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Review article

Effect of micro-fractures on gas flow behavior in coal for enhanced coal bed methane recovery and CO_2 storage

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ABSTRACT

This study investigates the impact of micro-fractures on gas flow behavior in coal formations, specifically within the context of CO_2-based Enhanced Coal Bed Methane Recovery (ECBMR). Employing comparative analysis, various gas flow models, including Unipore Diffusion Model (UDM), Bidispersed Diffusion Model (BDM), Fractal Fractional Diffusion Model (FFDM), Time-Dependent Diffusivity Model (TDDM), Anomalous Sub-Diffusion Model (ASM), and Free Gas Density Gradient Model (FGDGM), are evaluated for their efficacy in capturing the complexities. The study aims to provide insights into the accuracy and applicability of these models, considering the heterogeneity of coal seams and the influence of micro-fractures on gas flow dynamics. The major findings include the categorization of different gas flow models based on their applicability to CO_2-based ECBMR. For instance, the study suggests utilizing BDM and FFDM models while considering the heterogeneity of coal seams. Similarly using the TDDM model for time dynamics of ECBMR will give higher accuracy. The article contributes to a deeper understanding of gas migration processes in coal, particularly in the context of ECBMR, with implications for optimizing recovery strategies and addressing challenges associated with micro-fracture-induced variations in gas flow behavior.

1. Introduction

Global carbon emission in the year 2020 was reported to fall by around 5.8% which is the largest fall after the global financial crisis in year 2009. Also, with the hitting of COVID-19, this figure declined further attributing a positive impact on the environment [1]. Despite this fall, the planet recorded a total average annual concentration of CO_2 in the environment of around 417.06 ppm in the year 2022 which further increased to 423.28 ppm in the year April 2023 [2]. The continuous surge of CO_2 in the atmosphere is leading to a global climate crisis by fuelling extreme weather events, jeopardizing food security, and escalating health risks (Table 1). The impact of CO_2 rise is quantified in terms of the social cost of carbon (SCC) that provides insights into the societal sacrifices required to mitigate climate change and can be defined as an estimate that quantifies the economic damage (USD) from the release of one ton of extra CO_2 in the atmosphere [3](Fig. 1). The SCC translates the consequences of climate change into economic terms, providing policymakers and decision-makers with a framework to comprehend the economic ramifications of choices that either amplify or diminish CO_2 emissions. In the computation of the social cost of carbon, key factors encompass alterations in climate and the subsequent economic repercussions, encompassing shifts in agricultural productivity, impacts from rising sea levels, and declines in human health and labor

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Abbreviations

ASM	Anomalous Subdiffusion Model
BDM	Bidispersed Diffusion Model
CBM	Coal Bed Methane
CH_4	Methane
CO_2	Carbon Dioxide
ECBMR	Enhanced Coal Bed Methane Recovery
EOR	Enhanced Oil Recovery
mm	Micrometres
nm	Nanometres
FFDM	Fractal Fractional Diffusion Model
FGDGM	Free Gas Density Gradient Model
TDDM	Time-Dependent Diffusivity Model
UDM	Unipore Diffusion Model
µm	Micrometres

efficiency [4].

The computation of the social cost of carbon underscores the urgency of addressing the deteriorating condition of the Earth, as nations worldwide become increasingly alarmed. This concern has prompted a global shift from conventional energy systems to unconventional energy sources, renewables, and green technologies. As a result, alternatives like solar energy, wind energy, small hydropower systems, hydrogen energy, electric vehicles, etc are gaining momentum at a faster pace [6,7]. The above-mentioned techniques are useful for curbing future emissions and in removing past or existing emissions techniques like carbon capture utilization & and storage (CCUS) have shown great potential [8,9]. CCUS is a four-step process that includes capturing carbon (by techniques like bioenergy with carbon capture and storage, direct air capture, pre-combustion, post-combustion, and oxyfuel combustion), transportation (by ships, railways, marine vessels, pipelines, etc.), and utilization (fuel, construction materials, plastic, chemicals etc.) or storage (geological storage, oceanic storage, and storage in other formations) [10] (Fig. 2).

CO_2 storage is an eminent and indispensable part of the CCUS process that aids in reducing the CO_2 content on Earth. CO_2 storage is a complex process and involves techniques like employing CO_2 as injecting gas for enhanced oil/gas recovery. CO_2-based EOR/EGR offers the dual advantage that it stores the gas in geological formations and results in the high production of hydrocarbons [11]. Due to this feature, the technique of storing CO_2 in petroleum reservoirs, coal seams, etc. is being implemented at various basins across the globe [12]. Coal seams offer a better affinity towards CO_2 due to their small molecular size and less density. Due to this it easily replaces CBM gas from the reservoir to the wellbore resulting in enhanced production of CBM gas and CO_2 storage in coal. The technique is termed ECBM recovery [13].

CBM or Coal bed methane is an unconventional gas that is formed during the coalification process. It is also known as clean or sweet gas because it lacks hydrogen sulfides and can be utilized for numerical applications including power generation, manufacturing, chemicals, and transportation with almost very less or nil emissions of CO_2 [14]. Countries like the USA, China, and Britain are focusing more on the gas economy due to the diverse advantages of CBM towards society and the environment. The potential for Coal Bed Methane (CBM) production in India has garnered significant attention, owing to the extensive coal reserves within the country. Current estimates indicate that Indian states harbor around 92 trillion cubic feet (2600 billion cubic meters) of CBM resources. In 1997, the Indian government established a CBM policy to optimize its use as a natural gas source, aligning with the directives outlined in the Oil Fields (Regulation & Development) Act of 1948 [15,16]. The Gondwana sediments, specifically in the Damodar, Koel, and Son valleys in eastern India, have been identified as promising regions for CBM development. Several CBM projects are underway, including those in the East and West Bokaro coal fields, the Parbatpur block in the Jharia coalfield, and the South, East, and North sectors of Raniganj. Notably, commercial production has been successfully achieved in the Raniganj South CBM block operated by M/s.

Table 1

Region-wise long-term impact of the global climate crisis [5].

Region	Long-Term Impact of Climate Change
Northeast	• Rise in sea level, downpours, and heat waves. • New crop options are emerging in the region but the question about being low-cost and low-risk crops is a concern.
Northwest	• Rivers and natural streams are displaying changes in their peak flow timings leading to fluctuations in the water supply • Variations in oceanic pH, flooding, erosion, and rise in sea level. • Wildlife issues, outbreaks of insects, and botanical diseases are also prevailing due to climate change.
Midwest	• Very heavy downpours and very high-temperature heat waves are affecting the Midwest region. • Climate change is also posing great risk to lakes in the area.
Southeast	• The rise in sea level is being recorded with the danger of floods. • Heat waves and scarcity of fresh water.
Southwest	• Out breach of insects and heat waves has impacted the wildlife of the area. • Reduction in agriculture yields and human diseases.

GEECL since July 2007 and the recovery of ECBM through CO_2 injection has been achieved in several lab scale studies and the field applications are yet to be achieved. The recovery of CBM through CO_2 injection has been successfully demonstrated in various lab-scale studies [16]. However, translating these achievements to field applications is still pending. This transition is particularly challenging given the dual porosity system inherent in coal, encompassing both pores and fracture systems, commonly referred to as cleats. The effectiveness of CO_2 injection for ECBM recovery hinges on a comprehensive understanding of these complex dual-porosity characteristics, emphasizing the need for further research and field applications to bridge the gap between successful lab-scale studies and practical implementation in coal reservoirs.

Coal has a dual porosity system which includes pores and fractures systems also called cleats. The pores system in the CBM reservoir is complex and generally categorized into three types of pores namely micropores, mesopores, and macropores [17]. Micropores are pore systems having a size of less than 2 nm and are solely responsible for the storage of gas. Although CBM gas is also available in Free State in cleat systems, it is predominantly stored in micropores. Mesopores are small fracture systems having sizes ranging from 2 to 50 nm [18]. Macropores are an important aspect in terms of the production of gas as they solely contribute to permeability resulting in ease of flow of gas from matrix to wellbore. These pores are greater than 50 nm and constitute the cleat network or natural fracture systems in coal reservoirs. Cleats are categorized into two sets of fractures perpendicular to each other known as face cleats and butt cleats. Also, these cleats in most cases are perpendicular to bedding [19]. Internal (like composition and rank of coal) as well as external (like tectonic stresses) are both types of factors responsible for the formation of this cleat system. Face cleats are well developed, primarily formed in coal matrix perpendicular to bedding while secondarily formed cleats are butt cleats, and they are discontinuous, short and have the tendency to terminate towards face cleats [20]. The cleat system varies with coal composition, and it is one of the crucial factors that determines the permeability of coal (Fig. 3).

Understanding coal's behavior and its potential for different applications depends on its permeability, which refers to its capacity to let liquids or gases pass through its structure. The existence of microfractures inside the structure of coal is a significant aspect that influences permeability [21]. Microfractures are tiny cracks or fractures that form spontaneously in coal as a result of different geological processes. These fractures, which can be tiny or up to a few mm in size, can significantly affect coal's permeability. As routes for the transport of materials through the coal seam, microfractures in the coal matrix operate as paths for fluid or gas flow [22]. Interconnected microfractures boost the coal's effective permeability, allowing for easier passage of liquids or gases through the coal seam. This improved permeability makes it possible to produce gas from the coal reservoir more effectively, which can be helpful in the extraction of coalbed methane [23].

Additionally, during procedures like coal gasification or coalbed methane depletion, microfractures in coal may have an impact on permeability. These microfractures can spread or shut as the coal is subjected to heat or stress changes, changing the permeability of the coal seam [24,25]. Foreseeing variations in coal permeability and optimizing the extraction or utilization processes requires an understanding of how microfractures behave under various conditions. Therefore, research on coal microfractures and how they affect permeability is crucial for several coal-related sectors, such as underground coal gasification, coalbed methane recovery, and coal seam gas extraction [26,27].

This review article presents a methodical analysis of the literature published in the past 10 years, by numerous authors and institutional reports of national and international organizations, that concluded the role of CBM as an energy source to achieve energy security along with CO_2 storage in coal seams under CCUS process to achieve the net zero goals. The article addresses the following gaps [28–31].

- Quantification and characterization: Accurately estimating and describing microfractures in coal is a significant challenge. Microfractures are difficult to measure and characterize due to their small size and complicated makeup.

