INTRODUCTION

Coal is a good natural adsorbent due to its large specific surface area\(^1\) which can generally reach 20-200 m\(^2\)/g.\(^2\) Due to coal deformation of swelling/shrinkage induced by gas adsorption/desorption,\(^3-6\) the permeability of coal seams that are primarily determined by coal seam fracture apertures\(^7-9\) is more complicated than that in conventional gas reservoirs.\(^10-12\) On one hand, the shrinkage of a coal matrix caused by gas desorption tends to increase the fracture aperture and coalbed permeability. On the other
hand, due to the drawdown of the coalbed, the increase in effective stress results in the decrease of the fracture aperture and coalbed permeability. Therefore, the coalbed permeability does not have a simple diminishing relationship with gas depletion. In practice, the most dramatic examples of this are several producing reservoirs in the San Juan Basin, with permeability increases of as much as 100 times. Therefore, the deformation of fracture volume induced by gas significantly influences the evolution of coalbed permeability during gas recovery. Additionally, under the coal seam field conditions, the bulk coal deformation induced by gas is unlikely to undergo free expansion, and additional stress will be generated in the coal seam, namely adsorption stress, which is a key factor leading to a coal and gas outburst, one of the serious disasters in coal mines. Therefore, the establishment of theoretical models of coal deformation induced by gas under coal seam field conditions may provide a basis for the research of gas recovery and the prevention of coal and gas outbursts.

Currently, coal deformation induced by gas has been studied by many scholars. Gray used experimental methods to determine the coal deformation during gas adsorption, and the results indicate that the coal volumetric strain and pressure satisfied a linear relationship. Using the same experimental methods, Levine found that Gray’s model overestimated the impact from coal deformation, especially at high pressures, and used a Langmuir-like equation to describe coal deformation behavior. The similar experimental results also have been reported by other scholars. In other studies, the coal deformation induced by gas adsorption was described by the theoretical model. On the basis of Scherer’s work, Pan and Connell established the theoretical model for gas adsorption-induced coal swelling; they believed that the observed swelling represents the difference between two opposing effects: volumetric expansion of the coal due to the gas adsorption and the coal compression as a result of pore pressure. In addition, this theoretical model was verified by using Moffat and Weale’s data.

However, the above research was focused on the study of the bulk coal deformation induced by gas, but they rarely considered the relationships among the bulk coal, coal matrix, and fracture volumetric strains. Cui and Bustin considered the relationships among the bulk coal, fracture, and matrix, respectively, and thought that the adsorption-induced bulk coal volumetric strain was equal to the coal fracture volumetric strain. However, Connell et al. believed that adsorption-induced coal matrix and fracture volumetric strains were the functions of the bulk coal, that was \( \epsilon_f = \psi_p (\epsilon_b) \) and \( \epsilon_m = \psi_m (\epsilon_b) \), where \( \epsilon_f, \epsilon_m \) are the adsorption-induced volumetric strains of bulk coal, fracture, and matrix, respectively, and \( \psi_p \) and \( \psi_m \) are considered constants.

As stated above, the scholars studied the coal deformation caused by gas adsorption from various perspectives. Nevertheless, their research was focused on the study of the bulk coal deformation, and the deformation of the coal matrix and fracture was not studied enough. The coupling mechanism of the deformation between the coal fracture, matrix, and bulk coal is still unclear. Additionally, these models of coal deformation also do not fully consider the coal seam field conditions. To better fit the actual coal seam field conditions and provide a basis for engineering applications, in this paper, based on the energy balance approach, the physical structure of coal, coal seam field conditions, poroelasticity, mathematical differentiation, and previous scholars’ research results, the volumetric strain models of bulk coal, coal fracture, and coal matrix under coal seam field conditions were established. Furthermore, based on the analysis of the effect of gas pressure on coal deformation, the difference in the gas pressure effect on the bulk coal deformation between experimental conditions and coal seam field conditions is revealed. Finally, the developed models were analyzed and verified from various perspectives. Conclusions of this work may help to establish the coalbed permeability model to better describe the evolution of coalbed permeability during gas recovery and provide a basis for the research of coal and gas outbursts prevention.

