Review Article

Study on Competitive Adsorption and Displacing Properties of CO₂ Enhanced Shale Gas Recovery: Advances and Challenges

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CO₂ enhanced shale gas recovery (CO₂-ESGR) draws worldwide attentions in recent years with having significant environmental benefit of CO₂ geological storage and economic benefit of shale gas production. This paper is aimed at reviewing the state of experiment and model studies on gas adsorption, competitive adsorption of CO₂/CH₄, and displacement of CO₂-CH₄ in shale in the process of CO₂-ESGR and pointing out the related challenges and opportunities. Gas adsorption mechanism in shale, influencing factors (organic matter content, kerogen type, thermal maturity, inorganic compositions, moisture, and micro/nano-scale pore), and adsorption models are described in this work. The competitive adsorption mechanisms are qualitatively ascertained by analysis of unique molecular and supercritical properties of CO₂ and the interaction of CO₂ with shale matrix. Shale matrix shows a stronger affinity with CO₂, and thus, adsorption capacity of CO₂ is larger than that of CH₄ even with the coexistence of CO₂-CH₄ mixture. Displacement experiments of CO₂-CH₄ in shale proved that shale gas recovery is enhanced by the competitive adsorption of CO₂ to CH₄. Although the competitive adsorption mechanism is preliminary revealed, some challenges still exist. Competitive adsorption behavior is not fully understood in the coexistence of CO₂ and CH₄ components, and more experiment and model studies on adsorption of CO₂-CH₄ mixtures need to be conducted under field conditions. Coupling of competitive adsorption with displacing flow is key factor for CO₂-ESGR but not comprehensively studied. More displacement experiments of CO₂-CH₄ in shale are required for revealing the mechanism of flow and transport of gas in CO₂-ESGR.

1. Introduction

Due to increasing combustion of fossil fuels and the ensuing large-scale CO₂ emissions, the high level of CO₂ content in the global atmosphere is believed as the main driving force of global climate change [1, 2], which may cause climate disasters, seriously affecting human life and the earth’s ecology [3, 4]. CO₂ capture, utilization, and storage (CCUS) technology is a promising and practical CO₂ mitigation technology by injecting the captured CO₂ into underground formation for permanent sequestration and enhanced oil/gas recovery and other underground energy recovery [5–8], drawing worldwide attentions.

Natural gas is regarded as one of the most promising alternatives of traditional fossil fuels, such as coal and oil, as it is one of the efficient and clean energy sources for environmental protection. In recent years, large-scale shale gas reservoirs have been discovered worldwide as one of the typical unconventional natural gas resources. The global shale gas is reported as five times conventional gas reserves [9] with the large technically recoverable resources reported in China (1115 tcf), US (665 tcf), and Canada (573 tcf) [10]. The development of shale gas reservoir is imminent. Shale formations are commonly tight with low intrinsic permeability, and thus, it is difficult to be exploited by conventional development technologies. It is necessary to increase permeability and pore connectivity by fracturing technology for exploitation. At present, hydraulic fracturing is the main reservoir reconstruction technology to artificially fracture and extend natural microcracks for shale gas exploitation [6, 7].
However, hydraulic fracturing has many problems such as water consumption, chemical additive pollution, and reservoir damage [11].

Compared to hydraulic fracturing, CO₂ fracturing has many advantages such as reducing fracturing pressure, reducing flow blockage, and avoiding reservoir damage and pollution [6, 12]. The conception of CO₂ enhanced shale gas recovery (CO₂-ESGR) technology comes out by combining CO₂ fracturing and CO₂ injection for shale gas exploitation. CO₂ replaces the adsorbed CH₄ in shale matrix (kerogen or clay) through competitive adsorption and displaces the free CH₄ in the fractured pores during the process of CO₂-ESGR, thereby increasing the recovery of shale gas. Notably, CO₂-ESGR is one of the promising CCUS technologies to store CO₂ into the shale formation for greenhouse gas emission reduction [13]. Thus, CO₂-ESGR has great application potential for both the economic benefit of efficient exploitation of shale gas reservoirs and the simultaneous environmental benefit of CO₂ mitigation.

CO₂-ESGR contains several processes, such as shale fracturing, CO₂ displacement of the free CH₄ in pore and fractures, CH₄ desorption and CO₂ competitive adsorption, and CO₂ geological storage. The schematic diagram of CO₂-ESGR is shown in Figure 1. Therefore, in order to achieve effective development of CO₂-ESGR technology, some relevant key scientific problems must be solved, including mechanism of CH₄ adsorption/desorption, CO₂/CH₄ competitive adsorption mechanism in shale matrix, and CO₂ displacement CH₄ flow and mass transfer mechanism. The adsorption/desorption characteristic of single-component gas (CH₄ or CO₂) in shale has also been fundamentally studied [14–16]. Among these key scientific problems, mechanism of CO₂/CH₄ competitive adsorption in shale matrix and flow and mass transfer in the displacement of CO₂–CH₄ has not been fully understood and has attracted widespread attention and curiosity worldwide. Recently, more and more studies are focused on these issues.

