1 INTRODUCTION

As an important source of fossil energy, coal contributes the rapid development of the world economy. However, the mine gas disasters—coal and gas outburst, gas explosion, often occur accompanying coal mining. Underground gas drainage has been proved as an effective approach to eliminate gas disaster. The complex geological condition results in the low permeability and large gas content in coal seam. How to improve the efficiency of gas drainage is an urgent issue.

Injection of foreign gases into coal seam is considered an effective method to enhance gas drainage. This process relates complex responses among ternary gases (CH4, CO2, and N2) competitive sorption on coals, gas diffusion, gas-water migration by means of two-phase flow, and coal deformation. In this paper, an improved hydraulic-mechanical model coupling above interactions is established for flue gas injection enhanced gas drainage. This model is used to simulate flue gas enhanced drainage by finite element method. The sensitivity analyses of key factors are made to recover a better understanding on the processes controlling flue gas enhanced drainage. Results show that the flue gas enhanced drainage can indeed improve the efficiency of gas extraction and reduce the gas pressure to the required value in a shorter duration. Due to the competitive adsorption and gas sweeping effect of injected flue gas, CH4 is driven toward drainage borehole, and CH4 pressure and content near the injection borehole decrease faster than that near the drainage borehole. The peak CH4 pressure laterally moves from the injection borehole to the drainage borehole. Higher injection pressure, initial permeability, and smaller sorption affinity ratios may lead to greater CH4 production rate at early drainage stage, but smaller CH4 production rate at late stage. The factors controlling the behavior of flue gas enhanced drainage are initial permeability, injection pressure, and sorption affinity ratios in order. This work offers useful framework to investigate important technical challenges associated with enhanced mine gas drainage, as well as unconventional gas development.

KEYWORDS
coal seam gas, enhanced drainage, flue gas, hydraulic-mechanical coupling, numerical simulation
process expedites the gas transport by competitive sorption and sweeping effects and maintaining pressure gradient between coal seam and borehole.\textsuperscript{17-21} The gases commonly used as injectants are nitrogen (N\textsubscript{2}), carbon dioxide (CO\textsubscript{2}), and gas mixture (N\textsubscript{2}/CO\textsubscript{2}).\textsuperscript{22,23} CO\textsubscript{2} injection in coal seam may cause great adsorption-induced swelling and reduce the coal permeability, which in turn hinders injection operation.\textsuperscript{24-26} Hence, CO\textsubscript{2} injection is usually applied to coal seam with high permeability. Compared to CO\textsubscript{2} injection, N\textsubscript{2} injection may be more suitable for low permeability seam due to its lower sorption affinity on coal (approximately one-fourth of CO\textsubscript{2}) and thus smaller induced swelling.\textsuperscript{17,27,28} However, the small viscosity of N\textsubscript{2} may result in the early breakthrough of N\textsubscript{2} as well as a large amount of injection volume. Injection of gas mixture (flue gas) can balance the excessive CO\textsubscript{2} adsorption-induced swelling and the early N\textsubscript{2} breakthrough induced huge injection volume.\textsuperscript{29-31}

The flue gas injection enhanced coal seam gas drainage involves the interactions among ternary gases (CH\textsubscript{4}, N\textsubscript{2}, and CO\textsubscript{2}) co-adsorption, gas diffusion, gas-water migration by means of two-phase flow, and stress evolution caused coal deformation.\textsuperscript{32-34} Due to these complex responses, the field and laboratory tests are difficult and almost nonrepeatable.\textsuperscript{35,36} So far, simulations were widely conducted to give a scientific insight into gas injection enhanced drainage.\textsuperscript{37} Durucan and Shi\textsuperscript{14} carried out a simulation of gas injection in coalbeds to investigate the overall injection performances. Wu et al.\textsuperscript{38} numerically investigated CO\textsubscript{2}-ECBM recovery combining the infiltration and diffusion of binary gases (CO\textsubscript{2}, CH\textsubscript{4}), competitive sorption and deformation. Ren et al.\textsuperscript{27} proposed a binary gas transport model for N\textsubscript{2} injection enhanced gas drainage. Lin et al.\textsuperscript{39,40} investigated the N\textsubscript{2} and CO\textsubscript{2} adsorption-induced coal matrix swelling, and its impact on N\textsubscript{2} injection enhanced gas drainage in CO\textsubscript{2}-rich coal seam by conducting experiments. Wang et al.\textsuperscript{41} determined the diffusion coefficient of CO\textsubscript{2} and CH\textsubscript{4} diffusion in coal. Ma et al.\textsuperscript{42} analyzed the influence of groundwater migration on the mechanical properties of coal seam. Wang et al.\textsuperscript{43,44} studied the microscopic structure, coal deformation, gas and water transport behaviors in heterogenous coal by CT three-dimensional reconstruction. The processes of mixture adsorption, mass transfer within fractures and matrix, mass migration in fractures governed by thermo-hydro-mechanical responses.\textsuperscript{45-47} These investigations provide a useful theoretical basis for gas injection enhanced drainage. But, the established models were either not fully coupled or one or more critical interactions were ignored. These include the incorporation of the role of binary gas transport, sorption between matrix and fractures, and two-phase flow in water-rich reservoir. Therefore, a more comprehensive coupled model for flue gas enhanced drainage needs to be further developed.

In this paper, we will develop an improved hydraulic-mechanical (HM) model, including the governing equations of gas competitive sorption, mass transport by means of diffusion in matrix and two-phase flow in fractures, and the coupling terms of porosity and permeability. This model is applied to simulate and explore the evolutions of key parameters during regular and flue gas enhanced drainages, followed by sensitivity analyses on influencing factors of initial permeability, injection pressure, and sorption affinity ratios ($R_{nm}$, $R_{cm}$). The result will give an insight into the key processes controlling flue gas enhanced drainage.