### 2 | COAL SEAM PHYSICAL STRUCTURE

Many scholars believed that the coal seam is a kind of dual-porosity medium, including pores, solid skeleton, and cleats. A micropore is less than 2 nm, and a mesopore is 2-50 nm in diameter. The micropores and mesopores compose the coal seam pore system, and the coal seam fractures are composed of butt cleats and face cleats. It is generally considered that the solid skeleton and pores constitute the coal matrix, and the bulk coal is composed of the fractures and coal matrix. Almost all coal seams contain methane, which exists in a free state in fractures, while it is mainly reserved in an adsorption state in micropores and mesopores. Of this methane, free gas accounts for 10%-20% of the coal seam total gas content, and adsorption gas accounts for 80%-90%. Additionally, Liu and Rutqvist found that the coal matrix was not completely separated from each other by cleats and connected by the coal matrix bridge. Therefore, the coal seam physical structure can be simply described, as shown in Figure 1.

### 3 | MODELS DEVELOPMENT

Prior to the derivation of coal adsorption deformation models, the sign of the strain is defined. The strain is positive when the coal expands; conversely, the strain is negative when the coal is compressed. Additionally, in order to simplify the
model derivation process without affecting the analysis results, the following assumptions are made.

a The deformation elastic energy of the coal matrix caused by gas adsorption is equal to the reduction of the coal matrix surface energy.\(^5,21\)

b The coal matrix is considered as an isotropic elastic medium, and its deformation caused by adsorption is equal in all directions (\(\varepsilon_x = \varepsilon_y = \varepsilon_z\)).

c The elastic modulus of the coal matrix is a constant.

d Gas fugacity equals gas pressure.

### 3.1 Models of BCVS

#### 3.1.1 Model of BCVS under experimental conditions

Many scholars used experimental methods to determine the BCVS. The experimental method principle is shown in Figure 2. Their experimental results\(^{18-20}\) indicate that the BCVS followed a Langmuir-like equation, and it can be defined as:

\[
\varepsilon_b = \frac{\varepsilon_L P}{P_L + P'},
\]

where \(\varepsilon_L\), the Langmuir volumetric strain, is a constant and represents the volumetric strain at an infinite pore pressure; \(P_L\), the Langmuir pressure, is a constant.

#### 3.1.2 Model of BCVS under coal seam field conditions

For a porous material, if a loading pressure \((P_1)\) applied over its entire outer surface equals the loading pressure \((P_2)\) applied over its entire interior pore surface, then the mechanical behavior of the loading pressures can be considered as the only loading pressure applied over its entire outer surface throughout the solid media without any pores (see Figure 3).\(^{30,31}\)
The test of the bulk coal volumetric strain is generally carried out in the adsorption tank, as shown in Figure 2. Thus, the gas pressure applied on the coal sample can be considered equal to the gas pressure in the coal sample fractures and pores. Therefore, for the effect of gas pressure on bulk coal deformation under experimental conditions, the bulk coal can be considered as a solid without any pores and fractures, merely containing coal solid. Its volumetric strain (\(\varepsilon'^c_{b1}\)) under experimental conditions can be written as:

\[
\varepsilon'^c_{b1} = \frac{3(1-2\mu_s)}{E_s} P, \tag{2}
\]

where \(P\) is the gas pressure, \(E_s\) and \(\mu_s\) are the coal solid elastic modulus and Poisson's ratio, respectively, and \(\varepsilon'^c_{b1}\) is the BCVS induced by gas pressure under experimental conditions.

Pan and Connell suggested that the observed bulk coal deformation under experimental conditions represented the difference between two effects: volumetric expansion of the coal due to the adsorption of gas and the coal compression as a result of gas pressure. \(\varepsilon_{b1}\) can be expressed as:

\[
\varepsilon_{b1} = \varepsilon^s_b + \varepsilon'^c_{b1}, \tag{3}
\]

where \(\varepsilon_{b1}\) is the BCVS induced by coupling of gas pressure and gas adsorption under experimental conditions, and \(\varepsilon'^c_{b1}\) is the BCVS induced by gas adsorption.

