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# The dynamic evolution model and experimental study of gas permeability under multiple factors

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**ABSTRACT**

This paper aims to ascertain the relationship between permeability and temperature of gas-filled coal. For this purpose, the author probed into various influencing factors of permeability, and constructed a permeability evolution model involving temperature, effective stress, gas pressure and humidity. Then, the proposed model was improved through an experimental research using thermal-fluid-solid coupling triaxial seepage test device. It is found that the theoretical results of the model agree well with the experimental data, indicating that the improved model is an ideal tool for predicting the gas flow pattern. The research results lay a solid basis for enhancing gas drainage efficiency and preventing gas outburst.

## 1. INTRODUCTION

In coal mining, permeability measures the ability of the coal seam to allow gas to pass through it. It is ever-changing and affected by multiple factors, such as in-situ stress, pore pressure and temperature. Over the years, permeability has been frequently applied to explore the gas seepage of coal seam under multiple physical fields.

Taking the coal seam as a cube model, Harpalani [1] developed a permeability computing method based on coal matrix coefficient and effective stress. Focusing on stress-strain, Shi, Durucan, Cui and Bustin [2, 3] created different permeability evolution models, of which the SD model successfully predicted the variation law of coal seam gas in San Juan Basin, US. McKee [4] proposed an empirical formula for coal permeability based on effective stress, and achieved desirable lab and field application effects with the formula. Tao Yunqi [5] analysed the compression before the expansion of coal, presented a permeability model considering the impact of effective stress, temperature and gas pressure, and performed experimental verification of the model. Inspired by fractured plate model, Wei Jianping [6] put forward a permeability evolution model in light of surface chemistry principles and effective stress theory, and tested the reliability of the model. Zhao Yangsheng [7] experimentally investigated the correlations of permeability with volumetric stress and gas pressure. Through a triaxial test of gas desorption and seepage, Tang Jupeng [8] discovered that the relationship between permeability and effective stress is a positive yet declining exponential curve under loading and a parabolic curve under unloading.

In general, most of the above permeability evolution strategies only concern a single influencing factor of permeability, failing to present a full picture of the permeability variation under multiple physical fields. In particular, there is no report on the relationship between permeability and temperature. To make up for the gap, this paper probes into various influencing factors of permeability, and constructs a permeability evolution model involving temperature, effective stress, gas pressure and humidity. Then, the proposed model was improved through an experimental research. The improved model was proved as an ideal tool for predicting the gas flow pattern.

## 2. INFLUENCING FACTORS OF PERMEABILITY

The coal seam permeability hinges on such features of the natural fracture system as stratum porosity, fracture shape, fracture size, and fracture orientation in the direction of fluid permeation.

### 2.1 Effective stress in adsorption expansion

In the effective stress theory [9], effective stress refers to the difference between the overburden pressure on the coal-rock and the fluid pressure in pores and fractures. The theory was later modified to suit porous medium like coal-rock mass [10]. Suppose the pressure of coal seam gas falls from $P_0$ to $P$. Then, the increment of effective stress $\Delta\sigma_E$ can be expressed as:

$$\Delta\sigma_E = \alpha(p_0 - p) \tag{1}$$

where $\alpha$ is the Biot number (common value: 1); $p$ is the pore pressure of coal seam gas (MPa).

So far, scholars have reached a consensus over the variation in size and mechnical properties of gas-filled coal with effective stresses after gas adsorption[11-13]. The coal expansion induced by gas adsorption is often attributed to following factors: the entry of gas molecues into the ultramicropores, the expansion of ultramicropore wedges under pore gas pressure, the widening of carbon molecue spacing due to the growing number of gas molecues, and the gas molecue-size opening of ultramicropore wedges resulted from gsa adsroption.

In addition, the previous studies have yielded the following hypotheses on the swellings stress of adsorption and strain [6, 8]:

(1)The size of ultramicropores and adsorption features of coal remain basically unchanged in spite of external constraints [14-15].

(2) The adsorption expansion process is isothermal; the adsorption obeys the Langmuir adsorption model of single molecule layer; both adsoption and desorption complete instantaneously.

(3) Under ideal constraints, the swelling stress generated in gas adsorption is entirely converted to elastic expansion energy.

(4) The fracture system of coal originates from the cutting of three groups of planes that are perpendicular to one another.