## 2 | MATHEMATICAL MODEL FOR FLUE GAS ENHANCED COAL SEAM GAS DRAINAGE

The gas and water migration law during mine gas drainage is greatly affected by the coupling relations between hydraulic and mechanical fields. The hydraulic field includes the processes of competitive adsorption of flue gas (CO\textsubscript{2}, N\textsubscript{2}) and CH\textsubscript{4} in coal matrix, gas diffusion between matrix and fractures, and gas and water mixture seepage in fractures. The involved processes are affected by the evolutions of permeability and porosity caused by the change in effective stress. Due to rich in formation water within natural fractures, gas migration at the initial stage is largely hindered by the low gas relative permeability. Additionally, the effective stress will be altered when the operation of gas drainage and injection continues, as the pressure of CH\textsubscript{4} decreases and of CO\textsubscript{2} and N\textsubscript{2} increases. Gas and water mixture transport within the pores and fractures will in turn cause coal deformation in mechanical field. In the following sections, a fully coupled HM model will consider above interactions.

Due to the complexity of the HM model, the following assumptions are adopted:\textsuperscript{12,27,29,38,47-49} (a) coal seam is assumed as a dual-porosity (fractures and matrix pores) single-permeability elastic medium; (b) the free gases conform to the ideal gas law, and they exist and migrate in the space of fractures and pores; (c) the adsorbed gas exists on the surface of pores, and water only migrates in fractures; (d) for the transport of methane, it first desorbs from the surface of matrix pores—Langmuir equation, then diffuses from the pores to the fractures—Fick’s law, and finally seepages from fractures to drainage borehole—Darcy’s law; while for the injected flue gas, the transport direction is opposite—gas mixture first seepages from the injection borehole to the fractures, then diffuses from the fractures to the matrix, followed by the competitive adsorption with CH\textsubscript{4} on pore surfaces. The mass transport of gas and water mixture in the process of flue gas enhanced drainage is shown in Figure 1.
2.1 | Governing equations for hydraulic field

2.1.1 | Gas migration in the coal matrix

In the space of pores and fractures, ternary gases (CH₄, CO₂, and N₂) are in the state of free which obeys the ideal gas law:

\[ \rho_g = \frac{M_g}{RT} p_g, \]  

where subscript “i” denotes for gas component (i = 1 for CH₄, i = 2 for CO₂ and i = 3 for N₂), \( p_g \) is gas pressure, Pa; \( T \) is gas temperature, K; \( M_g \) is the molar mass, g/mol; \( R \) is gas molar constant, J/(mol K).

The gas content is defined as the adsorbed gas volume per unit mass. A modified Langmuir Equation is applied to calculate the gas content:

\[ V_{sgi} = \frac{V_L b_L p_{mg_i}}{1 + (b_{L1} p_{mg1} + b_{L2} p_{mg2} + b_{L3} p_{mg3})}, \]

where \( p_{mg} \) means the gas pressure in coal matrix, Pa; \( V_L \) means the Langmuir volume constant, m³/kg; \( b_L \) means the Langmuir pressure constant, 1/Pa.

Gas migration in the coal matrix is largely controlled by the concentration-gradient driven diffusion satisfying the Fick’s law. CH₄ desorbs from the pore surface into pore space and then diffuses to the fractures, while flue gas (CO₂ and N₂) has the opposite migration direction. The initially dynamic sorption/desorption equilibrium state will be broken by gas drainage and injection operations. By using the mass conservation law and Fick’s law, the gas migration in matrix is defined as:

\[ \frac{\partial}{\partial t} \left( \phi_m p_{mg_i} + V_{sgi} \rho_c \rho_{gs} \right) = -D_i \frac{M_g}{RT} \left( p_{mg_i} - p_{fgi} \right), \]  

where \( D \) is the gas diffusion coefficient, m²/s; \( \delta \) is the shape factor of cubic coal matrix blocks; \( \rho_c \) is the coal density, kg/m³; \( \rho_{gs} \) is the gas density under standard condition, kg/m³; and \( p_{fgi} \) is gas pressure in fractures.

By defining \( \tau = 1/D \delta \) as the desorption time and substituting Equations 1 and 2 into Equation 3, the equation for gas transport in coal matrix can be obtained:

\[ \phi_m \frac{M_g}{RT} \frac{\partial p_{mg_i}}{\partial t} + \frac{M_g}{RT} \rho_c \phi_m \rho_{gs} \frac{\partial}{\partial t} \left( \frac{V_L b_L p_{mg_i}}{1 + \sum_{i=1}^{3} b_{L_i} p_{mg_i}} \right) \]

\[ = - \frac{M_g}{\tau_i RT} (p_{mg_i} - p_{fgi}). \]

2.1.2 | Gas migration in the fractures

As gas drainage and injection proceeding, the fractures are filling with preexisting methane, water, and injected flue gas. For CH₄ migration in the fractures, gas desorption from the
coal matrix provides a mass source and drainage borehole acts as a mass sink; while for flue gas migration, the injection borehole provides a mass source and the adsorption of flue gas in matrix acts as a mass sink. The gas migration in fractures is defined as\textsuperscript{23,29}:

$$\frac{\partial (s_g \phi_l p_{tg})}{\partial t} + \nabla \cdot \left( \rho_{tg} q_{gi} \right) = \frac{1}{\tau_i} \frac{M_{gi}}{RT} (p_{mgi} - p_{tg}),$$  \hspace{1cm} (5)

where $s_g$ is the gas saturation in fracture; $\rho_{tg}$ is the gas density in fracture, kg/m\textsuperscript{3}; $q_{gi}$ is the gas transport velocity, m/s.

By applying the generalized Darcy’s law (gas-water two-phase flow) and considering the Klinkenberg effect, the gas seepage velocity within fractures is defined as\textsuperscript{50}:

$$q_{gi} = -\frac{k k_{tg}}{\mu_{tg}} \left( 1 + \frac{b_k}{p_{tg}} \right) \nabla p_{tg},$$ \hspace{1cm} (6)

where $k$ is the absolute permeability, m\textsuperscript{2}; $k_{tg}$ is gas relative permeability; $\mu_{tg}$ is the dynamic viscosity, Pa·s; $b_k$ is the Klinkenberg factor, Pa.