Substituting Equations (1) and (2) into Equation (3), \(\varepsilon'^c_b\) can be written as:

\[
\varepsilon'^c_b = \frac{\varepsilon^s_b L P}{P_L + P} + \frac{3(1-2\mu_s)}{E_s} P. \tag{4}
\]

However, unlike in the experimental conditions, under coal seam field conditions, gas exists only in pores and fractures, and there is no gas on the outside of the coal seam (see Figure 1). Thus, the gas pressure effect on the bulk coal deformation under coal seam field conditions is different from that under experimental conditions, which has a swelling effect on the bulk coal. According to the influence mechanism of gas pressure on the effective stress of a coal seam, the BCVS (\(\varepsilon'^c_{b2}\)) induced by gas pressure under coal seam field conditions can be written as:

\[
\varepsilon'^c_{b2} = \frac{3(1-2\mu_b)}{E_b} P aP, \tag{5}
\]

where \(E_b\) and \(\mu_b\) are the bulk coal elastic modulus and Poisson's ratio, respectively, and \(a\) is the Biot's coefficient, which represents the inherent properties of coal and can be expressed as:

\[
a = 1 - \frac{K}{K_s}. \tag{6}
\]

where \(K\) represents the bulk modulus rock-fracture assemblage, and \(K_s\) represents the bulk modulus of rock matrixes; for well-fractured coal, \(K \gg K_s\), \(a\) can be considered to be 1.33.

With Equations (4) and (5), under coal seam field conditions, the BCVS (\(\varepsilon_b\)) induced by coupling of gas pressure and gas adsorption can be expressed as:

\[
\varepsilon_b = \frac{\varepsilon^s_b L P}{P_L + P} + \frac{3(1-2\mu_m)}{E_m} P + \frac{3(1-2\mu_b)}{E_b} \frac{P aP}{.} \tag{7}
\]

### 3.2 Models of CMVS

#### 3.2.1 Gas pressure-induced CMVS

For dual-porosity coal (see Figure 1), it is generally believed that the gas pressure within pores equals the gas pressure within fractures. Therefore, in the derivation of coal matrix deformation induced by gas pressure under coal seam field conditions, the coal matrix can be considered as a solid without any pores, merely containing coal solid (see Figure 3). The CMVS (\(\varepsilon^c_m\)) induced by gas pressure under coal seam field conditions can be written as:

\[
\varepsilon^c_m = -\frac{3(1-2\mu_s)}{E_s} P. \tag{8}
\]

#### 3.2.2 Gas adsorption-induced CMVS

**The elastic energy of the coal matrix**

Based on the principle of elastic energy, the elastic energy of per unit of coal matrix volume caused by the reduction of the surface energy during gas adsorption can be expressed as:

\[
\frac{\varepsilon^c_m}{E_s} P. \tag{8}
\]
where $\varepsilon_x$, $\varepsilon_y$, and $\varepsilon_z$ are the coal matrix volumetric strains in the directions of x, y, and z, respectively.

Under the assumptions (b) and (c), the coal matrix can be considered as an isotropic elastic medium, and the volumetric strains caused by adsorption are equal in all directions. Equation (9) can be simplified as:

$$ W_m^\sigma = \frac{E_m}{2(1+\mu_m)} \left[ \frac{\mu_m}{1-2\mu_m} (\varepsilon_x + \varepsilon_y + \varepsilon_z)^2 + \varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2 \right] $$

where $\varepsilon_m^s = \varepsilon_x + \varepsilon_y + \varepsilon_z$ and $\varepsilon_x = \varepsilon_y = \varepsilon_z$.

### Surface potential energy of the coal matrix

Following Myers’ work, the surface potential for the unit mass of adsorbent can be written as:

$$ \varphi = RT \ln \left( \frac{P}{1 + BP} \right) \left( \sum_{i=1}^C n_i^a \ln f_i \right), $$

where $n_i^a = \frac{LBP}{1 + BP}$; $f$ is the gas fugacity, and $P$ is the gas pressure.