(5) The surface of coal is smooth and in full contact with the constraint boundary.

(6) The moisture is uniformly distributed within the coal.

(7) The coal matrix suffers purely from elastic deformation during desorption expansion and desorption shrinkage.

According to the theoretical analysis, the adsorption expansion stress and the strain of gas-filled coal can be expressed as:

$$\begin{cases} \sigma_p = \dfrac{2\mathrm{aRT}\rho_s(1-2\upsilon)\ln(1+\mathrm{b}p)}{3\mathrm{V_m}} \\ \varepsilon_1 = \dfrac{2\mathrm{aRT}\rho_s(1-2\upsilon)\ln(1+\mathrm{b}p)}{3\mathrm{EV_m}} \end{cases} \tag{2}$$

where $\sigma_p$ is the expansion stress (Pa); $\varepsilon_1$ is the linear strain of adsorption expansion (%); a and b are Langmuir adsorption constants ($\mathrm{Pa}^{-1}$); T is the absolute temperature of coal (K); $p$ is the pore pressure of coal (Pa); $\rho_s$ is the apparent density of coal ($\mathrm{t/m^3}$); $\mathrm{V_m}$ is the molar volume of gas (22. 4L/mol in standard state); E is the elastic modulus (Pa); $\upsilon$ is Poisson's ratio.

Considering the effect of adsorption expansion on effective stress, the formula of effective stress can be obtained based on fomrula (1):

$$\Delta\sigma_E = p_0 - p - \sigma_p \tag{3}$$

### 2.2 Effect of temperature on permeability

In recent decades, much research has been done on the effect of temperature on permeability at home and abroad. For instance, Somerton [16] examined the permeability of sandstone under the effect of temperature in 1956. Morrow [17] tested the permeability of granite at high temperature, and found the negative correlation between permeability and temperature. Li Z Q [18] dug deep into the contradictions in previous studies, pointing out that the relationship between permeability and temperature is not purely monotonic under constant effective stress.

Zhao Y S [19] experimentally explored the permeabilities of anthracite, lignite and bitumite under high temperature, and discovered the threshold and multiple phases of permeability under changing temperature. Through an experiment on gas seepage flow in coal, Yang Xinle[20] discovered the quadratic parabolic decreasing of permeability with the declining in temperature and effective stress, and the exponential increase of permeability with the growth in temperature and effective stress. Focusing on temperture-induced changes to high-rank coal, Chen Shuyuan[21] concluded that the permeability of high-rank coal is insensitive to temperature, and its relationship with temprature is undetermined: the permeability-temperature relationship is negative when the pressure is below 2MPa, and the relationship turns positive when the pressure is above 2MPa.

Jiang Yongdong [22] studied coal permeability in temperature, stress and acoustic fields, and derived a seepage flow equation under the coupling of multiple factors. Yu Yongjiang [23] carried out experiments on briqutte samples in temperature and stress fields, and observed an obvious increase in permeability with the increase in temeprature. Reference [24] suggests that the permeability of sandstone is negatively correlated with temperature when the latter is below 150°C, while Reference [25] draws exactly the opposite conclusion. Under high temperature, however, the sandstone permeability always increases with the temperture [26]. Reference [27] argues that the temperature-induced variation in coal and rock permeability consists of several phases: the permeability, changing inobviously at low temperature (below 150°C), fluctuates violently after the temperature surpasses a threshold, and increases againt under high temperature. However, Reference [28] holds that the relationship between rock permeability and temperature is positive exponential, and there is no temperature threshold for the permeability vairation.

To sum up, the previous research results differ greatly in the relationship between permeatbility and temperature, espeically that of coal and rock.

Here, the thermal expansion coefficient of coal matrix can be expressed as:

$$\beta = \frac{1}{V}\frac{dV}{dT} \tag{4}$$

The temperature-induced volume variation per unit of coal can be expressed as:

$$V_0 = V_\mathrm{T} e^{\beta\Delta T} \tag{5}$$

Based on these formulas, the temperature-induced volume strain produced by the thermal expansion of coal matrix can be expressed as:

$$\varepsilon_{VT} = e^{-\beta\Delta T} - 1 \tag{6}$$

where $V_0$ is the original volume per unit of coal; $V_\mathrm{T}$ is the volume of the micro unit after thermal expansion; $\Delta T$ is the increment of coal temperature; $\varepsilon_{VT}$ is volume strain induced solely by temperature.

