure medium containing pore and fissure structures. Due to disturbance, the original pore distribution is destroyed and a large number of fissure structures are produced during the mine production. Pore structures are the main space for gas adsorption, whereas fractures are the main channels for gas seepage. Generally, the coal matrix is composed of several small matrix elements separated by cracks. The outer surface of each small matrix is a fissured channel with multiple macropore or micropore structures as shown in Figure 1.

Methane is absorbed on the surface of the fissures, the micropore, and the coal matrix. Once it gains enough energy to overcome the van Edward force between the coal molecules and the methane molecules, it passes through the gas film layer formed by methane adsorption.

The process that the adsorb separates into free gas and diffuses into the coal fracture network under the effect of gas concentration gradient is called the desorption process in the coal body. When the coal is suddenly exposed to the atmosphere, the methane gas which is ejected or poured out contains the desorbed methane gas and the original free gas in the fractured network. The movement of methane molecules require external energy support and there must be temperature variation in the process of coal gas desorption and diffusion.

2.2. Mechanism of Thermal Change during the Coal Gas Desorption Process. The gas in the coal starts to desorb due to the pressure gradient, temperature, and stress disturbance. It is an endothermic process due to the following reasons: (1) the desorption of the adsorbed gas is endothermic; (2) the free gas within the coal body absorb energy due to expansion; (3) the diffusion is endothermic; and (4) the work done due to seepage adsorb heat.

2.2.1. Heat Adsorption in the Gas Desorption Process. In general, the undisturbed adsorbed gas in coal is in the state of adsorption equilibrium. The methane molecules on the surface of coal particles are in a state of vibration, centered at the lowest energy equilibrium point. The adsorption of

methane by coal is a reversible physical adsorption process. The desorption heat of unit mass q can be calculated with

$$q = cm\Delta T, \quad (1)$$

where c denotes the mole ratio heat capacity of methane, $\text{kJ}/(\text{mol} \cdot \text{K})$; m is the mole mass of desorbed methane, mol/g ; and ΔT is the temperature difference before and after desorption, K .

2.2.2. Expansion Heat of Free Gas. The expansion process of free gas can be regarded as an adiabatic process. When the gas expands, it expands outwards to do work. This energy comes from the internal energy of the gas. In order to expand continuously, energy will be absorbed from the surrounding area. This part of energy will be supplied from coal. Therefore, the temperature of coal will decrease due to energy loss.

According to the first law of thermodynamics,

$$w = \frac{1}{k-1} (p_2 v_2 - p_1 v_1), \quad (2)$$

where w is the work done during expansion, kJ/kg ; p_1 is the initial gas pressure, Pa ; v_1 is the initial gas volume, m^3 ; p_2 is the gas pressure after expansion, Pa ; v_2 is the gas volume after expansion, m^3 ; and k is the ratio of heat capacity at constant pressure to the heat capacity at constant volume of gas.

$$k = \frac{c_p}{c_v},$$

$$\Delta T = T_2 - T_1 = \frac{w}{c} = \frac{1}{1000(k-1)c} (p_2 V_2 - p_1 V_2), \quad (3)$$

$$\Delta E = \frac{\pi \eta E}{\omega_0},$$

$$\Delta U = \frac{1}{2} m v^2.$$

Therefore, the temperature change caused by gas expansion is

$$\Delta T = T_2 - T_1 = \frac{w}{c} = \frac{1}{1000(k-1)c} (p_2 V_2 - p_1 V_2), \quad (4)$$

where c is the specific heat capacity of coal, $\text{kJ}/(\text{kg} \cdot \text{K})$.

2.2.3. Heat Adsorption due to Gas Diffusion. When the adsorbed gas is desorbed, it starts to diffuse under the effect of concentration gradient. Assuming that the diffusion is one-dimensional in a square lattice, in which the methane molecules jump from one barrier to another, and the energy required is

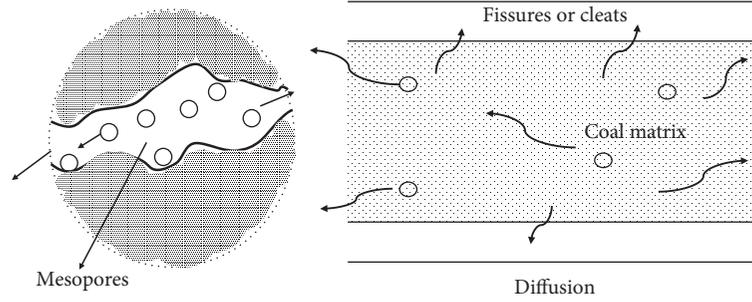


FIGURE 1: Schematic diagram of the coal desorption process.

$$\Delta E = \frac{\pi\eta E}{\omega_0}, \quad (5)$$

where ω_0 is the weak vibrational frequency of methane molecules at equilibrium positions; η is the friction coefficient in the diffusion of methane molecules; and E is the diffusion activation energy, J.