With the assumption (d) that $f = P$, Equation (11) can be simplified as:

$$ \varphi = RTL \ln (1 + BP), $$

where $R$ is the ideal gas constant, $T$ is the temperature in Kelvin, and $B$ is the Langmuir constant.

Using Equation (12), the specific surface energy of the coal matrix can be written as:

$$ \gamma = \frac{RTL \ln (1 + BP)}{A} $$

where $A$ is the surface area of per unit mass adsorbent, and $\gamma$ is the specific surface energy.

With the assumption (c) that the reduction of the coal matrix surface energy is equal to the addition of its elastic energy, Equations (10) and (13) satisfy:

$$ \gamma = W_m^\sigma $$

From Equations (10), (13) and (14), $\varepsilon_m^s$ can be expressed as:

$$ \varepsilon_m^s = \sqrt{6RTL \ln (1 + BP) \left( 1 - 2\mu_m \right) \over AE_m}, $$

where $\varepsilon_m^s$ is the CMVS induced by gas adsorption.

### 3.2.3 Model of CMVS under coal seam field conditions

Based on the results of Section 3.2.1, under coal seam field conditions, the observed volumetric strain of the coal matrix represents the difference between two effects. Following Equation (3), the CMVS ($\varepsilon_m$) induced by coupling of gas pressure and gas adsorption can be expressed as:

$$ \varepsilon_m = \varepsilon_m^s + \varepsilon_m^c. $$

Substituting Equations (8) and (15) into Equation (16) leads to:

$$ \varepsilon_m = \sqrt{6RTL \ln (1 + BP) \left( 1 - 2\mu_m \right) \over AE_m} - \frac{3 \left( 1 - 2\mu_m \right)}{E_s}P. $$

### 3.3 Model of CFVS under coal seam field conditions

For the bulk coal as a porous medium, its volume satisfies:

$$ V_b = V_m + V_f, $$

where $V_b$ is the volume of the bulk coal, $V_m$ is the volume of the coal matrix, and $V_f$ is the volume of the coal fractures.

The coal fracture porosity ($\varnothing$) can be expressed as:

$$ \varnothing = \frac{V_f}{V_b}. $$

The differential form of Equation (18) is:

$$ dV_b = dV_m + dV_f. $$

Dividing both sides of Equation (20) by $V_b$ results in:

$$ d\varepsilon_b = \frac{dV_m + dV_f}{V_b}. $$

where $d\varepsilon_b$ is defined as $d\varepsilon_b = \frac{dV}{V_b}.31$

Substituting Equations (19) and (20) into Equation (21) leads to:

$$ d\varepsilon_b = \frac{(1 - \varnothing) dV_m}{V_m} + \varnothing dV_f. $$

$$ \varepsilon_b = \frac{1 - \varnothing}{V_m} dV_m + \varnothing dV_f. $$
Through further processing, Equation (22) can be expressed as.

\[
d\varepsilon_b = (1 - \theta) d\varepsilon_m + \theta d\varepsilon_f. \tag{23}
\]

where \(d\varepsilon_m\) and \(d\varepsilon_p\) are defined as \(d\varepsilon_m = \frac{dV_m}{V_m}\) and \(d\varepsilon_f = \frac{dV_f}{V_f}\), respectively.

The integral form of Equation (23) is.

\[
\varepsilon_b = (1 - \theta) \frac{d\varepsilon_m}{\theta}. \tag{24}
\]

With Equation (24), \(\varepsilon_f\) satisfies.

\[
\varepsilon_f = \varepsilon_b - (1 - \theta) \frac{d\varepsilon_m}{\theta}. \tag{25}
\]

where \(\varepsilon_f\) is the coal fracture volumetric strain under coal seam field conditions.

Substituting Equations (1) and (17) into Equation (25) leads to.

\[
\varepsilon_f = \frac{\varepsilon_b (P_L + P)}{\theta} + \frac{3 (1 - 2\mu_m) \mu_b}{\theta E_m} + \frac{3 (1 - 2\mu_b) \mu_m}{\theta E_m} P - \frac{(1 - \theta) \left( \frac{6 R T L \ln (1 + B P)}{\Delta E_m} \right)}{\theta} - \frac{3 (1 - 2\mu_m) \mu_b}{\theta E_m} P. \tag{26}
\]

BCVS under different gas pressure conditions. The experimental results indicated that there was a strong similarity between the shape of the volumetric strain curve (Figure 4B) and that of the sorption isotherm (see Figure 4A) for the same coal specimen. Therefore, a Langmuir-like curve can be used to describe the relationship between the volumetric strain of the bulk coal and the pore gas pressure.