The capillary pressure in the fractures has been ignored. The Corey model has been used to evaluate gas/water relative permeability as follows\textsuperscript{51,52}:

$$s\w^{*}_w = \frac{s_w - s_{wr}}{1 - s_{wr}} \bigg| \begin{cases} \text{a} \\ \text{b} \end{cases}$$  \hspace{1cm} (7)

where $k_{tw}$ is the water relative permeability; $s_{wr}$ is the irreducible water saturation; $s_w$ is the water saturation.

Substituting Equations 6 and 7 into Equation 5, the governing equations for gas migration in fractures can be formulated:

$$\frac{s_g \phi_l}{\partial t} + \frac{\partial (s_g \phi_l p_{tg})}{\partial t} + s_g \phi_l \frac{\partial q_{gi}}{\partial t} + \nabla \cdot \left( \frac{k k_{tg}}{\mu_{tg}} \left( 1 + \frac{b_k}{p_{tg}} \right) \nabla p_{tg} \right) = \frac{1}{\tau_i} \frac{M_{gi}}{RT} (p_{mgi} - p_{tg}).$$  \hspace{1cm} (8)

where $p_{tg}$ is water pressure in fractures, Pa; $\rho_{tg}$ is water density, kg/m\textsuperscript{3}; $q_{gi}$ is the velocity of water, m/s; $\mu_{tg}$ is the dynamic viscosity of water, Pa·s.

Rewriting Equation 9, the governing equation for water migration in fractures can be obtained as:

$$\frac{\partial (s_w \phi_l p_w)}{\partial t} + \nabla \cdot \left( \rho_w q_w \right) = 0,$$  \hspace{1cm} (9)

$$q_w = -\frac{k k_{tw}}{\mu_w} \nabla p_{tw},$$

2.2 | Governing equations for mechanical field

The impact of geostress, gas pressure in pores/fractures and gas ad/desorption on coal skeleton will alter the deformation of coal seam. Considering the coal deformation induced by gas mixture pressure in pores and fractures (effective stress), and shrinkage/swelling resulted from gas ad/desorption, the total strain for coal seam can be expressed as\textsuperscript{12,38}:

$$\epsilon_{kl} = \frac{1}{2G} \sigma_{kl} - \left( \frac{1}{6G} - \frac{1}{9K} \right) \sigma_{ar} \delta_{kl} + \alpha_s p_m a_s + \alpha_t p_t a_t + \frac{\alpha_s}{3} \delta_{kl}$$  \hspace{1cm} (11)

where,$$

$$\left\{ \begin{array}{l}
G = D/2(1 + v)  \\
D = 1/\left[ 1/E + 1/(a \cdot K_n) \right]  \\
K = D/(1 - 2v)  \\
\alpha_m = 1 - K/K_s  \\
\alpha_t = 1 - K/(a \cdot K_n)
\end{array} \right\},$$

and $G$ is the effective bulk modulus of coal seam, Pa; $D$ is the effective elastic modulus, Pa; $K_s$ is the normal stiffness of fracture, Pa/m; $K$ is bulk modulus, Pa; $v$ is Poisson’s ratio; $a$ is the width of coal matrix, m; $E$ is elastic modulus, Pa; $\delta_{kl}$ is the Kronecker delta; $\alpha_m$ and $\alpha_t$ are the Biot effective stress coefficient for coal matrix and fracture, respectively; $K_s = E_s/(3(1 - 2v))$ is the skeleton bulk modulus, Pa; $E_s$ is the skeleton elastic modulus, Pa; $v_s$ is volumetric strain of matrix swelling/shrinkage induced by gas ad/desorption.

The gas sorption on coal matrix will cause coal deformation by means of swelling/shrinkage. For FG-ECMG, the gas sorption induced strain is the overlying of the swelling effect resulted from CO\textsubscript{2} and N\textsubscript{2} adsorption and the shrinkage effect...
resulted from CH₄ desorption. The Langmuir-type equation is applied to express the ternary gas mixture sorption induced volume strain⁵³,⁵⁴:

\[ \varepsilon_a = \sum_{i=1}^{3} \varepsilon_{ai} = \sum_{i=1}^{3} \frac{\varepsilon_i b_i p_{mgi}}{1 + (b_{i1} p_{mgi} + b_{i2} p_{mgi}^2 + b_{i3} p_{mgi}^3)}, \]  

(12)

where \( \varepsilon_i \) is the Langmuir-type strain coefficient, which means the maximum deformation capacity induced by sorption; \( b_i \) is the Langmuir-type pressure coefficient, Pa.

The Cauchy formula describes the strain-displacement relation⁵⁰:

\[ \varepsilon_{kl} = \frac{1}{2} (u_{k,l} + u_{l,k}), \]  

(13)

where \( u_k \) is the coal deformation at the \( k \) direction, m.

And the stress equilibrium equation gives the state of stress balance with the coal-gas-water system, which is expressed as:

\[ \sigma_{kl,l} + F_k = 0, \]  

(14)

where \( F_k \) is the volumetric force, N.

Combining Equations 11-14, the governing equation for coal deformation (mechanical field) can be acquired:

\[ Gu_{k,ll} + \frac{G}{1 - 2\nu} u_{l,kk} - (\alpha_m p_{m,k} + \alpha_p p_{l,k}) - K \left( \sum_{i=1}^{3} \frac{\varepsilon_i b_i p_{mgi}}{1 + \sum b_{ij} p_{mgi}} \right)_k + f_k = 0. \]  

(15)

2.3 Key coupling terms—porosity and permeability

As mentioned in assumption, the coal seam is a dual-porosity and single-permeability medium containing both fractures and matrix pores. The porosity of fracture and pore provides the storage and migration space for gas and water, while the permeability is a key parameter to evaluate the migration capacity of gas and water in coal seam. Both porosity and permeability will greatly affect the operation of gas drainage and flue gas injection. Since the porosity is sensitive to the stress state and the material properties of coal seam, the change in effective stress and gas sorption will alter the magnitude of porosity. The porosity model for matrix pores can be defined as⁵⁵,⁵⁶:

\[ \phi_m = \phi_{m0} + \frac{(\alpha_m - \phi_{m0})[(\varepsilon_v + p_m/K_s - \varepsilon_a) - (\varepsilon_v + p_{m0}/K_s - \varepsilon_a)\]}{[1 + (\varepsilon_v + p_m/K_s - \varepsilon_a)]}, \]  

(16)

where the subscript “0” represents the initial parameter value; \( \varepsilon_v \) is the volume strain of coal.