2.2.4. Heat Adsorption due to Gas Seepage. The desorbed gas and original free gas increases the gas concentration, and the accompanying pressure gradient causes gas flow within the fracture network of the coal body. The kinetic energy of gas was provided by the coal body. According to the conservation of energy,

$$\Delta U = \frac{1}{2}mv^2, \quad (6)$$

where ΔU is the internal energy loss of the coal body, J; m is the mass of gas flow, g; and v is the velocity of gas flow, m/s.

2.3. Equations Used for Gas Desorption Temperature Change Calculation. When studying the adsorption and desorption laws of gases, we usually refer to the knowledge of surface adsorption in physical chemistry, which regards desorption and diffusion as an entire process. When conducting experiments, the solid surface is usually exposed to the atmosphere. Therefore, when studying the endothermic effect, the heat absorption in the process of seepage can be neglected. The diffusion heat effect and gas expansion heat effect can be treated as the two main heat sources in the gas desorption process. In order to study the heat change during desorption, the system is assumed to be adiabatic.

2.3.1. Desorption Temperature of Absorbed Gas. Assuming the volume of desorbed gas is V_t , differential desorption is dv_t , and differential adsorption heat is dQ , we obtain

$$dT = \frac{dQ \cdot dv_t}{1000c}. \quad (7)$$

According to previous studies, the differential adsorption heat and the gas pressure have the following relations:

$$dQ = \frac{A}{(1 + Bp)}, \quad (8)$$

where A and B are 0.702 J/m^3 and 0.242 MPa^{-1} , respectively, and p is the pressure before desorption, Pa.

Combining Equations (7) and (8), we obtain

$$\Delta T_d = -\frac{A \cdot V_t \cdot \eta}{1000c_1(1 + Bp(1 - \eta)^2)}, \quad (9)$$

where c_1 is the specific heat of coal, $1.46 \text{ kJ}/(\text{kg}\cdot\text{K})$, and $\eta = V_t/V_{\max}$ is the gas emission rate.

According to Equation (9), the temperature decrease in the desorption process increases with the increase of the desorption rate, whose growth rate is accelerating.

2.3.2. Temperature Change of Free Gas due to Expansion.

Assuming the system is an adiabatic system and the expansion process of free gas is an isothermal process, the expansion energy of free gas can be thought that it comes from the coal. Assuming the gas pressure difference is dp in the expansion process and the volume of gas emit to the atmosphere is dV . The temperature of the coal body should decrease by

$$dT = -\frac{p_0}{1000c_1} \cdot \ln \frac{p}{p_0} \cdot dV, \quad (10)$$

where p is the gas pressure before desorption, Pa, and p_0 is the atmospheric pressure, Pa.

The volume of gas within a coal seam can be calculated by $V = \alpha\sqrt{p}$ [17], where α is the coal seam gas content coefficient, $\text{m}^3/(\text{t}\cdot\text{MPa}^{1/2})$. Therefore,

$$dV = \alpha \cdot \frac{dp}{2} \cdot p^{-1/2}. \quad (11)$$

Bringing it into Equation (10), we get

$$dT = -\frac{p_0}{1000c_1} \cdot \ln \frac{p}{p_0} \cdot \alpha \cdot \frac{dp}{2} \cdot p^{-1/2}. \quad (12)$$

Therefore,

$$\begin{aligned}\Delta T_e &= - \int_p^{p_0} \frac{p_0}{1000c_1} \cdot \ln \frac{p}{p_0} \cdot \alpha \cdot \frac{1}{2\sqrt{p}} dp \\ &= - \frac{p_0 \cdot V_0 \cdot \eta}{1000c_1} \cdot \left[\ln \frac{p}{p_0} - 2 \frac{1-\eta}{\eta} \ln(1-\eta) - 2 \right],\end{aligned}\quad (13)$$

where V_0 is the gas content before desorption, m^3/t , and η is gas emission rate.