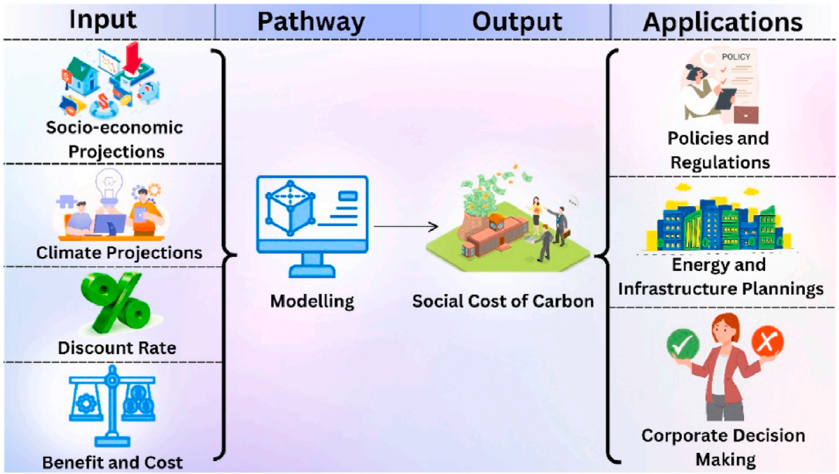

Fig. 1. The various input parameters and application of social cost of carbon for mitigating CO_2 emission.

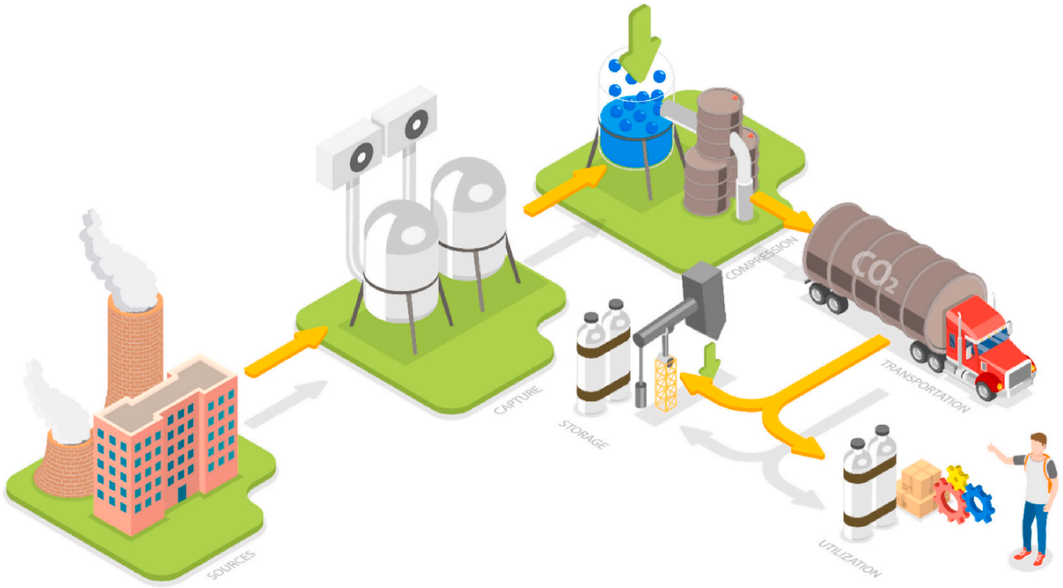

Fig. 2. CCUS process flow.

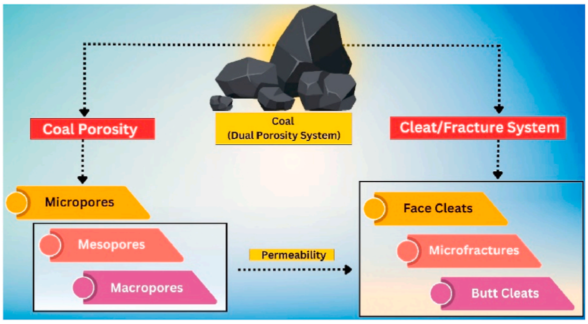

Fig. 3. Synergy between the porosity and permeability of coal in terms of porosity and cleat/fracture systems.

- Fluid flow mechanisms: It is essential to comprehend the mechanisms of fluid movement through coal's microfractures. Although it is recognized that the presence of microfractures increases permeability, the precise mechanisms influencing fluid flow within these fractures are not entirely understood. The primary flow processes, such as Knudsen diffusion, slip flow, or viscous flow, and how they change under various stress, pressure, and temperature conditions, require further study.
- Time-dependent behaviors: Coal microfractures may behave differently over time as a result of phenomena such as coal swelling, stress relaxation, and fracture closure. For long-term gas production forecasting and reservoir performance management, it's critical to comprehend the temporal evolution of microfractures and how they affect gas flow.

Thus, the following objectives have been drawn based on the existing gaps and are as follows.

- Study of microfractures and investigation of their impact on gas flow with the help of different gas flow models used for CO_2-based ECBMR.
- A comparative analysis of different gas flow models in terms of their advantages and disadvantages and estimation of suitable gas flow model for CO_2-based ECBMR

2. Microfractures

Microfractures are those fractures that differ in orientation when compared to face or cleat systems. These are tertiary fractures that either end at the face or butt [32]. The main reason for the formation of these types of microfractures can be attributed to coalification due to tectonic stress, desiccation, devolatilization, unloading overburden during uplift and erosion, rank, grade, and maceral type. Maceral type in coal can play a role in microfracture generation due to differences in their physical and chemical properties. Macerals are organic components of coal that include different types of plant matter such as vitrinite, inertinite, and liptinite [33]. Inertinite macerals, for example, are generally more brittle and have higher ash content than vitrinite macerals. This can make them more prone to breakage and generate more microfractures when subjected to stress. Additionally, differences in the chemical composition of macerals can affect their stress response. For instance, vitrinite macerals are more resistant to oxidation than inertinite macerals. If coal containing a high proportion of inertinite macerals is exposed to air and oxidized, the oxidized material may be weaker and more susceptible to micro-fracturing [34,35]. There are different approaches used by different researchers to describe the microfractures. For instance Ref. [36], described microfractures as structures of micrometer sizing that are not visible through the naked eye [37]. explains microfractures as structures having apertures around 0.15 mm with values greater than 0.15 mm called large microfractures and values less than 0.15 mm as small microfractures [38]. said that fractures that need a microscopic vision for their appearance are microfractures [39]. also stated that fractures having a size of less than 20 nm are microfractures. Although all the above description of microfractures is not precise and are qualitative. Thus, employing them for other studies was not considered feasible in terms of accuracy. Finally [40], gave his idea of explaining the term and said that microfractures can be categorized into four types based on their aperture and length. The categorization is as follows.

- Type A (aperture $\geq$5 μm, length $>$10 mm),
- Type B (aperture $\geq$5 μm, 1 mm $<$ length $\leq$10 mm)
- Type C (aperture $<$5 μm, 300 μm $<$ length $\leq$1 mm)
- Type D (aperture $<$5 μm, length $\leq$300 μm)

This classification is widely used in studies related to coal fractures. There are many ways by which microfractures can be analyzed. Techniques like mercury intrusion porosimeter (MIP), FESEM or filed emission scanning electron microscopy, and SEM scanning electron microscopy have been used conventionally for research but none of these techniques cannot directly observe the micro-fractures [41]. Also, MIP affects the samples due to its destructive nature and can alter the results. SEM and FESEM are intuitive methods and curtail the sample study to 2D information. Currently, X-ray computerized tomography is the widely used method due to its ability to generate 3D images, and being non-destructive does not alter the results [42]. An X-Ray CT scan can be employed for many studies apart from microfracture characterization like gas adsorption and its migration, mineral matter and lithotype and their effect on coal porosity & permeability, the evolution of coal fractures, etc. Although research related to rank and its correlation to fractures cannot be estimated from this method [43–45].

Fracture-related studies or fractal studies are difficult to analyze due to the complex and heterogenous nature of coal. Mandelbrot initially used the fractal theory for characterizing heterogeneous coal samples. This theory involves the description of fractal geometry based on fractal dimension (D) and it offers information that can help in simplifying the complexities and irregularities of coal samples while studying fractal aspects [46,47]. Studies related to fractal aspects of coal have been carried out by many researchers. For instance Ref. [48], characterized the changes occurring in the physical structural form of coal with the help of X-ray scattering and he concluded that fractal dimensions play a critical role in delineating changes in coal structure [49,50]. by integrating MIP with fractal analysis studied the coal texture and he found out that fractal analysis is the best way to understand coal structures [51]. carried-out fractal analysis studies on the porosity of low-rank coal with the help of nuclear magnetic resonance (low field) and he concluded that NMR-based fractal studies are efficient techniques to display pore-fracture heterogeneity. Liu et al., 2020 carried out experiments and tests to study the fractal dimension and its effect on the adsorption capacity of coal seams through SEM and nitrogen gas adsorption (low pressure) [52]. They concluded that fractal analysis is among the important studies that help in quantifying the methane storage capacity and assessing the irregularities on the surface of coal.

Thus, fractal dimension is an important tool used currently for the analysis of fractal objects and this is the only significant invariant that can display datasets about irregularities and complexities [53]. Hausdorff dimension is the oldest description available for fractal dimensions and it can show analytical properties when considered from a mathematical purview, but it is not sufficient when considering applications rather than mathematical aspects [54]. Apart from this, there are several other methods also available that can determine the fractal dimension. The method of box-counting is widely and commonly used for this purpose because of its properties like simplicity and high computations [55]. Pontrjagin et al., 1932 were the first to give a theoretical definition of this method. This technique involves binary images thus, images obtained from CT scans should be pre-processed before being employed for use. This method divides the images into grids leading to the formation of square boxes having equal dimensions of r. So, the quantum of non-empty boxes denoted as N(r) requires sheathing the fractal structural relies totally on r and can be expressed as [56].

$$\boldsymbol{N(r) \sim r^{-D}}$$

So, this algorithm quantifies the value of N(r) for variable value sets of r and leads to plotting between log N(r) Vs log r, and fractal dimension is estimated by best fitting slope in Richardson plot [57]:

$$\boldsymbol{-D = \lim_{r\to 0}(Log\ N(r)\ /\ Log\ r)}$$

Fractal dimensions can be calculated by using the above method. The estimation of fractal dimension is a crucial factor that defines the gas flow from coal to the wellbore. To increase the reduction of CBM fractal geometry that can help in easy gas flow is needed [58]. Fractures that are not connected will hinder the gas flow resulting in less production that's why techniques like fracking are used for CBM production currently. Microfractures are expected to have positive impacts on CO_2-based ECBMR processes including [59]:

Enhanced permeability: Microfractures enhance the permeability of coal, making it easier for gas to flow through the seam by creating additional pathways [60,61]. In CBM production, coal permeability is a critical factor that determines the rate at which the gas can be extracted from the seam. This means that CBM can be produced more efficiently and at a lower cost, as fewer stimulation techniques such as hydraulic fracturing are required. In CO_2 storage, the coal permeability is also important, as it determines the rate at which the injection and storage of CO_2 can be done in the coal seam [62].