According to our previous works, the fracture porosity can be defined as follows¹⁰,³⁷:

\[ \phi_f = \phi_{f0} \left( 1 + \frac{\Delta b}{b} \right) = \phi_{f0} + \frac{\phi_{f0} K_m}{3 (K_f a s_3 + K_m K_m - K_m a s_3)} \left( r_{as}^3 \Delta \sum_{i=1}^{3} \varepsilon_{ai} + \Delta \varepsilon, + \frac{r_{as}^3}{K_m a_m a_m p_{mg}} \right). \]  

(17)

where \( K_f \) is the modified fracture stiffness, Pa; \( K_m \) is the matrix bulk modulus, Pa; \( r_{as} = a(a + b) \) is the ratio of matrix width to the REV length.

The cubic law between fracture porosity and permeability is adopted⁵⁷,⁵⁸:

\[ \frac{k}{k_0} = \left( \frac{\phi_f}{\phi_{f0}} \right) \left[ 1 + \frac{K_m}{3(K_f a s_3 + K_m K_m - K_m a s_3)} \left( r_{as}^3 \Delta \sum_{i=1}^{3} \varepsilon_{ai} + \Delta \varepsilon, + \frac{r_{as}^3}{K_m a_m a_m p_{mg}} \right) \right]^{a}. \]  

(18)

where \( k_0 \) is the initial permeability of fracture, m².

The above-governing equations of both hydraulic and mechanical fields—Equations 4, 8, 10, and 15, along with the porosity and permeability—Equations 16 and 18, are assembled to establish the HM coupling model. This mathematic model includes several partial differential equations (PDEs), which are difficult to calculate theoretic solutions. Hence, we implement these equations into finite element method-based software to obtain numerical results.

3 SIMULATION OF FLUE GAS ENHANCED UNDERGROUND COAL SEAM GAS DRAINAGE

3.1 Objective and model geometry

The Changping coal mine is located in the middle of the Qinshui Coalfield in Shanxi Province, China, as shown in Figure 2. The stratum formation of Changping coal mine contains four layers of minable coal seam from top to bottom. They are the Nos. 2 and 3 coal seams in Shanxi group and the Nos. 8 and 15 coal seams in Taiyuan group.

No. 3 coal seam located in the lower part of Shanxi Formation is the stable mineable coal seam in the whole area. The thickest coal seam is 6.35 m, the thinnest is 4.6 m, and the average thickness is 5 m. It belongs to the gas content of the No. 3 coal seam—research target seam is 3.92-23.62 m³/t with an average value 13.77 m³/t. The results of experiments on isotherm sorption of gases (CH₄, N₂, and CO₂) on Changping coal samples are shown in Figure 3. The curve of absorbed methane volume is used to calculate the initial gas...
pressure. When the gas content is 13.77 m³/t, the gas pressure equals 3.24 MPa.

As shown in Figure 4, a rectangular geometry with 10 m × 5 m is used to simulate the process of flue gas injection enhanced underground coal seam gas drainage (flue gas enhanced drainage). Two boreholes are arranged in the geometry. The left borehole is for flue gas injection, and the right borehole is for gas drainage. The initial permeability in coal seam is 0.524 mD, the temperature is 305.5 K, initial water saturation is 0.82, and Young’s modulus of coal seam is 2.713 GPa. The drilled borehole is 100 m in length and 96 mm in diameter, which is the commonly used size of directional drilling bit in China. For hydraulic field, a constant pressure of 85 kPa is set on the boundary of drainage borehole. For the injection borehole, the injection pressure of flue gas is set as 4 MPa with N₂:CO₂ = 0.85:0.15. It will undoubtedly increase the workload of numerical calculation if the whole working face is simulated. For coal seam, each gas injection hole is separated by a gas drainage hole, indicating the geometry is symmetrical. According to the previous assumption that the coal seam is isotropic material, the flow and stress fields are symmetrical. The external boundaries are insulated for mass transport, except for the injection and production wells. For mechanical field, the slip condition is applied to the bottom boundary. The weight of overlying strata—15 MPa is adopted on the top boundary, and the symmetric condition is set to both left and right boundaries. Other related parameters
are listed in Table 1. These parameters are mainly recovered from field tests, laboratory experiments and recorded in the public literatures.1,8,11,12,27-29,37-39

As a contrast, the regular coal seam gas drainage (regular drainage) is investigated. Under this condition, the gas injection borehole is replaced by drainage boreholes. Namely, both two boreholes in the geometry are set as drainage borehole with constant gas pressure of 85 kPa. The section A-B and middle point C in the model are used to monitor the parameter evolutions in coal seam during regular drainage and flue gas enhanced drainage.

### 3.2 | Result comparisons between regular and flue gas enhanced drainages

In this section, the regular and flue gas enhanced drainages are simulated for 4 months using the established HM coupling model. The results of gas pressure, gas content, and gas production are comparatively analyzed. Figures 5 and 6 show the gas pressure (CH$_4$) distribution in the coal seam after 10, 30, 60, and 120 days of regular and flue gas enhanced drainages. With the drainage time increasing, the gas pressure in the coal seam decreases, especially in the zone near the drainage/injection borehole. As presented in Figure 5, the gas pressure decreasing zone has asymmetrical phenomena. However, as shown in Figure 6, the shape of this decreasing zone is always asymmetric as the gas pressure near the injection borehole decreases faster than that near the drainage borehole resulted by the competitive adsorption and sweeping effect of the injected flue gas.