Therefore, the temperature change in the process of coal gas desorption and diffusion is

$$\begin{aligned}\Delta T_{\text{total}} &= \Delta T_d + \Delta T_e \\ &= - \frac{A \cdot V_t \cdot \eta}{1000c_1(1 + Bp(1-\eta)^2)} \\ &\quad - \frac{p_0 \cdot V_{\text{max}} \cdot \eta}{1000c_1} \\ &\quad \cdot \left[\ln \frac{p}{p_0} - 2 \cdot \frac{1-\eta}{\eta} \ln(1-\eta) - 2 \right].\end{aligned}\quad (14)$$

The above analysis shows that the temperature decrease in the process of desorption is related to the gas desorption amount, the specific heat of the coal body, and the gas pressure. Large gas pressure and more desorption amount result in greater temperature change.

3. Calculation of Experimental Parameters of Coal Gas Desorption

Gas desorption experiments were conducted based on Malan 8# and Zhenxing2# coal samples. Gas desorption data was analyzed and calculated. Temperature changes under various experimental conditions were obtained.

As shown in Table 1, ΔT_{total} is the total temperature change of the coal body during the process of desorption, which is obtained from Equation (14); $\Delta T_{\text{max measured}}$ is the maximum temperature drop of unit mass coal during the desorption experiment.

The above results show that the two temperature values increase with the increasing adsorption equilibrium pressure. However, when the adsorption equilibrium pressure is small, the theoretical temperature difference is close to the measured temperature difference. As the adsorption equilibrium pressure increases, the theoretical temperature difference is larger than the measured temperature difference. The main reason is that the theoretical temperature difference is assumed to be an adiabatic process, which is not true in fact. When the desorption rate is greater, the rate of desorption and heat absorption is also faster. The heat at this time mainly comes from the coal body, and the measured temperature value should be closer to the theoretical value. But desorption rate decreases as time goes on, and the energy transfer between the environment and the

system is difficult to eliminate, which results in larger error.

The value of heat change during the process of desorption was calculated with Equation (1), as shown in Figures 2–5.

The temperature change is the result of the energy change. In this paper, the change of heat, which can be regarded as the change of heat absorption, is obtained according to the experimental measurements and theoretical calculations. It is positively correlated with coal gas pressure, gas content, and desorption. Based on that, the temperature variation of coal can be used as a sensitive index for predicting coal and gas outburst. However, the temperature change in the desorption process is affected by many factors such as the stress formation, occurrence conditions, and metamorphic degree of coal. The underground measurement method still needs to be studied from many aspects. The test and analysis of gas adsorption and desorption temperature of granular coal is feasible and can be used together with other outburst prediction sensitive indexes.

This method is feasible in theory, but the method of implementation and the determination of the critical value need further study.

4. Conclusions

- (1) From the point of view of molecular motion, the cause of thermal change in the coal gas desorption process was analyzed combined with the theory of thermodynamics, including desorption heat of absorbed gas, expansion heat of free gas, diffusion heat, and heat adsorption due to gas seepage.
- (2) The temperature variation mechanism of the whole process of gas desorption was analyzed, and a mathematical equation describing the temperature variation was established. The temperature variation in this equation is related to parameters such as gas pressure, limiting desorption volume, and desorption rate.
- (3) Through the calculation and analysis of the experimental data of two types of coal samples, the measured values and theoretical values of temperature and thermal energy changes during gas desorption were obtained. The results showed both the temperature and heat values increase with the increase of adsorption equilibrium pressure. However, when the adsorption equilibrium pressure is small, the theoretical temperature difference is close to the measured temperature difference. As the adsorption equilibrium pressure increases, the theoretical temperature difference is larger than the measured temperature difference.
- (4) The temperature variation of coal gas desorption can be considered as a sensitive index for the prediction of gas outburst, but the relevant implementation methods and critical values still need to be studied in the future.

TABLE 1: Theoretical and measured values of the two types of coal samples.