Increased gas storage capacity: Microfractures create additional space within coal seams, increasing the overall gas storage capacity. This can be beneficial for both CBM production and CO_2 storage, as it allows for more gas to be stored within the seam. When microfractures occur, they create cracks or voids within the coal matrix that are not present in unfractured coal [63]. These cracks or voids can provide additional space for gas storage in coal. The process by which gas is stored in coal is known as adsorption. Adsorption occurs when gas molecules are attracted and held at the external surface of coal particles. The gas quantity that is stored in the coal relies on the surface area of the particles of coal and the pressure and temperature of the system. When microfractures are present in the coal seam, they can increase the surface area of the coal particles and provide additional sites for gas adsorption [64].

Improved gas recovery: Microfractures enhance the desorption of gas within coal, making it easier to recover CBM by an increased rate of desorption [65,66]. Desorption refers to the process by which gas is released from the coal and flows into the fractures or pore space within the coal seam [67]. The presence of microfractures enhances gas diffusion within the coal seam. The phenomenon of diffusion involves the movement of gas molecules from regions of greater concentration to those of lower concentration. When microfractures are present, they can create a more interconnected network of pore space within the coal seam, allowing gas diffusion more easily. In addition, microfractures can also increase the surface area of the coal particles and provide additional sites for gas adsorption. This can increase the gas amount that can be stored within the coal seam and improve the overall recovery of CBM [68].

Greater predictability: While microfractures are difficult to predict and model accurately, their presence also provides crucial geological information that can help to improve the predictability of CBM production and CO_2 storage [69]. By better understanding the behavior of microfractures within coal seams, operators can optimize their operations and reduce uncertainty. By examining the size, distribution, and orientation of microfractures, geologists can gain information regarding the structural and mechanical properties of coal. The presence of microfractures can indicate areas of the coal seam that are more susceptible to fracturing or shearing [70]. This can be useful in identifying zones that may require additional stimulation techniques, such as hydraulic fracturing, to increase CBM recovery or CO_2 storage. In addition, microfractures can also provide information on the coal permeability. By measuring the size and distribution of microfractures, geologists can estimate the permeability and predict the flow rates of CBM or CO_2 within the seam. Microfractures can also provide information on the content of gas and the quality of the coal [71]. By examining the size and distribution of microfractures, geologists can estimate the gas amount which can be stored in coal. Finally, microfractures can provide information on the geomechanical behavior of the coal seam. By studying the orientation and distribution of microfractures, geologists can assess the stability of the coal seam and predict the likelihood of collapse or deformation [72].

The presence and characteristics of microfractures within coal formations significantly influence the gas flow behavior, as these fractures create pathways for the movement of gases. Understanding the intricate interplay between microfractures and gas flow is crucial for optimizing coal seam gas extraction processes and developing effective strategies for enhanced recovery and sustainable energy utilization.

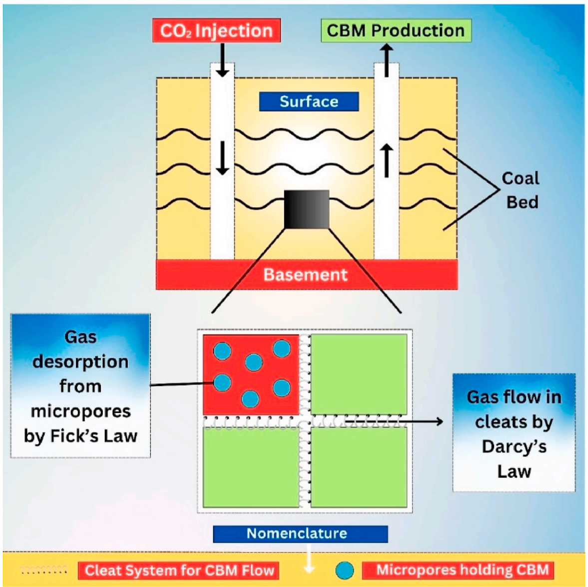

Fig. 4. Theoretical display of gas flow in coal seams.

3. Gas flow behavior in coal

CBM accounts for a huge economic benefit to the world but ambiguities associated with the mechanism of gas flow are still a hurdle in achieving estimated advantages of the gas in global economy. To achieve such a huge demand for energy India needs to focus on unconventional resources, especially CBM and Shale gas. In upcoming years, the demand for gas in the country is anticipated to rise to 746 MMSCMD in 2029–2030 from 242.6 MMSCMD in 2012–2013 offering numerous opportunities in CBM exploration and production [73]. To increase production understanding the gas flow behavior is an important aspect and includes two steps which are (Fig. 4).

A. Gas desorption from micropores from the internal surface of coal by Fick's law
B. The flow of gas to the outer surface of coal through a cleat system by Darcy's law

If we consider the sorption in terms of molecular motion, then the sorption process of methane molecules is instantaneous in the internal surface of pores but when escaping from these pores the gas molecules require some time which gives the basis that gas flow in coal seams relies on some mathematical rules and formulas [74]. Much research has been carried out globally that proves the fact that gas desorption from the internal surface of pores takes place through Fick's law of diffusion which states that gas content and flow rate of gas are directly proportional. For instance Ref. [75], established an equation that works on gas emission measurements to theoretically develop a diffusion model based on Fick's law. Similarly [76], also came up with a model which was like that developed by Yang. Coal seams have a maximum fraction of micropores or transition pores on their internal as well as external surface and gas flow in micropores is governed by Fick's law but in the case of mesopores or macropores research has shown that the gas movement is governed by Darcy law [77]. established a model for gas flow based on crystal, surface, transitional, Knudsen, and Fick's diffusion and concluded them as the main gas flow patterns in coal seams and large variations have been reported in calculations of values by Fick's model [78,79]. The next section describes the different gas flow models proposed.

4. Gas flow models

Reviewing gas flow models is crucial for their predictive accuracy, offering insights into the behavior of gases in diverse environments like coal seams. These models play a pivotal role in understanding the underlying physical and chemical processes governing gas flow, aiding in process optimization and risk assessment, particularly in activities such as carbon capture utilization & storage (CCUS) or natural gas extraction. Advancements in modeling techniques contribute to the development of new technologies, while a careful review ensures that models accurately capture environmental considerations, promoting responsible and sustainable gas-related practices. In industries like oil and gas, accurate models are vital for optimizing resource extraction and utilization, and compliance with regulatory standards is facilitated by aligning models with regulatory requirements. Based upon the literature review several existing models try to explain how gas flows in coal seams and some of them are the UDM, BDM, FFDM, TDDM, ASM and FGDGM. These models have been discussed briefly in the next sub-section.

4.1. Unipore diffusion model (UDM)

The UDM is a common approach to describe coal gas flow. In this model, the main assumption is that coal consists of a network of interconnected micropores, and gas flow occurs primarily through these micropores. Also, the model assumes that gas diffusion through the micropores is the main mechanism for gas transport and that the diffusion rate and the concentration gradient of the gas are proportional to each other [80]. The diffusion coefficient is a function of the gas pressure and temperature and can be estimated using empirical relationships or measured directly in laboratory experiments. The UDM is used for the simulation of gas flow in coal beds under various conditions, such as changes in pressure, temperature, and composition. It can also be used to estimate the amount of gas that can be recovered from a coal seam using various extraction methods, such as drilling and fracking [81]. The UDM can be mathematically expressed using Fick's law of diffusion. In the case of UDM, the flux of gas is primarily through the micropores of the coal matrix. The mathematical equation for the UDM is [82]:

$$J = -D\frac{\partial C}{\partial X}$$

where J = gas flux,
D = diffusion coefficient,
C = gas concentration, and.
X = distance along the micropore.

The negative sign in the above equation is an indicator that shows that gas flux is in the opposite direction of the concentration gradient.

The diffusion coefficient (D) can be expressed as [82]:

$$D = D_O * \left(\frac{P}{P_O}\right)^n * exp^{-\frac{Q}{RT}}$$

This equation is commonly known as the "Carman-Kozeny equation", which is a well-known empirical formula that relates the permeability of a porous medium to its porosity and specific surface area [83]. The equation can be used to estimate the permeability of various types of porous media, including coal.Where,

D_0 = diffusion coefficient at a reference pressure and temperature,
P = gas pressure,
P_0 = reference pressure,
n = pressure exponent,
Q = activation energy for diffusion,
R = gas constant, and.
T = temperature.

4.2. Bidispersed diffusion model (BDM)

This is the model that accounts for both micropore as well as macropore diffusion thus the name comes bidispersed diffusion model. The model was able to present transient sorption by considering micropore diffusion and macropore diffusion. In this the sorbent was uncovered to a sorbate with an infinite source considering that concentration remains constant at the sorbate's particle surface and uptake to equilibrium was observed [84]. The model works on the principle that a macropore particle (sorbent) is a collection of small micropores such that in addition to diffusing into and adhering to the sidewalls of micropores, sorbate also diffuses into macropores (Fig. 5). It is presumed that the adsorption mechanism is isothermal and that linear isotherms are applicable [85].

The bidisperse diffusion model consists of a system of partial differential equations that delineates the transportation of gas in coal. The model assumes that the coal matrix is composed of two types of pores, small micropores, and large macropores, and that gas diffusion and flow occur independently in each pore type. The mathematical equation for the bidisperse diffusion model is [86]:

$$\frac{D_\alpha \varepsilon_\alpha}{r_\alpha^2} \frac{\partial}{\partial r_\alpha}\left[r_\alpha^2 \left(\frac{\partial C_\alpha}{\partial r_\alpha} \right) \right] = \varepsilon_\alpha \frac{\partial C_\alpha}{\partial t} + S_\alpha \frac{\partial C_{s\alpha}}{\partial t} + n4\pi R_{macro}^2 \varepsilon_i D_i \left(\frac{\partial C_i}{\partial R_{micro}} \right)$$

Where,

Dα is diffusion coefficient for macropores (cm^2/s),
Di is diffusion coefficient for micropores (cm^2/s),
rα is the distance from the center of macropores (cm),
Cα is macropore fluid phase sorbate concentration (mol/cm^3),
Csα is macropore adsorber phase concentration (mol/cm^2),
N is the number of microspheres per unit volume of the macrosphere,
Ri is microsphere radius (cm),
Sα is macropore surface (cm^2/cm^3),
εα is macropore void fraction,
εi is the micropore void fraction and

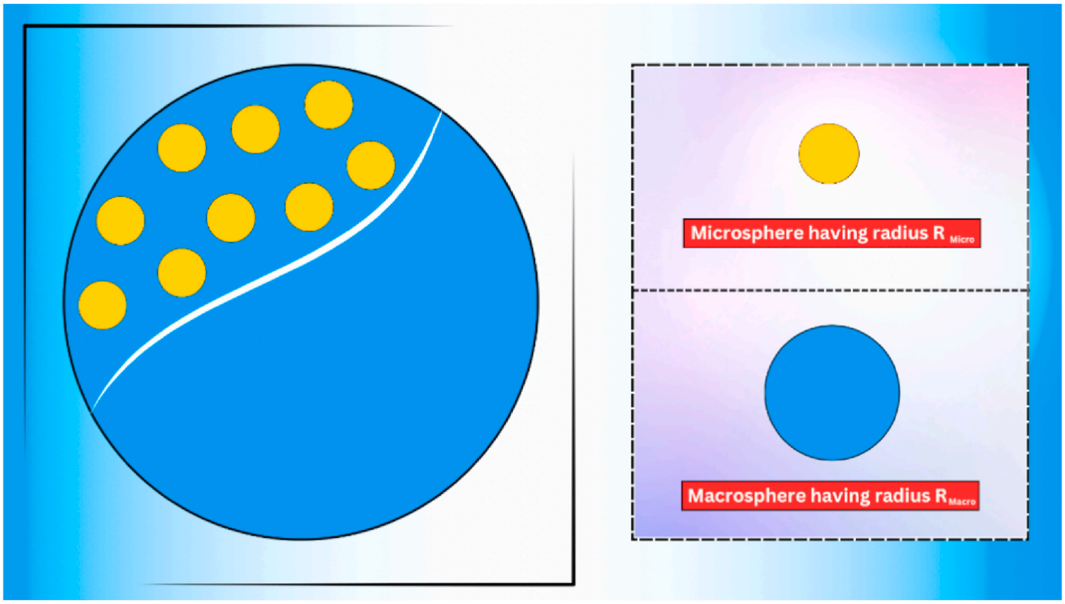

Fig. 5. Display of sorbent particle taken as an assumption for BDM.

t is time (s).