## 3. SECTION HEADINGS

Assuming that the coal seam is only saturated with single-phase gas fluid, the formula of permeability, in the form of porposity, can be derived according to the definition of porosity φ [29]:

$$\varphi = \frac{v_p}{v_B} = 1 - \frac{1-\varphi_0}{1+\varepsilon_V}(1+\frac{\Delta V_S}{V_{S0}}) \tag{7}$$

where $V_{s0}$ is the initial volume of the coal matrix; $\Delta V_S$ is volume variation of the coal matrix; $v_P$ is the porosity volume; $v_B$ is the total apparent volume of coal; $\varphi_0$ is the initial porosity; $\varepsilon_V$ is the volume strain (positive under expansion, and negative under compression).

There are three main causes to the total deformation of the coal seam, namely, thermal expansion, gas pressure and gas adsorption expansion. Under the changing temperature and gas pressure, the increment of coal volume strain can be expressed as:

$$\varepsilon_{V(\mathrm{T,p})} = \frac{\Delta V_S}{V_{S0}} = \beta\Delta T - \kappa_P \Delta P + \frac{\varepsilon_P}{1-\varphi_0} \tag{8}$$

where $\varepsilon_{V(\mathrm{T,\,p})}$ is the volume strain resulted from temperature and gas pressure; $\beta$ is the volume expansion coefficient of coal ($m^3/(m^3 \cdot K)$); $k_p$ is the volume compression coefficient of coal ($MPa^{-1}$) ($k_p$=3(1-2$\upsilon$)/E); E is the elastic modulus; $\nu$ is the Poisson's ratio; $\Delta T$ is the increment of absolute temperature (K) ($\Delta T = T - T_0$); $\Delta P$ is the increment of gas pore pressure (MPa) ($\Delta p = p - p_0$); $\varepsilon_p$ is adsorption expansion strain per unit volume of coal (3 times of linear strain).

The above formulas can be combined into the dynamic evolution model of porosity:

$$\varphi = \frac{v_p}{v_B} = 1 - \frac{1-\varphi_0}{1+\varepsilon_V}(1+\beta\Delta T - \kappa_P \Delta P + \frac{\varepsilon_P}{1-\varphi_0}) \tag{9}$$

Considering the interaction between temperature and porosity, the following formula was derived from the definition of volume compression coefficient:

$$1+\varepsilon_V = \exp(\beta \Delta \mathrm{T} - \kappa_p \Delta\sigma_E) \tag{10}$$

where $\Delta\sigma_E$ is the increment of effective stress on coal (MPa).

In light of the Kozeny-Carman equation[11], the relationship between permeability and porosity can be obtained as:

$$\kappa = \frac{\varphi}{\kappa_Z S_P^2} \tag{11}$$

where $k$ is permeability (mD); $K_Z$ is a constant (value: 5); $S_p$ is the surface area per unit volume of pore ($cm^2$).

From the above two formulas, the dynamic evolution model of coal permeability under elastic condition can be derived as:

$$\kappa = \frac{\kappa_0}{\exp(\beta\Delta T - \kappa_p \Delta\sigma_E)} \begin{bmatrix} 1+\frac{\varepsilon_V}{\varphi_0} - \\ \frac{(\beta\Delta T - \kappa_P \Delta \mathrm{P})(1-\varphi_0)}{\varphi_0} \\ -\frac{\varepsilon_P}{\varphi_0} \end{bmatrix}^3 \tag{12}$$

Hence, formula (11) is our dynamic evolution model of coal permeability under changing temperature, gas pressure and effective stress.

## 4. CORRECTION OF DYNAMIC EVOLUTION MODEL OF COAL PERMEABILITY

This section mainly corrects the dynamic evolution model of coal permeability in formula (12). In view of the previous discussion and the variation of temperature increment $\Delta \mathrm{T}$, the author put forward the coefficient of thermal expansion of the coal matrix induced by temperature variation ($\beta$). Since the coal is saturated with gas and isolated from the exterior space and the temperature changes instantly from one equlibrium state to another, the coal matrix will expand and the increment of pore pressure ($\Delta P_T = P - P_0$) will grow under the effect of gas when the coal temeprature shifts from $T_0$ to T, and the coal seam gas will be affected to a greater extent by the temperature than the coal matrix.