Sample name	Equilibrium pressure p (Pa)	V_{\max} (m^3/kg)	Desorption rate η	ΔT_d ($^{\circ}\text{C}\cdot\text{g}^{-1}$)	ΔT_e ($^{\circ}\text{C}\cdot\text{g}^{-1}$)	ΔT_{total} ($^{\circ}\text{C}\cdot\text{g}^{-1}$)	$\Delta T_{\text{max measured}}$ ($^{\circ}\text{C}\cdot\text{g}^{-1}$)
Malan 8#10-20	$6.00E+05$	$1.97E-03$	$5.20E-01$	$5.95E-04$	$8.10E-05$	$6.75E-04$	$1.25E-03$
	$1.21E+06$	$2.83E-03$	$6.20E-01$	$2.25E-03$	$2.02E-04$	$2.45E-03$	$2.31E-03$
	$1.90E+06$	$3.94E-03$	$6.70E-01$	$5.68E-03$	$3.70E-04$	$6.05E-03$	$2.71E-03$
	$2.10E+06$	$4.60E-03$	$7.40E-01$	$8.91E-03$	$4.66E-04$	$9.37E-03$	$3.21E-03$
Malan 8# 20-40	$5.39E+05$	$3.38E-03$	$6.20E-01$	$1.19E-03$	$1.25E-04$	$1.32E-03$	$6.57E-04$
	$1.12E+06$	$4.68E-03$	$9.20E-01$	$9.11E-03$	$2.49E-04$	$9.36E-03$	$1.52E-03$
	$1.65E+06$	$5.56E-03$	$9.30E-01$	$1.69E-02$	$4.26E-04$	$1.73E-02$	$1.90E-03$
	$2.24E+06$	$8.70E-03$	$7.70E-01$	$1.99E-02$	$9.16E-04$	$2.08E-02$	$2.42E-03$
Malan 8# 40-60	$4.34E+05$	$4.76E-03$	$6.00E-01$	$1.30E-03$	$1.34E-04$	$1.43E-03$	$1.34E-03$
	$7.92E+05$	$5.54E-03$	$7.00E-01$	$3.62E-03$	$2.93E-04$	$3.91E-03$	$2.36E-03$
	$1.73E+06$	$6.35E-03$	$7.40E-01$	$1.01E-02$	$5.80E-04$	$1.07E-02$	$3.40E-03$
	$2.16E+06$	$1.34E-02$	$8.00E-01$	$3.18E-02$	$1.38E-03$	$3.32E-02$	$4.16E-03$
Zhenxing 10-20	$3.30E+05$	$9.10E-03$	$4.00E-01$	$1.05E-03$	$1.80E-04$	$1.23E-03$	$2.53E-03$
	$8.46E+05$	$1.34E-02$	$6.60E-01$	$8.44E-03$	$7.54E-04$	$9.20E-03$	$6.66E-03$
	$1.32E+06$	$1.48E-02$	$8.10E-01$	$2.22E-02$	$1.12E-03$	$2.33E-02$	$8.83E-03$
	$3.42E+05$	$8.19E-03$	$3.80E-01$	$9.20E-04$	$1.68E-04$	$1.09E-03$	$3.19E-03$
Zhenxing 20-40	$9.00E+05$	$1.14E-02$	$5.80E-01$	$6.09E-03$	$6.61E-04$	$6.75E-03$	$7.07E-03$
	$1.01E+06$	$1.29E-02$	$7.90E-01$	$1.42E-02$	$7.94E-04$	$1.50E-02$	$7.40E-03$
	$1.80E+06$	$1.39E-02$	$9.10E-01$	$4.06E-02$	$1.20E-03$	$4.18E-02$	$9.92E-03$
	$3.40E+05$	$7.33E-03$	$5.50E-01$	$1.38E-03$	$1.45E-04$	$1.52E-03$	$4.44E-03$
Zhenxing 40-60	$1.10E+06$	$1.39E-02$	$7.87E-01$	$1.62E-02$	$9.25E-04$	$1.71E-02$	$1.12E-02$
	$1.43E+06$	$1.72E-02$	$8.40E-01$	$3.12E-02$	$1.35E-03$	$3.26E-02$	$1.31E-02$
	$1.70E+06$	$1.83E-02$	$9.20E-01$	$5.41E-02$	$1.47E-03$	$5.56E-02$	$1.50E-02$
	$2.37E+05$	$8.79E-03$	$5.40E-01$	$1.11E-03$	$5.70E-05$	$1.16E-03$	$2.49E-03$
Zhenxing 60-80	$6.71E+05$	$1.26E-02$	$8.00E-01$	$9.34E-03$	$4.88E-04$	$9.83E-03$	$7.99E-03$
	$1.25E+06$	$1.61E-02$	$9.00E-01$	$3.22E-02$	$1.02E-03$	$3.32E-02$	$1.21E-02$
	$1.87E+06$	$1.77E-02$	$9.10E-01$	$5.47E-02$	$1.56E-03$	$5.62E-02$	$1.46E-02$