The BDM is a more complex model than the UDM for gas flow in coal. It accounts for the presence of two types of pores in coal, small micropores, and large macropores, which are assumed to have different properties for gas diffusion and flow [82].

4.3. *Fractal theory-based fractional diffusion model (FFDM)*

The fractal Diffusion Model (FDM) is a mathematical equation that is suitable for describing the diffusivity of gases in coal, based on the anomalous diffusion behavior that occurs in the porosity of coal. The FDM model considers the statistical fractal nature of the pores in coal, which means that the pores have self-similar properties at different scales [87]. However, the suitability of the FDM model for describing gas flow under unsteady state conditions or when the pore structure is complex, such as when there are fractures or faults present in the coal matrix is uncertain [88]. In other words, the FDM model is more appropriate for the flow of gas when the porosity is stationary and has a simpler fractal geometry. Thus, a new and upgraded version of this model was developed namely fractal theory-based fractional diffusion model (FFDM) (Fig. 6). fractal diffusion model lags compared to the fractal theory-based fractional diffusion model because [89–92].

I. The fractal diffusion model may not fully capture the complexities and self-similar nature of the coal porosity, which can vary across different scales. The fractal theory-based fractional diffusion model, on the other hand, explicitly accounts for the fractal nature of the pores using fractional calculus.
II. The fractal diffusion model may have limitations in describing the anomalous diffusion shown by gas in the fractal coal pore structure, which is characterized by a non-linear relationship between gas concentration and time. The fractal theory-based fractional diffusion model specifically includes a fractional derivative to account for this anomalous diffusion behavior.
III. The fractal diffusion model may have limitations in simulating gas flow over a range of time scales, as it typically utilizes a classical diffusion equation that assumes a linear relationship between gas concentration and time. Contrary, the fractal theory-based fractional diffusion model, can simulate gas flow over a wider range of time scales due to its ability to describe anomalous diffusion.

The fractal theory-based fractional diffusion model is a relatively new approach for modeling gas flow in coal. The model considers the fractal nature of coal porosity, which shows self-similar properties across different scales. This fractal structure can be described mathematically using a fractional calculus approach, based on the concept of non-integer derivatives. The mathematical equation for the model is [93]:

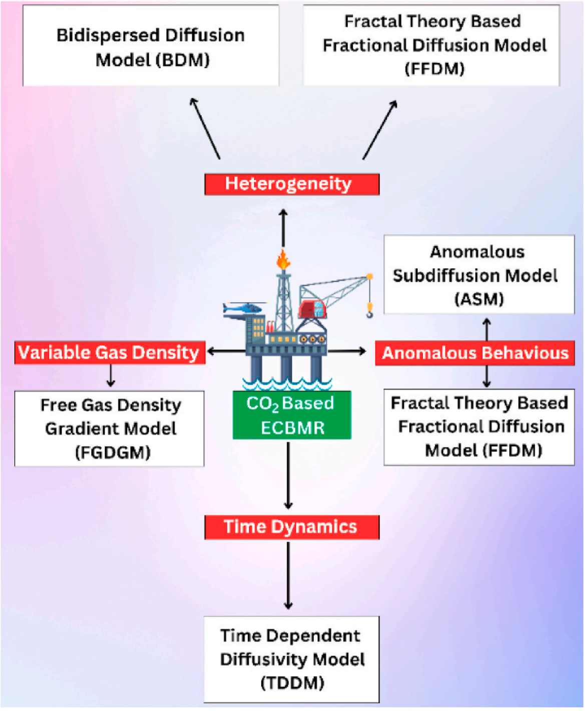

Fig. 6. Suitability of various gas flow models and how they can be utilized with respect to different requirements in CO$_2$-based ECBMR projects.

$$\frac{\partial^{\nu} C(r,t)}{\partial t^{\nu}} = \frac{D_0}{r^{d_f-1}} \frac{\partial}{\partial r}\left(r^{d_f-1-\theta} \frac{\partial C(r,t)}{\partial r} \right)$$

Where,

C = diffusion concentration (kg/m^3)
d = dimension for Euclidean geometry.
D = diffusion coefficient (m^2/s)
r = radius of particles (m)
t = time (s)
d_f = fractal dimensions.
D_o = Pre-exponential factor.
θ = structure parameter
C(r,t) = Conc. of diffusion component.

The fractional derivative in the above equation represents the anomalous diffusion of gas in the fractal coal pore structure, which is characterized by a non-linear relationship between gas concentration and time. The fractional order α can vary between 0 and 2 and determines the degree of anomalous diffusion. When $\alpha = 1$, the model reduces to the classical diffusion equation [94].

4.4. Time-dependent diffusivity model (TDDM)

This is a mathematical model that describes gas diffusion as a function of time. This model considers that the gas diffusivity in coal can vary over time due to various factors, like changes in coal porosity, the presence of fractures or faults, or changes in gas pressure or temperature. The Time-Dependent Diffusivity Model relies on the classical diffusion equation, which assumes a linear relationship between gas concentration and time [95]. However, this model includes a time-dependent diffusivity coefficient that varies over time, and this coefficient can be calculated based on various experimental or theoretical data. The Time-Dependent Diffusivity Model can be useful for predicting the flow behavior of gas in coal over time and is used for the simulation of gas production or injection in coal seams for ECBM recovery or CO_2 storage applications [96]. However, the accuracy of the model depends on the quality of the data used to calculate the time-dependent diffusivity coefficient, as well as the assumptions and simplifications made in the model. This model considers the diffusion process of free gas and adsorbed gas.

The model assumes the following considerations [97].

I. Coal particles have a spherical shape.
II. The porosity in these coal particles is cylindrical.
III. Gas adsorption in these pores occurs in a single layer with a certain thickness.
IV. The difference in pressure occurring at the two ends of pores is always constant.
V. Temperature as well as the gas viscosity remains constant during diffusion.

Mathematically equation of the model can be described for both conditions' laboratory as well field applications. For laboratory applications, TDDM is written as [95]:

$$\frac{M_t}{M_\infty} = 1 - \frac{6}{\pi}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left\{-\frac{n^2\pi^2}{r^2}\left[2\left(D_{f0}+D_{a0}\right)\sqrt{t}\right]\right\}$$

and for real field application, TDDM turns to Ref. [98]:

$$\frac{M_t}{M_\infty} = \frac{6}{\sqrt{\pi}}\left(\frac{\sqrt{2\left(D_{f0}+D_{a0}\right)\sqrt{t}}}{r^2}\right)$$

Where,

M_t = Diffusion amount of accumulated gas in time 't' (mL/g)
$M\ \infty$ = Gas ultimate diffusion amount (ml/g)
n = Series level
r = radius of pores (m)
D = Gas diffusion constant (m^2/s)
t = time (s)

The time-dependent diffusivity coefficient, D(t), is calculated based on experimental or theoretical data and may depend on various factors like the coal porosity, the gas pressure and gas temperature, and the presence of fractures or faults. The diffusivity coefficient is also expressed as a function of gas pressure or concentration, and this relationship can be used to model gas production or injection in coal seams for ECBM or CO_2 storage applications [99].

4.5. Anomalous subdiffusion model (ASM)

This is a mathematical model that describes the anomalous subdiffusive behavior of gas molecules in coal. This model relies on the theory of fractional calculus, which allows for the description of anomalous diffusion processes with power-law behavior that does not follow Fick's law of diffusion [83].

The ADM can be expressed mathematically as [100]:

$$D_f \frac{\varepsilon_m}{r^2} \frac{\partial}{\partial r}\left(r^2 \frac{\partial^{1-\alpha}}{\partial t^{1-\alpha}} \frac{\partial^{\beta} C_m}{\partial r^{\beta}} \right) = \varepsilon_m \left(\frac{\partial C_m}{\partial t} \right) + S_p \left(\frac{\partial C_{sm}}{\partial t} \right)$$

Where,

C_m = Free methane concentration.

C_{sm} = Adsorbed methane concentration.

D_f = Anomalous diffusion coefficient.

ε_m = Porosity of coal matrix

S_p = Surface area of pores.

$\frac{\partial^{1-\alpha}}{\partial t^{1-\alpha}}$ and $\frac{\partial \beta}{\partial r \beta}$ = Riemann-Liouville fractional operators

α is the anomalous diffusion exponent that determines the degree of sub-diffusivity.

The value of α can range from 0 to 1, with $\alpha = 1$ corresponding to normal diffusion behavior and $\alpha < 1$ corresponding to subdiffusive

Table 2

Advantages and Disadvantages of different gas flow models available for describing gas flow behaviors in coal.