Using the same experimental method, Levine\(^{18}\) tested the relationship between the line strain of the coal and the pore pressure under different methane and CO\(_2\) pressure conditions. The experimental results showed that the line strain and gas pressure also showed a good Langmuir-like relationship. The test results are shown in Figure 5.

Day et al\(^{20}\) tested the volumetric strains of Australian coal samples under different temperatures and pressures. The maximum pressure of CO\(_2\) was 15 MPa, and the experimental temperatures were 25°C, 40°C, and 55°C. The test results are shown in Figure 6. From the results, it is concluded that the volume strain and pore pressure under different temperature conditions also show the Langmuir-like relationship.

These scholars tested the BCVS under various conditions. The experimental results all showed that the relationship between the BCVS and the gas pressure was in line with a Langmuir-like relationship.

### 4.2 Analysis of the gas pressure effect on coal volumetric strains

The effect of gas pressure on coal volumetric strains was analyzed from the perspective of mechanics. For a homogeneous material, with a loading pressure applied over its entire outer surface (see Figure 7A), internal stress is generated inside the material. It is assumed that there is a closed surface in the material, and the stress generated on the inner side of the

\[\text{FIGURE 4} \quad \text{A. The volume of adsorbed gas with gas pressure, B. BCVS with gas pressure—Harpalani and Schraufnagel's data}^{19}\]
assumed surface equals the external stress due to the principle of forces interaction (see Figure 7B). Therefore, the mechanical behavior of the porous material under the action of external pressure and pore pressure can be considered the same as only external gas pressure loading on the homogeneous material (see Figure 7C), and when there is a pore in the interior of the material that has the same surface as the assumed surface, the gas pressure in the pore is equal to the external gas pressure.

For the coal seam under field conditions, the gas pressure within pores equals that in fractures (see Figure 1). Therefore, the coal matrix can be considered as a solid without any pores in the derivation of the gas pressure induced the CMVS. Thus, the effect of gas pressure on coal matrix deformation satisfies Equation (8) under coal seam field conditions.

When the bulk coal deformation is tested in the laboratory, it is generally carried out in the adsorption tank. Because the coal matrix was not completely separated from each other by cleats and connected by the coal bridge, both fractures and pores can be considered as the assemblage pores. After the experimental gas pressure reaches the equilibrium, the gas pressure applied to the coal sample and the gas pressure in the coal sample assemblage pores are equal to the experimental gas pressure; therefore, the effect of the gas pressure on BCVS satisfies Equation (2) under laboratory test conditions.

However, unlike laboratory test conditions, for coal seam field conditions, gas exists only in pores and fractures, and there is no gas on the outside of the coal seam (see Figure 1). Since the bulk coal is an elastic material, its stress and strain satisfy a linear relationship. Thereby, the effect of the gas pressure on the bulk coal deformation under coal seam field conditions can be obtained by measuring the influence of the gas pressure on the bulk coal stress. To avoid the influence of gas adsorption, no adsorptive gas helium was used as the experimental gas. The testing system is shown in Figure 8. During the test, the axial displacement of the coal sample was constrained, and a constant confining pressure of 4 MPa was applied in the radial direction. After the coal sample was stable, the gas valve was opened, and the coal sample was filled with helium. Due to the swelling effect of helium pressure on the coal sample and the constraint of the axial displacement, the swelling stress occurred in the axial direction and was collected by a pressure sensor.

A total of three coal samples were tested. Figure 9 represents the changes in stress with respect to the helium pressure. From Figure 9, it is concluded that the changes in stress increase with increasing helium pressure, they are linear in relation to helium pressures and can be expressed as $aP$. This indicates that the gas pressure exerts an expansion on the bulk coal under coal seam field conditions, and the BCVS induced by the gas pressure can be expressed as Equation (5).