Based on the Clausius-Clapeyron relation, the effect of temperature on gas can be expressed as:

$$\Delta p_T = p_0 \frac{\Delta T}{T_0} \tag{13}$$

where $\Delta P_T$ is gas increment under temperature variation (Pa); $P_0$ is the gas pressure at the coal temperature of $T_0$ (Pa).

As the gas pressure changes with the temperature, the gas adsorption capacity is bound to fluctuate, which, in turn, causes changes to he adsorption expansion stress. Thus, the above formula can be rewritten as:

$$\begin{cases} \sigma_p = \dfrac{2\mathrm{aRT}\rho_s(1-2\upsilon)\ln\left[1+\mathrm{b}\left(\Delta p + \Delta p_T\right)\right]}{3\mathrm{V_m}} \\ \varepsilon_1 = \dfrac{2\mathrm{aRT}\rho_s(1-2\upsilon)\ln\left[1+\mathrm{b}\left(\Delta p + \Delta p_T\right)\right]}{3\mathrm{EV_m}} \end{cases} \tag{14}$$

Here, the gas pressure vairation and the effect of gas pressure on coal temperature are neglected, leaving only the temperature-induced pore pressure variaiton. Substituting formula (13) into formula (11), the author obtained the dynamic evolution model for permeability of coal under changing temperature $\Delta \mathrm{T}$ and gas pressure in an enclosed space.

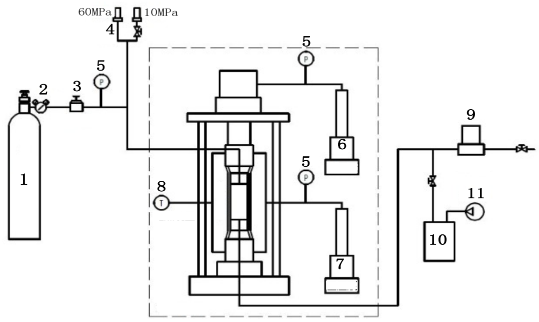
$$\kappa = \frac{\kappa_0}{\exp(\beta\Delta T - \kappa_p \Delta\sigma_E)} \begin{bmatrix} 1+\frac{\varepsilon_V}{\varphi_0} - \\ \frac{\left[\beta\Delta T - \kappa_P\left(\Delta p + \Delta p_T\right)\right](1-\varphi_0)}{\varphi_0} \\ -\frac{\varepsilon_P}{\varphi_0} \end{bmatrix}^3 \tag{15}$$

where $\varphi_0$ and $k_0$ can be obtained by fitting the expeirmental data; $\Delta \mathrm{T}$ can be inferred from the experiment plan. The effect of temperature variation can be identified by substituting $\Delta P = 0$ into formulas (14) and (15). Similarly, the effect of gas pressure can be identified by substituting $\Delta T=0$ into these formulas.

## 5. EXPERIMENT VERIFICATION AND ANALYSIS

### 5.1 Experiment design and physical parameters of coal sample

The experimental facility (Figure 1) was improved by adding an electric heating system to a facility designed for triaxial seepage experiment [30]. The purpose is to create the thermal-fluid-solid coupling condition.




1-Gas cylinder; 2-Gas pressure reducer; 3-Pressure regulator; 4-High and low pressure sensors; 5-Pressure gauge, 6-Axial pressure loading system; 7-Confining pressure loading system; 8-Electric heating device; 9-Gas flow meter, 10-Vacuum tank; 11-Vacuum pump

**Figure 1.** Triaxial seepage experimental system for thermal-fluid-solid coupling of gas-containing coal and rock

The coal samples were collected from No. 21 coal seam in Xindeng Coalmine of SDIC Zhengzhou Coal Energy Development Co., Ltd. The coal analysis shows] that[31] the moisture content (Mad) is 1.95%, ash content (Ad) is 14.91%, volatile content (Vdaf) is 7.38%, and fixed carbon content (Fcd) is 75.76%. The following two plans were prepared for the experiments.