Model	Advantages	Disadvantages	Ref.
UDM	Its versatility is highlighted by its ability to simulate gas flow under varied pressure and temperature conditions, enabling optimization of gas extraction and injection operations. The model proves valuable for evaluating the impact of critical factors on gas flow, including coal permeability, diffusion coefficient, and gas pressure	The model's simplicity may not fully capture real coal seam gas flow, as it overlooks critical factors like coal swelling, sorption, and desorption. Its assumption of a coal structure with interconnected micropores oversimplifies the actual complexity involving various pore types and fractures. The model also lacks accuracy in representing the impact of geological heterogeneities, such as faults and fractures, on gas flow in coal. Additionally, reliance on challenging-to-measure input parameters like the diffusion coefficient adds complexity to the model's applicability and accuracy.	[80, 82]
BDM	The bidispersed diffusion model offers an enhanced representation of coal's intricate pore structure, encompassing both micropores and macropores. It incorporates the effects of sorption and desorption on gas flow within coal, particularly significant in the context of CO_2 storage. Moreover, the model enables the evaluation of geological heterogeneities like faults or fractures and their impact on gas flow within coal formations.	The bidispersed diffusion model comes with increased complexity and demands more input parameters, often challenging to measure experimentally. It assumes independent gas diffusion and flow in micropores and macropores, which might not entirely align with reality. The model overlooks crucial factors like coal swelling that affect gas flow.	[85, 86]
FFDM	The model considers the intricate fractal structure of coal pores and demonstrates versatility by simulating gas flow across a broad range of time scales (seconds to years). Additionally, the model facilitates the exploration of various geological parameters' impact on gas flow, including the presence of faults or fractures. It offers practical applicability by being calibratable using laboratory measurements or field data, enabling optimization of gas extraction or injection operations	The fractal theory-based fractional diffusion model lacks extensive testing and validation. Its practical application is constrained by the demand for increased computational resources compared to certain other models. Moreover, the model's requirement for accurate measurements of the fractal properties of coal pores poses a practical challenge, as obtaining such measurements may be difficult in practice	[100, 109]
TDDM	The model represents gas flow in coal by considering changes in diffusivity over time, enhancing accuracy across various conditions. Its adaptability is a notable feature, allowing customization and calibration based on experimental or theoretical data, specifically tailored to diverse coal seam properties and conditions.	The accuracy of the model hinges on the quality of data used for calculating the time-dependent diffusivity coefficient, alongside the assumptions and simplifications inherent in the model. Its computational intensity demands significant resources, especially for larger and more intricate coal seam models. The model does not encompass all factors influencing gas flow in coal like fractures or faults.	[95, 96]
ASM	The Model is designed to capture the anomalous subdiffusive behavior of gas molecules in coal seams, arising from the intricate and heterogeneous pore structure. Its application extends to simulating gas production or injection under varied conditions and scenarios, offering a more accurate representation of gas flow in coal compared to traditional diffusion models.	The accuracy model relies on precisely estimating the anomalous diffusion exponent α, a challenging task given the complex and variable pore structure of coal seams. Its computational complexity, particularly for large-scale simulations, may restrict its applicability.	[83, 104]
FGDGM	The model offers a straightforward and user-friendly approach for estimating gas concentration and distribution in a coal seam and it holds applicability across a diverse range of coal seams and gas compositions. This model stands out for its simplicity, requiring minimal input data and easily accommodating readily available coal seam and gas properties	The model, assumes a uniform coal seam and steady-state gas flow, potentially deviating from real-world complexities. It presupposes uniform gas saturation in the coal matrix, which may not align with all coal seams. Importantly, the model neglects the effects of temperature, pressure, and other environmental factors on gas transport and storage in coal seams.	[105, 106]

behavior. In coal seams, the subdiffusive behavior of gas molecules is caused by the complex and heterogeneous pore structure, which can lead to the trapping and slow diffusion of gas molecules [101,102].

The ADM is used for the prediction of gas transport and sorption in coal seams for ECBM and CO_2 storage applications. However, the model requires accurate estimation of the anomalous diffusion exponent α, which can be challenging due to complexities and variable coal porosity [103]. Additionally, the computational complexity of the model can be high, which may limit its applicability for large-scale simulations. Overall, the ADM provides a valuable tool for understanding the anomalous subdiffusive behavior of gas molecules in coal seams, but its limitations and challenges should be considered when applying it to real-world situations [104].

4.6. Free gas density gradient model (FGDGM)

The Free Gas Density Gradient Model is a mathematical model that describes the distribution of gas density in coal. This model relies on the principle that gas density decreases with increasing distance from the gas source due to the diffusive nature of gas and adsorption in coal [105].

The Free Gas Density Gradient Model can be expressed mathematically as [106]:

$$J_m = -D_{fg}\frac{\partial \rho_{fg}}{\partial L}$$

Where,

J_m = Gas mass flux in matrix (g/(cm^2·s))
D_{fg} = effective diffusion coefficient of free gas, (cm^2/s)
ρ_{fg} = free gas density (g/cm^3)
L = normal line length (cm)

The Model assumes that the gas available in the coal is in the free gas phase and that the coal matrix is uniformly saturated with gas. The model also assumes that the flow of gas is driven by pressure gradients and that the gas diffusion coefficient is constant throughout the coal seam. This Model is used to estimate the gas concentration and distribution in coal for ECBM and CO_2 storage. The model can also be used to estimate gas production rates and to optimize well placement and operation [107].

However, the model has limitations in that it assumes a uniform coal seam and a steady-state gas flow. Coal seams can be highly variable in terms of their porosity, permeability, and content of gas, and gas flow which is impacted by a range of factors, including fractures, faults, and stress conditions. Therefore, the accuracy of this model depends on the quality of input data and assumptions, and its results should be interpreted with caution [108].

5. Comparative analysis of gas flow models

The flow behavior of CBM and CO_2 in coal is another important factor that decides the production of CBM and CO_2 storage capacity. Literature suggests that there are several gas flow models available that describe the gas flow in coal under different conditions. The model considered for study includes the UDM, BDM, FFDM, TDDM, ASM and FGDGM. Table 2 summarizes the various models concerning their advantages and disadvantages while Table 3 shows the applicability of these models for CO_2-based ECBMR techniques.

6. Gaps and challenges

Apart from offering positive aspects to CBM production and CO_2 storage in coal, microfractures also possess some drawback that hinders these processes. These challenges include.

- Reduced permeability: This can occur when the size and distribution of the microfractures create a complex network of smaller, interconnected fractures that impede the flow of gas through the coal matrix. In addition, microfractures also create preferential pathways for water flow within the coal seam that can result in the formation of water channels blocking the flow of gas through the seam and further reducing permeability.

Table 3
Applicability of various gas flow models for CO_2-based ECBMR.

Model	Remarks
UDM	Applicable when CO_2 and CBM diffusion in coal seams is predominantly influenced by a single type of pore structure with consistent properties
BDM	Applicable when CO_2 and CBM diffusion involves interactions with different phases within the coal matrix, such as interactions with water or other gases.
FFDM	In ECBMR, it can capture the anomalous diffusion phenomena influenced by the fractal nature of the coal matrix.
TDDM	useful for modeling how the diffusivity of CO_2 and CBM evolves within the coal matrix, considering factors like changes in pressure and coal properties.
ASM	Applicable when the diffusion of CO_2 and CBM exhibits anomalous sub-diffusion, potentially due to irregularities in the coal matrix.
FGDGM	Useful in modeling the effects of density gradients on the diffusion of CO_2 and CBM within the coal seam, providing insights into how gas density variations influence ECBMR processes.

- Gas sorption and desorption: Microfractures affect the adsorption and desorption of gas within the coal. During the adsorption process, gas molecules are trapped in the micropores of the coal matrix. microfractures can hinder the adsorption process by disrupting the connectivity of the micropores within the coal matrix. This can create areas of low gas adsorption capacity and reduce overall gas storage capacity. During the desorption process, gas is released from the micropores of the coal matrix and flows through the fractures to the production well. microfractures can also hinder the desorption process by reducing the pressure within the coal seam. As gas is released from the micropores, it flows into the fractures and may escape to the surface, reducing the overall recovery of CBM or storage of CO_2.
- Water influx: Microfractures can also act as conduits for water influx into coal seams. This can dilute the CBM gas content and decrease its quality, as well as increase the risk of water-blocking CBM wells. This can reduce the economic viability of CBM production and make it more difficult to extract high-quality gas. When water enters the wellbore, it can reduce the flow of CBM gas and potentially block the well, hindering production.

Table 4
Research gaps and challenges associated with different gas flow models.

Model	Challenges	Remarks
Unipore Diffusion Model	Limited applicability	The model assumes gas flow in coal happens through a single pore system, which may not accurately represent diverse coal types or field conditions
	Uncertainty in pore size distribution	The model relies on a specific pore size distribution, but uncertainty in the actual pore size distribution in coal introduces difficulty in accurately predicting gas flow behavior.
	Lack of consideration for adsorption	The model does not consider the impact of gas adsorption on gas flow behavior. Gas adsorption can significantly affect the gas flow in coal, especially at low pressures.
	Temperature and pressure dependence	The Model assumes constant pore diffusivity for temperature and pressure, but this may vary significantly with changing conditions, making accurate prediction of gas flow challenging under different field conditions.
Bidispersed Diffusion Model	Limited applicability	The model assumes gas flow in coal involves two distinct pore sizes, which may not represent all coal types or field conditions accurately. Coal can have multiple pore systems or fractures that substantially influence gas flow.
	Incomplete understanding of gas adsorption	The model assumes that gas adsorption is negligible, which may not be true under all field conditions. Gas adsorption can significantly affect gas flow in coal, especially at low pressures.
	Difficulty in estimating pore size distribution	Estimating the pore size distribution in coal can be challenging and time-consuming.
	Uncertainty in pore size distribution	The model assumes a specific distribution of pore sizes, but there is uncertainty in the actual pore size distribution in coal.
Fractal Theory-Based Fractional Diffusion Model	Complexity	The model is a relatively complex model that involves multiple parameters, such as the fractal dimension and the anomalous diffusion coefficient.
	Lack of understanding of anomalous diffusion	The model is based on the concept of anomalous diffusion, which refers to diffusion processes that do not follow normal Gaussian diffusion. However, the physical mechanisms underlying anomalous diffusion in coal are not fully understood.
	Uncertainty in the fractal dimension	The fractal dimension is a key parameter in the model, but estimating the fractal dimension of coal pores is a challenging task.
Time-Dependent Diffusivity Model	Uncertainty in the temporal evolution of coal properties	The model assumes that coal properties, such as porosity and permeability, evolve with time due to coal compaction and stress changes.
	Incomplete understanding of gas sorption	The time-dependent diffusivity model assumes that gas sorption is negligible, which may not be true under all field conditions. Gas sorption can significantly affect gas flow in coal, especially at low pressures.
	Complexity	The model involves solving partial differential equations that describe gas flow in the coal matrix, which can be computationally expensive and require significant computational resources.
	Limited understanding of coal compaction	The model assumes coal compaction as the main mechanism for changes in coal matrix properties. However, the unclear understanding of the physical mechanisms involved makes it challenging to predict coal property changes accurately over time.
Anomalous Sub-Diffusion Model	Interactions with other processes	Gas flow in coal is interconnected with processes like coal deformation, sorption, and chemical reactions. Integrating models to address these complex interactions remains a significant challenge.
	Time-dependent behavior	Gas flow in coal is a time-dependent process, with rates changing due to mining or other stresses. Modeling this dynamic behavior is challenging.
	Non-linear behavior	The Anomalous Sub-Diffusion Model assumes non-linear gas transport in coal, posing challenges in modeling and analysis.
	Complex geometries	Coal seams exhibit high complexity and heterogeneity with diverse pore sizes and shapes. Modeling gas flow in these intricate geometries is challenging.
Free Gas Density Gradient Model	Complex boundary conditions	The model assumes that the coal seam is in a state of steady-state flow, with constant boundary conditions. However, this is often not the case, as the coal seam may be subject to changing boundary conditions over time.
	Limited understanding of coal properties	The model assumes that the coal seam is a homogeneous medium, which is not always the case.
	Uncertainty in parameter values	The model relies on several parameters, including the gas diffusivity and porosity of the coal seam. However, there is often significant uncertainty in these parameter values.