As stated above, the gas pressure plays an opposite role in the bulk coal deformation between the laboratory test conditions and coal seam field conditions. Under the laboratory test conditions, the gas pressure exerts a compressive effect on the bulk coal. However, under the coal seam field conditions, the gas pressure has a swelling effect on the bulk coal. Therefore, the bulk coal deformation model determined in the laboratory must be corrected to meet the coal seam conditions, and the BCVS model proposed in this paper is more in line with the coal seam field conditions.

In addition, the deformation of coal fracture is the coupling of coal matrix and bulk coal. According to the coal seam physical structure (see Figure 1), the shrinkage of the matrix and the swelling of the bulk coal lead to the expansion of the coal fracture. Based on the effect mechanism of gas pressure on coal matrix and bulk coal, it is concluded that the gas pressure has a swelling effect on the coal fracture under coal seam field conditions.
There are no suitable methods to directly measure the coal fracture and coal matrix deformations in the process of gas adsorption. The models of CMVS and CFVS under coal seam field conditions were theoretically analyzed in this section.

The model of coal matrix deformation induced by gas adsorption assumes that the deformation elastic energy of the coal matrix is equal to its surface energy reduction. This hypothesis had been applied by many scholars. Scherer used the hypothesis to establish the glass deformation equation of water vapor adsorption, and the established model showed a good agreement with the experimental data. On the basis of Scherer’s work, Pan and Connell also used the same assumption to establish the coal deformation model. The established model and experimental data also maintained a high degree of agreement. Therefore, the gas adsorption-induced coal matrix strain model established in this paper can be considered reliable.

On the basis of models of coal matrix deformation induced by gas pressure and gas adsorption, the CMVS model by coupling of gas pressure and gas adsorption under coal seam conditions was established. All parameters in this model have physical meanings, and the establishment of this model fully considers the coal seam field conditions.

According to the relationship among the bulk coal volume, the coal matrix volume, and the coal fracture volume, the relationship among CBVS, CMVS, and CFVS was first established. With the models of CBVS and CMVS, the CFVS model was obtained. Compared with the previous CFVS
models, that were \( \varepsilon_1 = \varepsilon_b^{10.24} \) and \( \varepsilon_1 = \psi_p (\varepsilon_b) \). The derivation of the CFVS model proposed in this paper has a rigorous mathematical process, which more accurately reflects the CFVS under the mutual coupling of the coal matrix deformation and the bulk coal deformation in coal seam field conditions. The CFVS model proposed in this paper may help to establish the coalbed permeability model to better describe the evolution of coalbed permeability during gas recovery.

5 | CONCLUSIONS

Based on coal’s physical structure, coal seam field conditions, the energy balance approach, poroelasticity, mathematical differentiation, and previous scholars’ research, this paper presented three models to describe coal deformation induced by gas under coal seam field conditions, including the CBVS model (Equation 7), CMVS (Equation 17), and the CFVS model (Equation 26). These models fully consider the nature of the coal seam field conditions and were able to better reflect the coalbed permeability caused by gas.

According to the analysis of the gas pressure effect on bulk coal deformation under laboratory test conditions and coal seam field conditions, gas pressure has an opposite effect on the bulk coal deformation between laboratory test conditions and coal seam field conditions. When the bulk coal is tested in a laboratory, the gas pressure exerts a compressive effect on the bulk coal. However, under coal seam field conditions, the gas pressure has a swelling effect on the bulk coal. Furthermore, the effect of the gas pressure on the coal matrix and fracture was also revealed to exert a compressive effect on the coal matrix and a swelling effect on the coal fracture under coal seam field conditions. The bulk coal deformation model determined in the laboratory must be corrected to meet the coal seam conditions.

Finally, the established models were analyzed and verified from multiple perspectives, and it is concluded that these models are all accurate and reliable. However, due to the limitation of experimental conditions, the models of CMVS and CFVS have not been experimentally verified. More in-depth research is needed to verify and discuss the CMVS and CFVS models.

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