Plan 1: To simulate the underground geothermal conditions, the temperature was adjusted between 20℃ and 80℃. The temperature was automatically controlled by the PID with the precision of ±0.5℃ [32]. The gas pressure was applied constantly to the upper surface of each coal sample at 1MPa or 1.6MPa. A negative pressure tacking pump was placed at the bottom of the sample to apply the negative pressure constantly at 20KPa, so that the pore pressure remained constant in the sample. The experiment started 8h after the confining pressure, axial pressure and gas pressure reached the equilibrium state. The temperature was changed by 5℃ each time and maintained for 4h. The flow values were recorded when the permeability was stable.

Plan 2: The gas pressure was adjusted between 0.3MPa and 1.5MPa [33], while the temperature was maintianed at 20℃. After applying the axial pressure and confining pressure, the gas pressure was altered and the resulting variation of gas flow was measured.

Since the gas flow in the sample follows Darcy's law, the permeability can be calculated by flow capacity.

$$k=\frac{2\mu p_0 Q_0 L}{[p_1^2-(p_0-p_2)^2]S} \tag{16}$$

where $\mu$ is the dynamic gas viscosity coefficient, whose value depends on the setting temperature; $P_0$ is the standard atmospheric pressure (MPa); $Q_0$ is the seepage quantity under the standard atmospheric pressure ($m^3/s$); $L$ is the length of coal sample (m); $p_1$ is the inlet gas pressure on the top surface of coal sample (MPa); $p_2$ is the outlet gas pressure on the bottom surface of coal sample (MPa); S is the cross-sectional area of coal sample ($m^2$).

The basic parameters of the samples were obtained by volumetric gas adsorption measuring method.

**Table 1.** Basic physical parameters of coal samples

| Gas adsorption volume constant $a$ /($m^3.t^{-1}$) | Adsorption pressure constant $b$ /$MPa^{-1}$ | Elastic modulus E/GPa | Poisson's ratio $\mu$ | Thermal expansion coefficient of coal matrix $\beta$ /$T^{-1}$ | Elastic modulus of coal matrix E/GPa | Apparent density of coal matrix $\rho_s$ /$kgm^{-3}$ |
|---|---|---|---|---|---|---|
| 39.565 | 1.135 | 2.1 | 0.33 | 0.000116 | 5.62 | 1400 |

### 5.2 Results and comparison

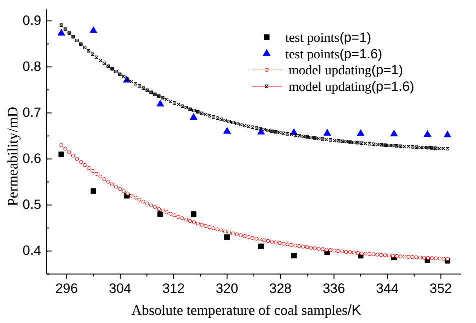



**Figure 2.** Relationship between permeability and temperature variation

Through experiments and calculation of mdoel data, the author obtained the relationship between permeability and temperature variation (Figure 2) and that between permeability and gas pressure variation (Figure 3).

During the calculation, the elastic modulus of the coal matrix was introduced to calculate the strain from the increasing gas pressure temperature vairation when the external pressure was on the rise. The experimental results shows and that the results of the corrected model agree well with the test points.

The consistency with the test points before and after the correction was also investiagted. As shown in Figure 2, the mean relative deviation of the original model from the test points was 4.19%, and that of the corrected model was 2.22%, when the gas pressure on the coal sample surface was 1MPa; the deviations were 4.6% and 1.04%, respectively, when the gas pressure was 1.6MPa. As shown in Figure 3, the mean relative error of the original model from the test points was

5.22%, and that of the corrected model was 3.36%, when the axial pressure was 4MPa and the confining pressure was 4MPa; the deviations were 4.6% and 1.04%, respectively, when the axial pressure was 6MPa and the confining pressure was 4 MPa.