Figure 7 shows movement of the peak CH$_4$ pressure within the simulated 4 months. It can be seen the gas pressure drops quickly in the first month due to the great pressure gradient between coal seam and drainage borehole, and then gas pressure drops slowly, especially in the last month, due to the dropped low-pressure gradient. For the regular gas drainage, the peak gas pressure always occurs at the middle position of the simulated geometry, and the movement curve is a vertical line. For the flue gas enhanced gas drainage, the peak gas pressure laterally moves from the left boundary (injection borehole) to the right boundary (drainage borehole), and the moving trajectory is an inclined line.

Figure 8 illustrates the evolution of CH$_4$ content on the position of the simulated geometry, and the movement curve is a vertical line. For the flue gas enhanced gas drainage, the peak gas pressure laterally moves from the left boundary (injection borehole) to the right boundary (drainage borehole), and the moving trajectory is an inclined line.
drainage and only one for flue gas enhanced drainage, and initially the injected flue gas transports limited distance, the CH₄ content of flue gas enhanced drainage first decreases slower and then decreases faster than that of regular drainage.

For flue gas enhanced drainage, the variation of gas content of injected CO₂ and N₂ on the section A-B after 10, 30, 60, and 120 days’ drainage is shown in Figure 10. N₂ has the smaller adsorption affinity to coal than CO₂, as the gas content of CO₂ near injection borehole is ~10 m³/t and that of N₂...
is ~4.6 m³/t. Apparently, N₂ transports faster than CO₂ does. For instance, the CO₂ content at 5 m distance is 1.01, 1.12, 1.54, 2.88 m³/t at 10, 30, 60, and 120 days, respectively, while N₂ content is 0.32, 1.34, 2.62, 3.9 m³/t.

In order to evaluate the efficiency of enhancement, we compared the production rate of enhanced drainage to both conditions of single-hole and total (two-hole) production rate of regular drainage. Figure 11A shows the variation of CH₄ production rate during regular and flue gas enhanced drainages. The initial CH₄ production rate of regular drainage is greater than that of flue gas enhanced drainage. With the increase of time, CH₄ production rate decreases quickly due to the drop of gas pressure gradient within coal seam and drainage borehole. Gas is forced to migrate from the injection borehole to the drainage borehole by displacement effect of injected flue gas. When the gas drainage/injection operation takes place for 16 days, the CH₄ production rate of the two methods is the same, namely ~706 m³/d. At the late stage of operation, a large part of CH₄ has been extracted out, and the low-pressure gradient leads to small CH₄ production rate, especially for flue gas enhanced drainage method. The average total and single-hole production rates of regular drainage are 386.6 and 193.3 m³/d, and the average total production rate of flue gas enhanced drainage is 407.4 m³/d, which shows a priority of flue gas enhanced drainage.

Due to the large partial injection pressure and small dynamic viscosity of N₂, the high N₂ injection and production rates are obviously recovered from Figure 11B. On the contrary, the injection and production rates of CO₂ are relatively low. The strong adsorption capacity and large dynamic viscosity together with the small partial gas pressure result in almost no CO₂ production throughout the whole process. The total gas production rate of flue gas enhanced drainage is much greater than both total and single-hole rate of regular drainage. Hence, the flue gas enhanced drainage can indeed improve the efficiency of gas extraction and reduce the gas pressure in coal seam to the required value in a shorter duration than regular drainage.

4 | SENSITIVITY ANALYSES ON KEY FACTORS OF FLUE GAS ENHANCED DRAINAGE

In this section, we will discuss some key factors that influence the simulated results during flue gas enhanced drainage,
including the injection pressure, initial permeability, and sorption affinity ratios of CO₂/CH₄ and N₂/CH₄. Here, the sorption affinity ratio of CO₂/CH₄ ($R_{cm}$) is defined as the proportion of Langmuir volume constant of carbon dioxide to that of methane, and the sorption affinity ratio of N₂/CH₄ ($R_{nm}$) is defined as the proportion of Langmuir volume constant of nitrogen to that of methane.

4.1 Influence of injection pressure

As shown in Figure 12A,B, both CO₂ and N₂ injection rates increase with the increase of injection pressure of flue gas. Making the case of injection pressure of 3.5 MPa as a reference, the average CO₂ injection rate for injection pressure of 4, 4.5 and 5 MPa is increased by 10.42%, 20.59%, and 31.49%, and the average N₂ injection rate is increased by 17.2%, 36.71%, and 59.18%, respectively. Apparently, the injection pressure has greater impact on the N₂ injection rate than that on CO₂ injection rate.

The variation of N₂ and CH₄ production rates with injection pressure is shown in Figure 12C,D. A higher injection pressure will result in greater N₂ production rate and earlier breakthrough of injected N₂ at the drainage borehole. The average N₂ production rate throughout the operation is 62.35, 97.13, 142.23, and 196.43 m³/d for the injection pressure of 3.5, 4, 4.5, and 5 MPa, respectively. As illustrated in Figure...
12D, at the early stage, higher injection pressure will lead to greater CH\(_4\) production rate. However, at the late stage, the higher the injection pressure, the smaller the CH\(_4\) production rate. This is because when the injection pressure is high, CH\(_4\) pressure gradient between coal seam and drainage borehole drops to low magnitude which restricts the CH\(_4\) migration to drainage borehole. Hence, a very high injection pressure is not an ideal operation parameter, as it requires higher equipment, dissipates more energy and is difficult to obtain more gas production.

### 4.2 Influence of initial permeability

As presented in Figure 13A,B, CO\(_2\) and N\(_2\) injection rates increase with the initial permeability of coal seam. When initial permeability is 2.62, 5.24, 7.86, and \(10.48 \times 10^{-17}\) m\(^2\), the average CO\(_2\) injection rate is 26.78, 46.09, 64.82, and 81.58 m\(^3\)/d, and the average N\(_2\) injection rate is 146.69, 263.48, 376.12, and 486.88 m\(^3\)/d, respectively. From the perspectives of the increase magnitudes of injection rate, the permeability of coal seams has a great influence on the law of gas migration.