- Geological uncertainty: The presence and distribution of microfractures in coal are highly variable and difficult to predict. This can make it challenging to accurately model CBM production or CO_2 storage and increase the risk of unexpected outcomes or difficulties during operations.

Apart from the role of microfractures gas flow mechanism is also important when planning for CBM production or CO_2 storage in coal. Although there are numerous models developed for depicting gas flow in coal and their accuracy to predict the gas flow in coal is yet to be developed. Different models developed include the unipore diffusion model (UDM), bidispersed diffusion model (BDM), fractal fractional diffusion model (FFDM), time-dependent diffusivity model (TDDM), anomalous sub diffusion model (ASM) and free gas density gradient model (FGDGM). These models apply to real-field application up to an extent only and thus needs modifications. Table 4 describes various challenges associated with these models.

7. Conclusion

CBM is a crucial resource when considering the energy security of the globe having a cumulative population of 8 billion and to feed energy requirements of such a large population is a tedious task. Thus, major economies like the USA, China, Russia, etc. are shifting their focus towards a gas-based economy which makes the exploitation of CBM resources indispensable. Also, the total carbon emission and its impact on our environment is a topic of concern. During 2019-20 the carbon emission declined due to covid-19 but in 2021 it rebounded with 416.5 ppm carbon emission in the atmosphere which is a huge hurdle to achieving the net zero emission goals set by the United Nations.

Considering these problems ECBM recovery can be seen as an impeccable solution as it involves both injection of CO_2 (CO_2 storage via CCUS technique) into coal seams for a very long duration of time resulting in mitigation of emission of GHG and increased production of coal bed methane gas. CO_2 storage and ECBM recovery both depend on the mechanism of the gas flow inside the coal and factors like microfractures as the gas flow is largely controlled by the cleat system including microfractures.

microfractures play a crucial role in enhancing the efficiency of the ECBM recovery technique and CO_2 storage in coal seams. The creation of microfractures allows for the efficient injection of CO_2, which displaces methane and increases the recovery rate of coalbed methane. Additionally, the microfractures provide pathways for CO_2 migration and storage within the coal matrix, reducing the risk of CO_2 leakage into the atmosphere. The understanding and utilization of microfractures in these processes are vital for achieving sustainable energy development and mitigating the effects of climate change. According to research, the creation of microfractures can increase the methane recovery rate by up to 50% and reduce the time required for CO_2 injection by up to 80%. Furthermore, the use of microfractures for CO_2 storage can result in a storage capacity of up to 7.5 tons per hectare. Contrary to their positive impact, microfractures can also have a negative effect on ECBM recovery and CO_2 storage in coal. Research has shown that microfractures can decrease methane recovery rates by up to 20% due to the release of stored gas. Additionally, these fractures can decrease CO_2 storage capacity by up to 40% by providing pathways for CO_2 leakage into the atmosphere.

Like microfractures, the gas flow mechanism is also an important phenomenon that needs to be studied while planning CBM production or CO_2 storage in coal. Various models have been developed to display the gas flow behavior but their accuracy in applicability to real fields is still not clear. Several models developed include the unipore diffusion model (UDM), bidispersed diffusion model (BDM), fractal fractional diffusion model (FFDM), time-dependent diffusivity model (TDDM), anomalous sub diffusion model (ASM) and free gas density gradient model (FGDGM). It is difficult to say which of these models is the best as each model has its strengths and weaknesses and its applicability depends on the specific coal type and field conditions. There are several reasons which show that these models are not universal and vary with different conditions and the reasons are.

- The complexity of coal structure: Coal is a complex and heterogeneous material with a complex internal structure that can be difficult to accurately model. There can be significant variations in coal properties such as porosity, permeability, and gas content even within a single seam.
- Non-linear behavior: The behavior of coal can be non-linear and can vary depending on the stress conditions, temperature, pressure, and other factors. This can make it difficult to accurately predict gas flow behavior.
- Heterogeneous field conditions: Real field conditions can be highly heterogeneous, with variations in coal properties, stress conditions, and other factors. Gas flow models developed under controlled laboratory conditions may not be able to accurately capture the complexity of real-world field conditions.
- Inadequate calibration: Gas flow models need to be calibrated using real field data to ensure that they accurately reflect the behavior of the coal. Inadequate calibration or validation of models can lead to inaccurate predictions.

To overcome these challenges, it is important to develop gas flow models that are based on sound theoretical principles, incorporate the latest advances in modeling techniques, and are calibrated and validated using comprehensive field data. It is also important to continue to gather data and conduct research to better understand the behavior of coal and improve gas flow modeling techniques. Also, an integrating approach to compile different models developed will be useful in increasing the accuracy of the model in terms of applicability to real field applications.

Data availability

No data has been used.

CRediT authorship contribution statement

Rahul Kumar Singh: Writing – original draft, Methodology, Investigation, Data curation. **Nirlipta Priyadarshini Nayak:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Sanjeev Kumar:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] R. Shaw, S. Mukherjee, The development of carbon capture and storage (CCS) in India: a critical review, Carbon Capture Science & Technology 2 (Mar. 2022) 100036, https://doi.org/10.1016/j.ccst.2022.100036.
[2] https://www.statista.com/statistics/1091999/atmospheric-concentration-of-co2-historic/).".
[3] K. Rennert, et al., Comprehensive evidence implies a higher social cost of CO2, Nature 610 (7933) (Oct. 2022) 687–692, https://doi.org/10.1038/s41586-022-05224-9.
[4] R.S.J. Tol, Social cost of carbon estimates have increased over time, Nat Clim Chang 13 (6) (Jun. 2023) 532–536, https://doi.org/10.1038/s41558-023-01680-x.
[5] https://climate.nasa.gov/effects/.".
[6] K. Seetharaman, Moorthy, N. Patwa, Saravanan, Y. Gupta, Breaking barriers in deployment of renewable energy, Heliyon 5 (1) (Feb. 2019) e01166, https://doi.org/10.1016/j.heliyon.2019.e01166.
[7] Singh Rahul Kumar, Atul Kumar Patidar, A systematic approach for planning a Geochemical survey for Hydrocarbon exploration: an overview, Iranian J. Earth Sci. (2023), https://doi.org/10.30495/IJES.2023.1975491.1821.
[8] S. Hazarika, R.K. Singh, Prediction of isotherm model for alum shale, Denmark by statistical modelling-case study, Arabian J. Geosci. 16 (12) (Dec. 2023) 652, https://doi.org/10.1007/s12517-023-11776-5.
[9] R. Kumar Singh, N. Priyadarshini Nayak, Complications in drilling operations in basalt for CO2 sequestration: an overview, Mater Today Proc (May 2023), https://doi.org/10.1016/j.matpr.2023.04.441.
[10] A.K. Patidar, R.K. Singh, T. Choudhury, The prominence of carbon capture, utilization and storage technique, a special consideration on India, Gas Science and Engineering 115 (Jul. 2023) 204999, https://doi.org/10.1016/j.jgsce.2023.204999.
[11] R. Kumar Singh, N. Priyadarshini Nayak, Opportunities and challenges of nanotechnology in enhanced oil recovery: an overview, Mater Today Proc (May 2023), https://doi.org/10.1016/j.matpr.2023.04.392.
[12] G.K. Mishra, et al., Planning India's first CO2-EOR project as carbon capture utilization & storage: a step towards sustainable growth, in: Day 2 Wed, Feb. 2019, https://doi.org/10.2118/194629-MS. April 10, 2019, SPE.
[13] F. Gozalpour, S.R. Ren, B. Tohidi, CO2 EOR and storage in oil reservoirs, Oil Gas Sci Technol Revue D IFP Energies N 60 (2005), https://doi.org/10.2516/ogst:2005036.
[14] A. Busch, Y. Gensterblum, CBM and CO2-ECBM related sorption processes in coal: a review, Int. J. Coal Geol. 87 (2) (2011) 49–71, https://doi.org/10.1016/J.COAL.2011.04.011.
[15] R. Sharma, S. Singh, S. Anand, R. Kumar, A review of coal bed methane production techniques and prospects in India, Mater Today Proc (Aug. 2023), https://doi.org/10.1016/j.matpr.2023.08.150.
[16] T.A. Moore, Coalbed methane: a review, Int. J. Coal Geol. 101 (Nov. 2012) 36–81, https://doi.org/10.1016/j.coal.2012.05.011.
[17] Y. Li, D. Tang, H. Xu, T. Chen, Fracture characterisation of coal and its implication on coalbed methane development, Int. J. Oil Gas Coal Technol. 12 (4) (2016) 396, https://doi.org/10.1504/IJOGCT.2016.077299.
[18] B. Gao, et al., Effects of coalification on nano-micron scale pore development: from bituminous to semi-anthracite, J. Nat. Gas Sci. Eng. 105 (Feb. 2022), https://doi.org/10.1016/j.jngse.2022.104681.
[19] M. Pillalamarry, S. Harpalani, S. Liu, Gas diffusion behavior of coal and its impact on production from coalbed methane reservoirs, Int. J. Coal Geol. 86 (4) (2011) 342–348, https://doi.org/10.1016/j.coal.2011.03.007.
[20] S. Wong, D. Law, X. Deng, J. Robinson, B. Kadatz, W.D. Gunter, Enhanced coalbed methane and CO2 storage in anthracitic coals—micro-pilot test at South Qinshui, Shanxi, China, Int. J. Greenh. Gas Control 1 (2007), https://doi.org/10.1016/s1750-5836(06)00005-3.
[21] Y. Yao, D. Liu, Microscopic characteristics of microfractures in coals: an investigation into permeability of coal, Procedia Earth and Planetary Science 1 (1) (2009) 903–910, https://doi.org/10.1016/j.proeps.2009.09.140.
[22] X.R. Wei, G.X. Wang, P. Massarotto, S.D. Golding, V. Rudolph, Numerical simulation of multicomponent gas diffusion and flow in coals for CO2 enhanced coalbed methane recovery, Chem. Eng. Sci. 62 (16) (2007) 4193–4203, https://doi.org/10.1016/j.ces.2007.04.032.
[23] S. Durucan, J.Q. Shi, A. Korre, Numerical modeling and prediction of abandoned mine methane recovery: field application at the Saar Coalfield, Germany, Geol. Belg. 7 (2004).
[24] L. Hong, W. Wang, D. Gao, W. Liu, Critical pore size for micropore filling in coal samples with different rank coals, PLoS One 17 (3) (2022) e0264225–e0264225, https://doi.org/10.1371/journal.pone.0264225.
[25] T.A. Moore, Coalbed methane: a review, Int. J. Coal Geol. 101 (Feb. 2012) 36–81, https://doi.org/10.1016/j.coal.2012.05.011.
[26] Y. Cai, et al., Permeability evolution in fractured coal—Combining triaxial confinement with X-ray computed tomography, acoustic emission and ultrasonic techniques, Int. J. Coal Geol. 122 (2014) 91–104.
[27] Z.J. Pan, J.P. Ye, F.B. Zhou, Y.L. Tan, L.D. Connell, J.J. Fan, CO2 storage in coal to enhance coalbed methane recovery: a review of field experiments in China, Int. Geol. Rev. 60 (2018), https://doi.org/10.1080/00206814.2017.1373607.
[28] J. Yi, I.Y. Akkutlu, C. V Deutsch, Gas transport in bidisperse coal particles: investigation for an effective diffusion coefficient in coalbeds, J. Can. Petrol. Technol. 47 (10) (2008) 20–26, https://doi.org/10.2118/08-10-20.
[29] Y.-.F. Liu, X.-.C. Li, B. Bai, Preliminary estimation of CO2 storage capacity of coalbeds in China, J Rock Mech Eng 24 (2005).
[30] M. Pillalamarry, S. Harpalani, S. Liu, Gas diffusion behavior of coal and its impact on production from coalbed methane reservoirs, Int. J. Coal Geol. 86 (4) (Feb. 2011) 342–348, https://doi.org/10.1016/j.coal.2011.03.007.
[31] A. Keshavarz, R. Sakurovs, M. Grigore, M. Sayyafzadeh, Effect of maceral composition and coal rank on gas diffusion in Australian coals, Int. J. Coal Geol. 173 (Feb. 2017) 65–75, https://doi.org/10.1016/j.coal.2017.02.005.