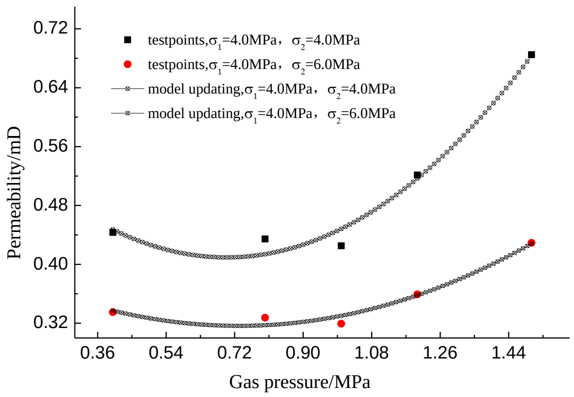



**Figure 3.** Relationship between permeability and gas pressure variation

## 6. MODEL ANALYSIS

During the model derivation, the coal sample, gas, temperature field and stress field were considered as one system. After the variation of temperature increment, the equilibrium state was isolated from the external environment, that is, there was no energy or heat exchange. During the instant state shift of the temperature, variations occurred in coal matrix volume, gas pressure and gas adsorption balance. Then, the adsorption balance caused the variation in adsorption expansion stress. According to the definition of porosity, the proposed model successfully predicted the generation of adsorption expansion stress and the variation of pore pressure induced by temperature increment. This means the proposed model is theoretically workable.

According to the theoretical results and experimental data, the permeability exhibited a negative exponential trend with the increase in temperature. The trend was obvious at the beginning and turned flat in the later phase. This is consistent with the conclusions in References [17] and [19]. Both references agree that permeability declines under temperature variation, except for a slight difference in the pattern of decline.

Without changing the temperature and external force, our model shows that the permeaibility decreased rapidly and then gradually stablized with the increase of gas pressure. The trend echoes with the theoretical and experimental results in References [5-7, 34]. These only difference lies in the critial gas pressure at which the permeability gets out of the decline and starts to increase. This pressure was about p>3.4MPa in Reference [6], and P>1.25MPa in References [5, 7, 34]. The difference is attibuted to the gas adsorption featues of the coal, and the compression of coal matrix under gas pressure. In general, the permeability decreases with the increase in adsorption expansion strain, and increases as the coal matrix is compressed by gas pressure. The critial gas pressures are different because of the varied elastic moduluses and adsorption features of coal samples.

Owing to the multiple hypotheses, the dynamic evolution model of coal permeability may produce different results from different angles. The analysis results also depend on the various coal parameters. Considering the multiple influencing factors, the model must be verified through expeirments. For isntance, this paper performs the permeability experiments with temperature variaiton. During the 4h temperature holding period, the permeability is also affected by the creep of the coal. This effect will be discussed in the future research.

## 7. CONCLUSIONS

Through theoretical and experimental analysis, this paper studies the variation in coal permeability with temperatures and gas pressures. Specifically, the formula of adsorption expansion stress and strain was corrected by Clausius-Clapeyron relation, and the dynamic evolution model of coal permeability was created based on Kozeny-Carman equation, considering effective stress, temperature and gas pressure. Through the experimental analysis, it is proved that the corrected model can accurately reflect the variation trend of permeability caused by temperature variation. The research results lay a soild basis for enhancing gas drainage efficiency and preventing gas outburst.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## NOMENCLATURE

$T$ absolute temperature of coal (K);
$\varepsilon_1$ linear strain of adsorption expansion (%);
$\sigma_p$ expansion stress (Pa)
$\Delta\sigma_E$ increment of effective stress(MPa)
$p$ pore pressure of coal seam gas (MPa)
$\rho_s$ apparent density of coal (t/m$^3$)
$V_m$ molar volume of gas (22.4L/mol in standard state)
$E$ elastic modulus (Pa)
$\upsilon$ Poisson's ratio(%)
$V_T$ volume of the micro unit after thermal expansion(cm$^3$)
$V_0$ original volume per unit of coal(cm$^3$)
$V_{S0}$ initial volume of the coal matrix(cm$^3$)
$V_B$ total apparent volume of coal
$\varphi_0$ initial porosity(%)
$\varepsilon_{V(T,p)}$ volume strain resulted from temperature and gas pressure(cm$^3$)
$\Delta p_T$ gas increment under temperature variation (Pa)

### Greek symbols

$\alpha$ Biot number(common value: 1)
$\beta$ volume expansion coefficient of coal (m$^3$/(m$^3$·K))
$\varphi$ void ratio（%）
$\kappa$ Permeability(mD)
$a$ Gas adsorption volume constant $a$ /(m$^3$.t$^{-1}$)
$b$ Adsorption pressure constant $b$ /MPa$^{-1}$
$\mu$ Poisson's ratio