This work is aimed at addressing the issue of CO₂ replacing and displacing shale gas in CO₂-ESGR, link the study on adsorption/desorption of CO₂/CH₄ in shale and flow characteristics of CO₂ displacing CH₄. The advances on competitive adsorption of CO₂/CH₄ during CO₂ displacing CH₄ in shale related to CO₂-ESGR are review, and the challenges and opportunities are address.

2. Gas Adsorption in Shale

The natural gas in shale is generated in situ from the organic-rich deposition through biogenic and thermogenic processes [17]. Shale gas is consisted of predominant CH₄ (>94%), other higher hydrocarbons (ethane, propane, and butane), and minor fraction of inorganic gases [18]. Shale gas is mainly stored in three states: adsorbed gas on the micro/nano-scale pore of shale matrix, free gas in natural cracks and pores, and a small amount of solution gas dissolved in the connate water [19]. The adsorbed CH₄ in the micro/nano-scale pores accounts for a great proportion (20–80%) of the total shale gas resources [14, 20, 21]. Therefore, gas adsorption in shale is one of the most important mechanism of gas storage. Thus, adsorption/desorption characteristics of CH₄ in shale play a key role in the determination of economic feasibility and exploration mode of shale gas reservoirs. The knowledge of gas storage and transport mechanisms related to adsorption is required for resource quantification and evaluation of long-term production behavior. [22]

2.1. Adsorption Mechanism. Gas adsorption is the accumulation process of gas molecules on the rock surface by two kinds of mechanism: physisorption (physical adsorption) through van der Waals forces and chemisorption (chemical adsorption) through bonds by electron sharing or transfer [23]. Thereby, a high density in adsorbed phase is formed different from the free gas present in the surrounding [24]. Thus, the gas storage potential of shale is increased by twice or more than rocks in absence of adsorption due to the adsorption mechanism [25]. Commonly, the gas adsorption in shale is mainly considered as physisorption [26, 27]. Physisorption is an exothermic process, and the adsorption heat is in the range from 8 to 40 kJ/mol [28]. It is believed that two kinds of physisorption mechanism take place for gas adsorption in shale: monolayer adsorption at low pressures and multilayer adsorption at high pressures [23]. Desorption is regarded as the counter process of adsorption with gas released from shale matrix surface.

The gas adsorption characteristics in shale are usually evaluated by the measurement of adsorption isotherms in laboratory, which involves measuring the uptake or release of either gas species on a shale sample at certain temperature and pressure conditions [29–32]. Adsorption isotherm curves are commonly measured by gravimetric, volumetric/manometric, and chromatographic methods [30, 33, 34]. Thus, the gas storage capacity in shale due to adsorption can be estimated under certain temperature and pressure according to the adsorption isotherms. Based on the experimental data of adsorption/desorption isotherm, models are established for predicting gas adsorption behavior in shale, such as Langmuir model and Brunauer-Emmett-Teller models.

2.2. Influence of Various Factors on CH₄ Adsorption. Shale commonly consists of organic matter (kerogen), inorganic clay, and other mineral compositions, such as quartz and mica. The related mineral and geological properties of shale play a key role in controlling the gas adsorption characteristics in shale. For the purpose of evaluating shale gas reservoir resources, researchers concentrated on the adsorption/desorption mechanism of CH₄ in shale in the early studies, and the main influencing factors were analyzed: organic matter content, kerogen type, mineralogy, thermal maturity (Rₒ), moisture, micropore structure and pore size distribution, etc. Thus, the main controlling mechanism of influencing factors is described, and no more details are introduced here because the influence of various factors on adsorption has been reviewed by Rani et al. [24] and Klewiah et al. [32].

The organic matter content in shale is usually quantified by the total organic carbon (TOC), and it is one of the most significant controlling factors on adsorption characteristics. Some studies [22, 35] confirmed that the amount of adsorbed
CH₄ in shale is proportional to the organic matter content, and the larger TOC can improve the adsorption capacity of CH₄. This phenomenon can take place in almost all kinds of shales. Klewiah et al. [32] summarized a lot of experimental data [22, 29, 35–45] in different shales and confirmed the strong correlation of gas capacity with TOC, shown in Figure 2. The adsorption capacities of CH₄ have strong positive linearity with TOC for both dry and moist shales. The probable reason is that organic richness is believed to be primarily responsible for the microporous nature of shale and the main contributor to the surface area and total pore volume [43, 46]. Thus, gas adsorption capacity increases with rising content of TOC in shale.