[32] M.N. Heriawan, K. Koike, Coal quality related to microfractures identified by CT image analysis, Int. J. Coal Geol. 140 (Feb. 2015) 97–110, https://doi.org/10.1016/j.coal.2015.02.001.

[33] M.J. Afshari Moein, B. Valley, K.F. Evans, Scaling of fracture patterns in three deep boreholes and implications for constraining fractal discrete fracture network models, Rock Mech. Rock Eng. 52 (6) (Jun. 2019) 1723–1743, https://doi.org/10.1007/s00603-019-1739-7.

[34] J. Pan, K. Wang, Q. Hou, Q. Niu, H. Wang, Z. Ji, Micro-pores and fractures of coals analysed by field emission scanning electron microscopy and fractal theory, Fuel 164 (Jan. 2016) 277–285, https://doi.org/10.1016/j.fuel.2015.10.011.

[35] X. Shi, et al., Micrometer-scale fractures in coal related to coal rank based on micro-CT scanning and fractal theory, Fuel 212 (Jan. 2018) 162–172, https://doi.org/10.1016/j.fuel.2017.09.115.

[36] Y. Yao, D. Liu, Y. Che, D. Tang, S. Tang, W. Huang, Non-destructive characterization of coal samples from China using microfocus X-ray computed tomography, Int. J. Coal Geol. 80 (2) (2009) 113–123.

[37] K. Vandersteen, B. Busselen, K. Van Den Abeele, J. Carmeliet, Quantitative characterization of fracture apertures using microfocus computed tomography, Geological Society, London, Special Publications 215 (1) (2003) 61–68.

[38] T. Li, C. Wu, Q. Liu, Characteristics of coal fractures and the influence of coal facies on coalbed methane productivity in the South Yanchuan Block, China, J. Nat. Gas Sci. Eng. 22 (2015) 625–632.

[39] Y. Zhang, M. Lebedev, M. Sarmadivaleh, A. Barifcani, T. Rahman, S. Iglauer, Swelling effect on coal micro structure and associated permeability reduction, Fuel 182 (2016) 568–576.

[40] Y. Chen, et al., Pore and fracture characteristics of different rank coals in the eastern margin of the Ordos Basin, China, J. Nat. Gas Sci. Eng. 26 (2015) 1264–1277.

[41] C. Liu, B. Shi, J. Zhou, C. Tang, Quantification and characterization of microporosity by image processing, geometric measurement and statistical methods: application on SEM images of clay materials, Appl. Clay Sci. 54 (1) (2011) 97–106.

[42] X. Shi, et al., Micrometer-scale fractures in coal related to coal rank based on micro-CT scanning and fractal theory, Fuel 212 (2018) 162–172, https://doi.org/10.1016/j.fuel.2017.09.115.

[43] G. Wang, J. Shen, S. Liu, C. Jiang, X. Qin, Three-dimensional modeling and analysis of macro-pore structure of coal using combined X-ray CT imaging and fractal theory, Int. J. Rock Mech. Min. Sci. 123 (2019), https://doi.org/10.1016/j.ijrmms.2019.104082.

[44] C.O. Karacan, E. Okandan, Adsorption and gas transport in coal microstructure: investigation and evaluation by quantitative X-ray CT imaging, Fuel 80 (4) (2001) 509–520.

[45] B. Callow, I. Falcon-Suarez, S. Ahmed, J.M. Matter, Assessing the carbon sequestration potential of basalt using X-ray micro-CT and rock mechanics, Int. J. Greenh. Gas Control 70 (2018).

[46] B.B. Mandelbrot, The Fractal Geometry of Nature, W.H. Freeman and Company Press, New York, 1982.

[47] B. Mandelbrot, Fractals: Form, Chance and Dimension, W H Freeman and Co, San Francisco, 1977.

[48] T. Nakagawa, I. Komaki, M. Sakawa, K. Nishikawa, Small angle X-ray scattering study on change of fractal property of Witbank coal with heat treatment, Fuel 79 (11) (2000) 1341–1346.

[49] M.M. Mahamud, M.F. Novo, The use of fractal analysis in the textural characterization of coals, Fuel 87 (2) (2008) 222–231.

[50] M. Mahamud, Ó. López, J.J. Pis, J.A. Pajares, Textural characterization of coals using fractal analysis, Fuel Process. Technol. 81 (2) (2003) 127–142.

[51] Y. Zhao, Y. Feng, X. Zhang, Molecular simulation of CO2/CH4 self- and transport diffusion coefficients in coal, Fuel 165 (2016) 19–27, https://doi.org/10.1016/j.fuel.2015.10.035.

[52] A. Liu, P. Liu, S. Liu, Gas diffusion coefficient estimation of coal: a dimensionless numerical method and its experimental validation, Int J Heat Mass Transf 162 (2020), https://doi.org/10.1016/j.ijheatmasstransfer.2020.120336.

[53] M. Fernández-Martínez, M. Sánchez-Granero, A new fractal dimension for curves based on fractal structures, Topol. Appl. 203 (2016) 108–124.

[54] K. Falconer, Fractal Geometry: Mathematical Foundations and Applications, John Wiley & Sons, 2004.

[55] M. Mahamud, Ó. López, J.J. Pis, J.A. Pajares, Textural characterization of coals using fractal analysis, Fuel Process. Technol. 81 (2) (2003) 127–142.

[56] L. Pontrjagin, L. Schnirelmann, Sur une propriété métrique de la dimension, Ann. Math. (1932) 156–162.

[57] L. Pontrjagin, L. Schnirelmann, Sur une propriété métrique de la dimension, Ann. Math. (1932) 156–162.

[58] G. Wang, J. Shen, S. Liu, C. Jiang, X. Qin, Three-dimensional modeling and analysis of macro-pore structure of coal using combined X-ray CT imaging and fractal theory, Int. J. Rock Mech. Min. Sci. 123 (Feb. 2019), https://doi.org/10.1016/j.ijrmms.2019.104082.

[59] M.N. Heriawan, K. Koike, Coal quality related to microfractures identified by CT image analysis, Int. J. Coal Geol. 140 (2015) 97–110, https://doi.org/10.1016/j.coal.2015.02.001.

[60] Y. Yao, D. Liu, Microscopic characteristics of microfractures in coals: an investigation into permeability of coal, Procedia Earth and Planetary Science 1 (1) (2009) 903–910, https://doi.org/10.1016/j.proeps.2009.09.140.

[61] A. Busch, Y. Gensterblum, CBM and CO2-ECBM related sorption processes in coal: a review, Int. J. Coal Geol. 7 (2011), https://doi.org/10.1016/j.coal.2011.04.011.

[62] L. Fengli, J. Bo, C. Guoxi, S. Yu, T. Zheng, Structural and evolutionary characteristics of pores-microfractures and their influence on coalbed methane exploitation in high-rank brittle tectonically deformed coals of the Yangquan mining area, northeastern Qinshui basin, China, J. Pet. Sci. Eng. 174 (2019) 1290–1302, https://doi.org/10.1016/j.petrol.2018.11.081.

[63] Md M. Hossain, M.K. Rahman, Numerical simulation of complex fracture growth during tight reservoir stimulation by hydraulic fracturing, J. Pet. Sci. Eng. 60 (2) (Feb. 2008) 86–104, https://doi.org/10.1016/j.petrol.2007.05.007.

[64] W. Jin, M. Gao, B. Yu, R. Zhang, J. Xie, Z. Qiu, Elliptical fracture network modeling with validation in Datong Mine, China, Environ. Earth Sci. 73 (11) (Jun. 2015) 7089–7101, https://doi.org/10.1007/s12665-015-4158-4.

[65] W. Zhao, X. Su, D. Xia, S. Hou, Q. Wang, Y. Zhou, Enhanced coalbed methane recovery by the modification of coal reservoir under the supercritical CO2 extraction and anaerobic digestion, Energy 259 (Feb. 2022), https://doi.org/10.1016/j.energy.2022.124914.

[66] X. Du, et al., CO2 and CH4 adsorption on different rank coals: a thermodynamics study of surface potential, Gibbs free energy change and entropy loss, Fuel 283 (Feb. 2021) 118886, https://doi.org/10.1016/J.FUEL.2020.118886.

[67] Y. Jing, R.T. Armstrong, P. Mostaghimi, Rough-walled discrete fracture network modelling for coal characterisation, Fuel 191 (Mar. 2017) 442–453, https://doi.org/10.1016/j.fuel.2016.11.094.

[68] Y. Ju, C. Xi, Y. Zhang, L. Mao, F. Gao, H. Xie, Laboratory in situ CT observation of the evolution of 3D fracture networks in coal subjected to confining pressures and axial compressive loads: a novel approach, Rock Mech. Rock Eng. 51 (11) (Nov. 2018) 3361–3375, https://doi.org/10.1007/s00603-018-1459-4.