As illustrated in Figure 13C, the greater initial permeability, the higher N\(_2\) production rates, and earlier N\(_2\) breakthrough. The average N\(_2\) production rate is 10.78, 97.13, 223.35, and 358.89 m\(^3\)/d for the initial permeability of 2.62, 5.24, 7.86, and \(10.48 \times 10^{-17}\) m\(^2\), respectively. And the breakthrough time is 67, 33, 21, and 16 days, respectively. In Figure 13D, greater permeability usually has higher initial CH\(_4\) production rate, but lower CH\(_4\) rate in the late stage. This verifies the CH\(_4\) pressure within the coal seam has been depleted, which can hardly motivate CH\(_4\) transport into the drainage borehole. Increasing
permeability can quickly reduce coal seam gas and achieve the purpose of preventing gas disasters.

4.3 Influence of sorption affinity ratio of CO₂/CH₄ ($R_{cm}$)

We keep the Langmuir volume constant of CH₄ as $V_{L1} = 0.0196 \text{ m}^3/\text{kg}$ and change the Langmuir volume constant of CO₂ ($V_{L2}$) to obtain the influence of sorption affinity ratio of CO₂/CH₄ ($R_{cm}$) on the behavior of FG-ECMG drainage, as presented in Figure 14. The sorption affinity ratio of CO₂/CH₄ ($R_{cm}$) has greater influence on CO₂ injection rate than that on N₂ injection rate. In other words, the Langmuir volume constant of CO₂ contributes more to CO₂ injection rate, but less to the N₂ injection rate. Making the case of $R_{cm} = 1.15$ as a reference, the average CO₂ injection rate for $R_{cm} = 1.35$, 1.55, and 1.75 is increased by 3.76%, 7.12%, and 10.21%, and the average N₂ injection rate is increased by 0.51%, 0.92%, and 1.31%, respectively.

In Figure 14C, greater sorption affinity ratio of CO₂/CH₄ ($R_{cm}$) will lead to higher N₂ production rates although the increasing magnitude is small. Compared to N₂ production rate, CH₄ production rate has a little influence from the change in the Langmuir volume constant of CO₂ as shown in Figure 14D.

4.4 Influence of sorption affinity ratio of N₂/CH₄ ($R_{nm}$)

Keeping $V_{L1} = 0.0196 \text{ m}^3/\text{kg}$ as a constant, the evolution of injection and production rates of FG-ECMG resulted from the change in Langmuir volume constant of N₂ ($V_{L3}$) is shown in
As illustrated in Figure 15A, B, with the increase of sorption affinity ratio of N₂/CH₄ ($R_{nm}$), the CO₂ injection rate decreases, while N₂ injection rate increases. This implies that stronger sorption affinity of N₂ on coal usually raises the adsorbed N₂ in coal seam and increases the N₂ injection rate.

In Figure 15C, greater sorption affinity ratio of N₂/CH₄ ($R_{nm}$) always results in a lower N₂ production rate and a later arrive of N₂ breakthrough. Specifically, for $R_{nm} = 0.55, 0.65, 0.75, \text{ and } 0.85$, the average N₂ production rate is 118.67, 107.68, 97.14, and 87.26 m³/d, and the breakthrough time is 26, 29, 33, and 36 days, respectively. As presented in Figure 15D, greater sorption affinity ratio of N₂/CH₄ ($R_{nm}$) will lead to lower CH₄ production rate at the early stage, but higher CH₄ production rate at the late stage.

From the above analyses, it can be known that the initial permeability may be the significant factors controlling the behavior of flue gas enhanced drainage, followed by the injection pressure, and sorption affinity ratios. The influence of sorption affinity ratios on flue gas enhanced drainage is the result of competitive adsorption among CH₄, N₂, and CO₂.

**5 | CONCLUSIONS**

In this paper, we established an improved HM coupling model, which is used to simulate flue gas injection enhanced coal seam gas drainage. Sensitivity analyses are conducted on the key factors in this process. The result provides a better...
understanding on the processes controlling flue gas enhanced drainage. Conclusions are recovered as follows:

1. The established HM model couplings the responses of coal deformation, mass transport by means of two-phase flow, and competitive adsorption of gas ternary gases (CH₄, CO₂, and N₂) on coal. These governing equations together with porosity and permeability are partial differential equations and can be solved by FE method to explore the regularity of flue gas enhance drainage.

2. Due to the competitive adsorption and gas sweep effect of injected flue gas, CH₄ is driven toward the drainage borehole, and CH₄ pressure and content near the injection borehole decrease faster than that near the drainage borehole. The peak CH₄ pressure laterally moves from the injection borehole to the drainage borehole.

3. The total gas production rate of flue gas enhanced drainage is much greater than both total and single-hole rates of regular drainage. Hence, the flue gas enhanced drainage can indeed improve the efficiency of gas drainage and reduce gas pressure in coal seam to the required value in a shorter duration.

4. Higher injection pressure, initial permeability and smaller sorption affinity ratios may lead to greater CH₄ production rate at early drainage stage, but smaller CH₄ production rate at late stage. The factors controlling the behavior of flue gas enhanced drainage are initial permeability, injection pressure, and sorption affinity ratios in order. The sorption affinity ratios act on the behavior via the competitive adsorption characteristics of gas mixtures (CH₄, N₂, and CO₂).

**Figure 15** Influence of sorption affinity ratio of N₂/CH₄ ($R_{nm}$) on flue gas enhanced drainage
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CONFLICT OF INTEREST

The authors declare no competing financial interest.