Besides TOC, kerogen type plays a significant role on controlling gas adsorption capacity. Considering the nature of organic matter and surroundings, kerogen is categorized as three types based on its composition and type of generating hydrocarbon [47–49]. Type I, Type II, and Type III kerogen are attributed to extensive aromatization from immature to overmature organic matter [32]. Type I kerogen mainly consists of algal and amorphous kerogen, which is mostly generated from lacustrine and marine environments.

**Figure 1:** (a) Schematic diagram of CO₂ enhanced shale gas recovery; (b) schematic diagram of CO₂ displacing/replacing CH₄ in shale during CO₂ fracturing for enhanced shale gas recovery [12].
Type I kerogen is highly likely to generate oil and has ability to produce gas in the proper thermal maturity. Type II kerogen is rich in hydrogen and low in carbon, and it is formed from mixed terrestrial and marine source materials. Type II kerogen can generate both oil and gas. Type III kerogen is rich in oxygen and poor in hydrogen, and it is formed from terrestrial plant debris. Type III kerogen generally generates gas. Due to the different source rock material and deposition environments of kerogen, some studies [35, 50] have proved that the gas adsorption capacity is in the order of Type III > Type II > Type I.

Thermal maturity ($R_o$) is another key influencing factor in gas adsorption capacity of shales. Thermal maturity is an indicator to show the heat-driven diagenetic changes of organic matter in sedimentary source rocks to generate hydrocarbons [32]. With the structural transformation of kerogen during maturation, more additional micro/nano-scale pores are generated [50–52]. Correspondingly, the gas adsorption capacity in shale increases with the higher thermal maturity in general, although a few studies found that the thermal maturity has little effect on adsorption [35] or CH$_4$ adsorption capacity concomitantly decrease with increasing maturity [50, 53].

The main inorganic compositions of shale include clay, quartz, mica, albite, pyrite, carbonate, and mineral, and these inorganic compositions, particularly the clay minerals, contribute enormously to the inner surface area and micropore volume and affect adsorption properties [54–56]. Thus, clay types (illite, smectite, kaolinite) and contents are one of the significant factors on gas adsorption in shale. The larger clay contents in shale are believed to increase the gas adsorption capacity [22, 57, 58]. However, the influence of inorganic mineral matters on different gas adsorption shows different behaviors in various studies. CH$_4$ adsorption capacity is affected little by the inorganic matter in some studies [59], but several researches also show that the inorganic matter has significant influence on CO$_2$ adsorption [29]. Nevertheless, more researchers have proven that the mineral components have appreciable sorption capacity for both CH$_4$ and CO$_2$ [22, 40].

Moisture also plays a crucial role on analysis of gas adsorption characteristics. The effect of moisture in shale is always related to organic matters and clay contents [53, 60]. It is reported that water molecules would compete with gas for identical adsorption sites on organic matters via hydrogen bonding [22, 35, 45, 50] and interact with preadsorbed water and charged surfaces of mineral matter (especially chemisorptive clay) [32]. Thus, moisture weakens the adsorption capacity of CH$_4$ in shale, shown in Figure 2.

TOC content and shale mineral composition analysis may not fully explain the gas adsorption mechanism in shale; pore volume (especially micro/nano-scale pores) and inner surface area are crucial on the gas adsorption capacity [61]. Rexer et al. [61] showed that the main controlling factor for the amount of adsorbed gas in shale is the volume of adsorption pores, and most of the adsorbed CH$_4$ is in microscale pores with a diameter of less than 6 nm. Xue et al. [62] conducted on visualization study of shale micropore structure and mineral composition analysis and their influence on adsorption and found that the gas adsorption capacity is linearly related to the product of TOC and surface porosity.

Figure 2: Correlation between TOC and CH$_4$ and CO$_2$ sorption capacity in dry and moisture shales [32]. Experimental data points are selected from literature [22, 29, 35–45].
2.3. Adsorption Difference between CO₂ and CH₄ in Shale. Due to the physical properties difference, CO₂ and CH₄ have significantly different adsorption behavior in shale. The typical adsorption isotherms for CH₄ and CO₂ have been studied by Weniger et al. [29], shown in Figure 3. Under different TOC condition, the excess adsorption of CH₄ in shale consistently increases with pressure and gradually reach a constant value at high pressures [32, 63–65]. The adsorption of CO₂ is closely related to the phase state: in gas state, the excess adsorption of CO₂ increases with pressure by having a larger increasing rate than CH₄ before supercritical point, then reaches the maximum in the vicinity of supercritical pressure and then decreases in supercritical state. The mentioned difference in adsorption characteristics between CO₂ and CH₄ has also been clearly reported in other experiments [45, 66–70].