[69] J.Q. Shi, S. Durucan, M. Fujioka, A reservoir simulation study of CO2 injection and N2 flooding at the Ishikari coalfield CO2 storage pilot project, Japan, Int. J. Greenh. Gas Control 2 (2008), https://doi.org/10.1016/s1750-5836(07)00112-0.

[70] M. Klawitter, J. Esterle, S. Collins, A study of hardness and fracture propagation in coal, Int. J. Rock Mech. Min. Sci. 76 (Jun. 2015) 237–242, https://doi.org/10.1016/j.ijrmms.2015.02.006.

[71] H.G.E. Hentschel, I. Procaccia, The infinite number of generalized dimensions of fractals and strange attractors, Physica D 8 (3) (Sep. 1983) 435–444, https://doi.org/10.1016/0167-2789(83)90235-X.

[72] S. Lyu, et al., Natural fractures in soft coal seams and their effect on hydraulic fracture propagation: a field study, J. Pet. Sci. Eng. 192 (Sep. 2020) 107255, https://doi.org/10.1016/j.petrol.2020.107255.

[73] https://mopng.gov.in/en/exp-and-prod/unconventional.” .

[74] Z. Mingjun, W. Chongtao, P. Haiyang, C. Jia, Productivity of coalbed methane wells in southern of Qinshui Basin, Min. Sci. Technol. 20 (2010), https://doi.org/10.1016/s1674-5264(09)60278-7.

[75] Q. Yang, WANG You-an. Theory of methane diffusion from coal cuttings and its application [J], J. China Coal Soc. 3 (1986) 87–94.

[76] D.M. Smith, F.L. Williams, Diffusion models for gas production from coal, Fuel 63 (2) (1984) 256–261, https://doi.org/10.1016/0016-2361(84)90047-4.

[77] B. Nie, Y. Guo, S. Wu, L. Zhang, Theoretical model of gas diffusion through coal particles and its analytical solution, Zhongguo Kuangye Daxue Xuebao (Journal of China University of Mining and Technology) 30 (2001).

[78] A. Bani-Mustafa, K.M. Matawie, C.F. Finch, A. Al-Nasser, E. Ciavolino, Recursive residuals for linear mixed models, Qual Quant 53 (3) (May 2019) 1263–1274, https://doi.org/10.1007/s11135-018-0814-6.

[79] N. Ayawei, A.N. Ebelegi, D. Wankasi, Modelling and interpretation of adsorption isotherms, J. Chem. 2017 (2017) 1–11, https://doi.org/10.1155/2017/3039817.

[80] M. Wierzbicki, N. Skoczylas, M. Kudasik, The use of a unipore diffusion model to describe the kinetics of methane release from coal spoil in the longwall environment, Studia Geotechnica Mech. 39 (2) (Jun. 2017) 81–89, https://doi.org/10.1515/sgem-2017-0018.

[81] Z.-Q. Li, Y. Liu, Y.-P. Xu, D.-Y. Song, Gas Diffusion Mechanism in Multi-Scale Pores of Coal Particles and New Diffusion Model of Dynamic Diffusion Coefficient, 2016.

[82] M. Karbownik, J. Krawczyk, K. Godyń, T. Schlieter, J. Ščučka, Analysis of the influence of coal petrography on the proper application of the unipore and bidisperse models of methane diffusion, Energies 14 (24) (Dec. 2021) 8495, https://doi.org/10.3390/en14248495.

[83] R. Metzler, J. Klafter, The random walk's guide to anomalous diffusion: a fractional dynamics approach, Physics Report 339 (1) (2000) 1–77, https://doi.org/10.1016/S0370-1573(00)00070-3.

[84] G. Wang, T. Ren, Q. Qi, L. Zhang, Q. Liu, Prediction of coalbed methane (CBM) production considering bidisperse diffusion: model development, experimental test, and numerical simulation, Energy & Fuels 31 (6) (Jun. 2017) 5785–5797, https://doi.org/10.1021/acs.energyfuels.6b02500.

[85] E. Ruckenstein, A.S. Vaidyanathan, G.R. Youngquist, Sorption by solids with bidisperse pore structures, Chem. Eng. Sci. 26 (9) (Sep. 1971) 1305–1318, https://doi.org/10.1016/0009-2509(71)80051-9.

[86] J.Q. Shi, S. Durucan, A bidisperse pore diffusion model for methane displacement desorption in coal by CO2 injection, Fuel 82 (10) (Jul. 2003) 1219–1229, https://doi.org/10.1016/S0016-2361(03)00010-3.

[87] H. Jiang, Y. Cheng, L. Yuan, F. An, K. Jin, A fractal theory based fractional diffusion model used for the fast desorption process of methane in coal, Chaos 23 (3) (2013), https://doi.org/10.1063/1.4813597.

[88] S. Wang, Z. Ma, H. Yao, Fractal diffusion model used for diffusion in porous material within limited volume of stiff container, Chem. Eng. Sci. 64 (6) (Mar. 2009) 1318–1325, https://doi.org/10.1016/j.ces.2008.11.016.

[89] S. Wang, Z. Ma, H. Yao, Fractal diffusion model used for diffusion in porous material within limited volume of stiff container, Chem. Eng. Sci. 64 (6) (Mar. 2009) 1318–1325, https://doi.org/10.1016/j.ces.2008.11.016.

[90] H. Xu, et al., Numerical modeling of gas extraction from coal seam combined with a dual-porosity model: finite difference solution and multi-factor analysis, Fuel 313 (2022), https://doi.org/10.1016/j.fuel.2021.122687.

[91] L.-.Z. Hu, L. Sun, J.-.Z. Zhao, P. Wei, W.-.F. Pu, Influence of formation heterogeneity on foam flooding performance using 2D and 3D models: an experimental study, Pet Sci 17 (2020), https://doi.org/10.1007/s12182-019-00408-x.

[92] M. Zou, C. Wei, H. Yu, L. Song, Modeling and application of coalbed methane recovery performance based on a triple porosity/dual permeability model, J. Nat. Gas Sci. Eng. 22 (Feb. 2015) 679–688, https://doi.org/10.1016/j.jngse.2015.01.019.

[93] X. Jiang, M. Xu, H. Qi, The fractional diffusion model with an absorption term and modified Fick's law for non-local transport processes, Nonlinear Anal. R. World Appl. 11 (1) (Feb. 2010) 262–269, https://doi.org/10.1016/j.nonrwa.2008.10.057.

[94] W. Fan, X. Jiang, S. Chen, Parameter estimation for the fractional fractal diffusion model based on its numerical solution, Comput. Math. Appl. 71 (2) (Jan. 2016) 642–651, https://doi.org/10.1016/j.camwa.2015.12.030.

[95] T. Liu, B. Lin, Time-dependent dynamic diffusion processes in coal: model development and analysis, Int J Heat Mass Transf 134 (May 2019) 1–9, https://doi.org/10.1016/j.ijheatmasstransfer.2019.01.005.

[96] G. Yue, Z. Wang, C. Xie, X. Tang, J. Yuan, Time-dependent methane diffusion behavior in coal: measurement and modeling, Transp Porous Media 116 (1) (2017) 319–333, https://doi.org/10.1007/s11242-016-0776-x.

[97] Y. Qin, H. Xu, W. Liu, J. Liu, W. Duan, Time- and pressure-independent gas transport behavior in a coal matrix: model development and improvement, Energy & Fuels 34 (8) (2020) 9355–9370, https://doi.org/10.1021/acs.energyfuels.0c01182.

[98] S. Lu, et al., Gas time-dependent diffusion in pores of deformed coal particles: model development and analysis, Fuel 295 (2021) 120566.

[99] L. Cheng-Wu, X. Hong-Lai, G. Cheng, L. Wen-biao, Modeling and experiments for the time-dependent diffusion coefficient during methane desorption from coal, J. Geophys. Eng. 15 (2) (Apr. 2018) 315–329, https://doi.org/10.1088/1742-2140/aa98ba.

[100] J. Kang, F. Zhou, G. Ye, Y. Liu, An anomalous subdiffusion model with fractional derivatives for methane desorption in heterogeneous coal matrix, AIP Adv. 5 (12) (2015) 127119, https://doi.org/10.1063/1.4938518.

[101] J. Kang, F. Zhou, T. Xia, G. Ye, Numerical modeling and experimental validation of anomalous time and space subdiffusion for gas transport in porous coal matrix, Int J Heat Mass Transf 100 (2016) 747–757, https://doi.org/10.1016/j.ijheatmasstransfer.2016.04.110.

[102] Z. Pan, L.D. Connell, Modelling permeability for coal reservoirs: a review of analytical models and testing data, Int. J. Coal Geol. 92 (2012) 1–44, https://doi.org/10.1016/J.COAL.2011.12.009.

[103] M. Dentz, A. Cortis, H. Scher, B. Berkowitz, Time behavior of solute transport in heterogeneous media: transition from anomalous to normal transport, Adv. Water Resour. 27 (2) (Feb. 2004) 155–173, https://doi.org/10.1016/j.advwatres.2003.11.002.

[104] M.M. Meerschaert, Y. Zhang, B. Baeumer, Tempered anomalous diffusion in heterogeneous systems, Geophys. Res. Lett. 35 (17) (Sep. 2008) L17403, https://doi.org/10.1029/2008GL034899.

[105] W. Liu, Y. Qin, W. Zhao, D. Wu, J. Liu, C. He, Modeling of gas transport driven by density gradients of free gas within a coal matrix: perspective of isothermal adsorption, Energy & Fuels 34 (11) (2020) 13728–13739, https://doi.org/10.1021/acs.energyfuels.0c02442.

[106] W. Liu, et al., Theoretical model and numerical solution of gas desorption and flow mechanism in coal matrix based on free gas density gradient, J. Nat. Gas Sci. Eng. 90 (2021) 103932, https://doi.org/10.1016/j.jngse.2021.103932.

[107] W. Liu, H. Xu, D. Wu, Y. Qin, J. Liu, W. Zhao, Gases migration behavior of adsorption processes in coal particles: density gradient model and its experimental validation, Process Saf. Environ. Protect. 152 (Feb. 2021) 264–277, https://doi.org/10.1016/j.psep.2021.06.014.

[108] W. Liu, et al., Theoretical model and numerical solution of gas desorption and flow mechanism in coal matrix based on free gas density gradient, J. Nat. Gas Sci. Eng. 90 (2021) 103932, https://doi.org/10.1016/j.jngse.2021.103932.

[109] A. Khalilnezhad, M. Simjoo, N. Hamidian, Insights into viscous fingering effect induced by wettability alteration processes: a fractional flow study, J. Pet. Sci. Eng. 201 (2021), https://doi.org/10.1016/j.petrol.2021.108491.