ORCID

Chaojun Fan  https://orcid.org/0000-0003-4578-0760

REFERENCES

1. Fan CJ, Li S, Luo MK, Yang ZH, Lan TW. Numerical simulation of hydraulic fracturing in coal seam for enhancing underground gas drainage. *Energy Explor Exploit*. 2018;37(1):166–193.
2. Huang Q, Liu S, Wang G, Wu B, Zhang Y. Coalbed methane reservoir stimulation using guar-based fracturing fluid: a review. *J Nat Gas Sci Eng*. 2019;66:107–125.
3. Aguado M, Nicieza CG. Control and prevention of gas outbursts in coal mines, Riosa-Olloniego coalfield, Spain. *Int J Coal Geol*. 2007;69(4):253–266.
4. Fan C, Li S, Luo M, Du W, Yang Z. Coal and gas outburst dynamic system. *Int J Min Technol*. 2017;27(1):49–55.
5. Fang Z, Li X, Wang GX. A gas mixture enhanced coalbed methane recovery technology applied to underground coal mines. *J Min Sci*. 2013;49(1):106–117.
6. Zhang Y, Liu Y, Shi X, Yang C, Wang W, Li Y. Risk evaluation of coal spontaneous combustion on the basis of auto-ignition temperature. *Fuel*. 2018;233:68–76.
7. Zhou Z, Cai X, Ma D, Chen L, Wang S, Tan L. Dynamic tensile properties of sandstone subjected to wetting and drying cycles. *Constr Build Mater*. 2018;182:215–232.
8. Liu T, Lin B, Yang W, Zhai C, Liu T. Coal permeability evolution and gas migration under non-equilibrium state. *Transport Porous Med*. 2017;118(3):393–416.
9. Liu T, Lin B, Yang W. Impact of matrix–fracture interactions on coal permeability: model development and analysis. *Fuel*. 2017;207:522–532.
10. Wang G, Wang K, Wang S, Elsworth D, Jiang Y. An improved permeability evolution model and its application in fractured sorbing media. *J Nat Gas Sci Eng*. 2018;56:222–232.
11. Zhou F, Hou W, Allinson G, Wu J, Wang J, Cinar Y. A feasibility study of ECBM recovery and CO2 storage for a producing CBM field in Southeast Qinshui Basin, China. *Int J Greenh Gas Control*. 2013;19:26–40.

12. Fan Y, Deng C, Zhang X, Li F, Wang X, Qiao L. Numerical study of CO2-enhanced coalbed methane recovery. *Int J Greenh Gas Control*. 2018;76:12–23.
13. Huang Y, Zheng QP, Fan N, Aminian K. Optimal scheduling for enhanced coal bed methane production through CO2 injection. *Appl Energy*. 2014;113:1475–1483.
14. Durucan S, Shi JQ. Improving the CO2 well injectivity and enhanced coalbed methane production performance in coal seams. *Int J Coal Geol*. 2009;77(1–2):214–221.
15. Fujioka M, Yamaguchi S, Nako M. CO2-ECBM field tests in the Ishikari Coal Basin of Japan. *Int J Coal Geol*. 2010;82(3–4):287–298.
16. Zhang XG, Ranjith PG, Perera M, Ranathunga AS, Haque A. Gas transportation and enhanced coalbed methane recovery processes in deep coal seams: a review. *Energy Fuels*. 2016;30(11):8832–8849.
17. Lin J, Ren T, Wang G, Nemcik J. Simulation investigation of N2-injection enhanced gas drainage: Model development and identification of critical parameters. *J Nat Gas Sci Eng*. 2018;55:30–41.
18. Yin G, Deng B, Li M, et al. Impact of injection pressure on CO2-enhanced coalbed methane recovery considering mass transfer between coal fracture and matrix. *Fuel*. 2017;196:288–297.
19. Song Y, Jiang B, Qu MJ. Molecular dynamic simulation of self- and transport diffusion for CO2/N2/N2 in low-rank coal vitrinite. *Energy Fuels*. 2018;32(3):3085–3096.
20. Song Y, Jiang B, Lan FJ. Competitive adsorption of CO2/N2/CH4 onto coal vitrinite macromolecular: effects of electrostatic interactions and oxygen functionalities. *Fuel*. 2019;235:23–38.
21. Fan CJ, Li S, Luo MK, Zhou LJ, Zhang HH, Yang ZH. Effects of N- and S functionalities on binary gases co-adsorption onto coal macromolecule. *Energy Fuels*. 2019;33(5):3934–3946.
22. Shi JQ, Durucan S, Fujioka M. A reservoir simulation study of CO2 injection and N2 flooding at the Ishikari coalfield CO2 storage pilot project, Japan. *Int J Greenh Gas Control*. 2008;2(1):47–57.
23. Zhang XG, Ranjith PG, Li DY, Perera M, Ranathunga AS, Zhang BN. CO2 enhanced flow characteristics of naturally-fractured bituminous coals with N2 injection at different reservoir depths. *J CO2 Util*. 2018;28:393–402.
24. Harpalani S, Mitra A. Impact of CO2 injection on flow behavior of CBM reservoirs. *Transport Porous Med*. 2010;82:141–156.
25. Kiyama T, Nishimoto S, Fujioka M, et al. Coal swelling strain and permeability change of coal in response to CO2, injection for ECBM. *Int J Coal Geol*. 2013;85:56–64.
26. Mazumder S, Wolf K. Differential swelling and permeability change of coal in response to CO2 injection for ECBM. *Int J Coal Geol*. 2008;74:123–138.
27. Ren T, Wang G, Cheng Y, Qi Q. Model development and simulation study of the feasibility of enhancing gas drainage efficiency through nitrogen injection. *Fuel*. 2017;194:406–422.
28. Zhou F, Hussain F, Cinar Y. Injecting pure N2 and CO2 to coal for enhanced coalbed methane: experimental observations and numerical simulation. *Int J Coal Geol*. 2013;116:53–62.
29. Fan CJ, Elsworth D, Li S, et al. Modelling and optimization of enhanced coalbed methane recovery considering mass transfer between coal fracture and matrix. *Fuel*. 2019;253:1114–1129.
30. Sayyafzadeh M, Keshavarz A. Optimisation of gas mixture injection for enhanced coalbed methane recovery using a parallel genetic algorithm. *J Nat Gas Sci Eng*. 2016;33:942–953.
31. Sayyafzadeh M, Keshavarz A, Alias A, Dong KA, Manser M. Investigation of varying-composition gas injection for coalbed
methane recovery enhancement: a simulation-based study. *J Nat Gas Sci Eng*. 2015;27:1205-1212.