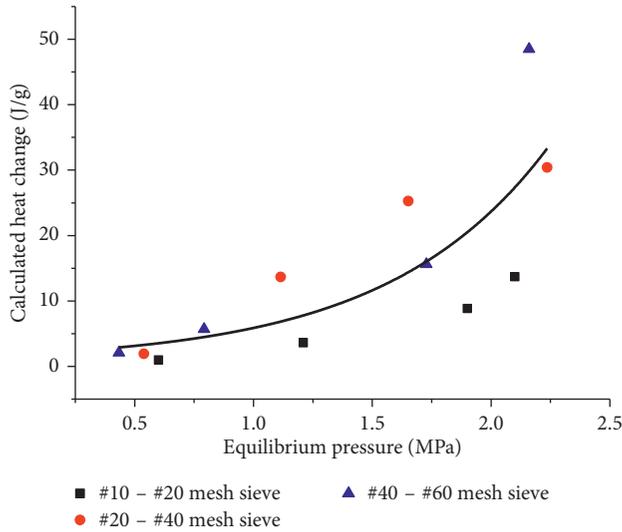


FIGURE 2: Theoretical desorption heat values of 8# Malan coal.

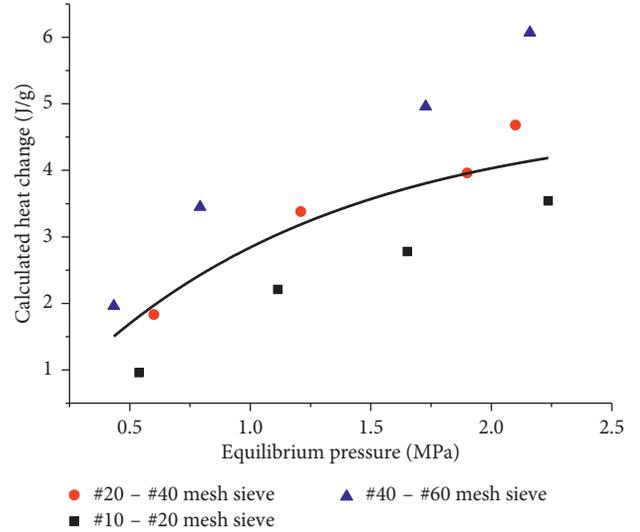


FIGURE 3: Measured desorption heat values of 8# Malan coal.

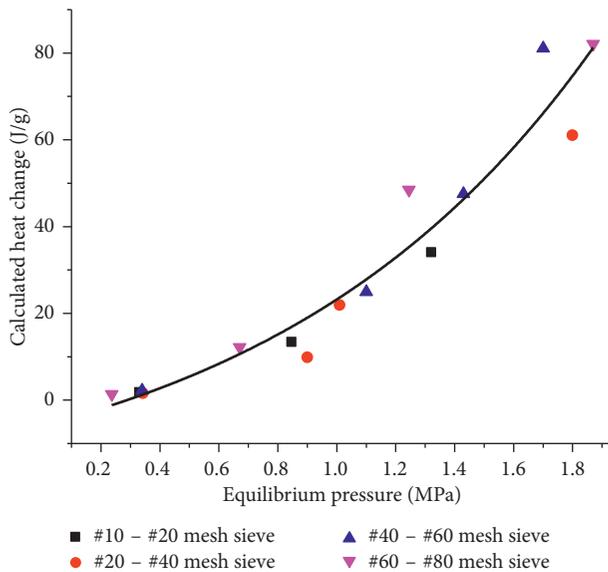


FIGURE 4: Theoretical desorption heat values of Zhenxing coal.

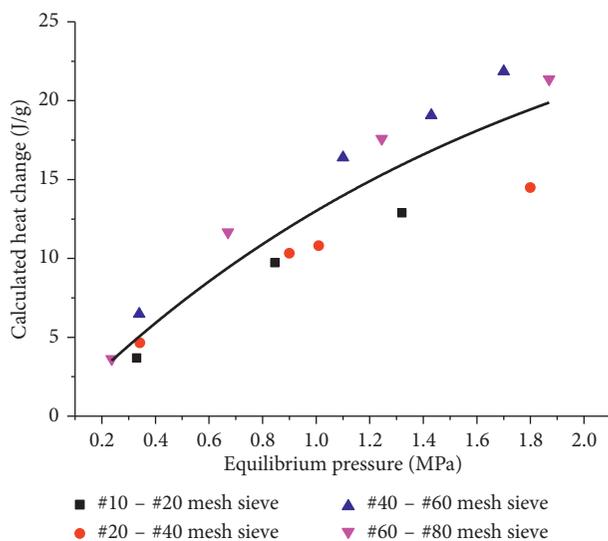


FIGURE 5: Measured desorption heat values of Zhenxing coal.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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