32. Durucan S, Ahsanb M, Shia JQ. Matrix shrinkage and swelling characteristics of European coals. *Energy Procedia*. 2009;1(1):3055-3062.

33. Shi R, Liu J, Wei M, Elsworth D, Wang X. Mechanistic analysis of coal permeability evolution data under stress-controlled conditions. *Int J Rock Mech Min Sci*. 2018;110:36-47.

34. Zhang Z, Zhang R, Xie H, Gao M. The relationships among stress, effective porosity and permeability of coal considering the distribution of natural fractures: theoretical and experimental analyses. *Environ Earth Sci*. 2015;73:5997-6007.

35. Jessen K, Tang GQ, Kovscek AR. Laboratory and simulation investigation of enhanced coalbed methane recovery by gas injection. *Transport Porous Med*. 2008;73(2):141-159.

36. Wang L, Cheng Y, Wang Y. Laboratory study of the displacement coalbed CH₄ process and efficiency of CO₂ and N₂ injection. *Sci World J*. 2014;2014:242947.

37. Fan CJ, Elsworth D, Li S, Zhou LJ, Yang ZH, Song Y. Thermo-hydro-mechanical-chemical couplings controlling CH₄ production and CO₂ sequestration in enhanced coalbed methane recovery. *Energy*. 2019;173:1054-1077.

38. Wu Y, Liu J, Chen Z, Elsworth D, Pone D. A dual poroelastic model for CO₂-enhanced coalbed methane recovery. *Int J Coal Geol*. 2011;86(2):177-189.

39. Lin J, Ren T, Wang G, Booth P, Nemcik J. Experimental study of the adsorption-induced coal matrix swelling and its impact on ECBM. *J Earth Sci*. 2017;28(5):917-925.

40. Lin J, Ren T, Wang G, Booth P, Nemcik J. Experimental investigation of N₂ injection to enhance gas drainage in CO₂-rich low permeable seam. *Fuel*. 2018;215:665-674.

41. Wang G, Ren T, Qi Q, Lin J, Liu Q, Zhang J. Determining the diffusion coefficient of gas diffusion in coal: development of numerical solution. *Fuel*. 2017;196:47-58.

42. Ma D, Cai X, Li Q, Duan H. In-situ and numerical investigation of groundwater inrush hazard from grouted karst collapse pillar in longwall mining. *Water*. 2018;10(9):1187.

43. Wang G, Qin X, Shen J, Zhang Z, Han D, Jiang C. Quantitative analysis of microscopic structure and gas seepage characteristics of low-rank coal based on CT three-dimensional reconstruction of CT images and fractal theory. *Fuel*. 2019;256:115900.

44. Wang G, Jiang C, Shen J, Han D, Qin X. Deformation and water transport behaviors study of heterogeneous coal using CT-based 3D simulation. *Int J Coal Geol*. 2019;211:103204.

45. Busch A, Gensterblum Y. CBM and CO₂-ECBM related sorption processes in coal: a review. *Int J Coal Geol*. 2011;87(2):49-71.

46. Gao F, Xue Y, Gao Y, Zhang Z, Teng T, Liang X. Fully coupled thermo-hydro-mechanical model for extraction of coal seam gas with slotted boreholes. *J Nat Gas Sci Eng*. 2016;31:226-235.

47. Hol S, Gensterblum Y, Massarotto P. Sorption and changes in bulk modulus of coal—experimental evidence and governing mechanisms for CBM and ECBM applications. *Int J Coal Geol*. 2014;128:119-133.

48. Li H, Shi S, Lu J, Ye Q, Lu Y, Zhu X. Pore structure and multifractal analysis of coal subjected to microwave heating. *Powder Technol*. 2019;346:97-108.

49. Li HE, Shi S, Lin B, et al. A fully coupled electromagnetic, heat transfer and multiphase porous media model for microwave heating of coal. *Fuel Process Technol*. 2019;189:49-61.

50. Li S, Fan C, Han J, Luo M, Yang Z, Bi H. A fully coupled thermal-hydraulic-mechanical model with two-phase flow for coalbed methane extraction. *J Nat Gas Sci Eng*. 2016;33:324-336.

51. Corey AT, Rathjens CH. Effect of stratification on relative permeability. *J Petrol Technol*. 1956;8(12):69-71.

52. Chen D, Pan Z, Liu J, Connell LD. An improved relative permeability model for coal reservoirs. *Int J Coal Geol*. 2013;109:45-57.

53. Cui X,ustin RM. Volumetric strain associated with methane desorption and its impact on coalbed gas production from deep coal seams. *AAPG Bull*. 2005;89(9):1181-1202.

54. Harpalani S, Schraufnagel R. Shrinkage of coal matrix with release of gas and its impact on permeability of coal. *Fuel*. 1990;69:551-556.

55. Zhang H, Liu J, Elsworth D. How sorption-induced matrix deformation affects gas flow in coal seams: a new FE model. *Int J Rock Mech Min Sci*. 2008;8:1226-1236.

56. Pan Z, Connell L. Modelling permeability for coal reservoirs: a review of analytical models and testing data. *Int J Coal Geol*. 2012;92:1-44.

57. Elsworth D, Bai M. Flow-deformation response of dual-porosity media. *J Geotech Eng*. 1992;118:107-124.

58. Huang Q, Liu S, Wang G, Wu B, Yang Y, Liu Y. Gas sorption and diffusion damages by guar-based fracturing fluid for CBM reservoirs. *Fuel*. 2019;251:30-44.

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