Compared to CH₄ adsorption in shale, some influencing factors have different performance for CO₂ adsorption in shale, which will be described as follows. Similar with CH₄, CO₂ adsorption capacity increases with higher TOC, shown in Figure 3. More precisely, the adsorption capacities of both two gases have strong positive linearity with TOC, summarized by Klewiah et al. [32], illustrated in Figure 2. Generally, the adsorption capacity of CO₂ is much larger than that of CH₄ at the same TOC for both dry and moist shale, and the increasing rate of the former versus TOC is much higher than that of the latter in dry shale. In contrast to that, the adsorption capacity of CH₄ in the moist shale is lower than that in dry one; CO₂ adsorption capacity in moist shale may larger than that in dry one at low TOC, shown in Figure 2. Results of experiments and molecule grand canonical Monte Carlo (GCMC) simulations in Huang et al. [70] showed that the maximum adsorption capacity of gas molecules for both CO₂ and CH₄ on kerogen is proportional to the effective pore volumes, which increases with kerogen maturity but decreases with moisture content. The effect of other factors on adsorption, such as thermal maturity and inorganic components, shows similar for both CO₂ and CH₄, which was described by Isaac et al. [32]

2.4. Adsorption Models. Adsorption models, such as Langmuir model and Brunauer-Emmett-Teller models, are frequently built based on the experimental adsorption isotherms. For the main adsorption mechanism of CH₄ in shale, Langmuir model is built for the evaluation of monolayer adsorption behavior, and Brunauer-Emmett-Teller (BET) and Freundlich’s isotherms are established for the multilayer adsorption (Table 1) [23].

Langmuir model and its improved model [15, 35, 61] are widely used for the adsorption/desorption of single-component gas under the conditions of low pressure in shale. Lu et al. [30] proved that the Langmuir model can accurately predict the adsorption characteristics at a single temperature, but the adsorption prediction of Langmuir under multitemperature conditions is not so accurate, while the bi-Langmuir model has a better prediction accuracy on the adsorption characteristics of single-component gas in shale by considering the influence of temperature changes.

Most of shale gas reservoirs are usually located in depth of 2000–4000 m underground, and the reservoir temperatures are in the range of 96–122°C with the pore pressures of 15–25 MPa [69]. The critical conditions are 31.1°C and 7.4 MPa for CO₂ and -82.6°C and 4.6 MPa for CH₄ [74, 75], and thereby, CH₄ and CO₂ are both in supercritical state in shale reservoirs. As the conventional adsorption model, such as Langmuir model, cannot precisely predict the adsorption behavior under shale gas reservoir conditions of high temperature and high pressure, and more fine models are needed in response to this situation.

The supercritical adsorption models based on adsorption potential theory, such as supercritical Dubinin-Radushkevich (SDR) model, are developed for accurate description of gas adsorption behaviors in shale under high-temperature and high-pressure reservoir conditions. However, Tian et al. [76] found that there is no significant improvement for SDR model in prediction of the maximum absolute CH₄ adsorption in the Sichuan Basin shale by comparing to Langmuir model. Song et al. [77] proposed an adaptive L-SDR model based on the combination of SDR model and Langmuir model, and the comparison of the adaptive L-SDR, Langmuir, and SDR for prediction of gas adsorption isotherm in Tarim Basin shale showed that the L-SDR model more accurately predicts the adsorption characteristics of supercritical CH₄ in shale at both low and high temperatures. The lattice density functional theory (LDFT) model is another supercritical adsorption model to predict the adsorption enthalpy. Hwang et al. [78] showed that even under high pressure, the predictive ability of the LDFT model was proved in revealing the pore-dependent adsorption behavior. Considering the difference in the adsorption mechanism of CH₄ with different pore diameters, Zhou et al. [79] proved that the adsorption form of CH₄ in shale is not only through single micropores or single layer adsorption and established a new supercritical adsorption model for shale gas. This supercritical adsorption model presents the adsorption mechanism in micro/nano-scale pores by comprehensively combining the coexistence of pore filling and single-molecule adsorption.

3. Competitive Adsorption between CH₄ and CO₂

The conception of CO₂-ESGR for shale gas exploitation has a unique promising potential through CO₂ competitive adsorption to release the adsorbed CH₄ from shale matrix into the fractures and cracks for production and thus to increase shale gas recovery [32]. Thus, the competitive adsorption of CO₂ to CH₄ in shale plays the key role on CO₂-ESGR. When CO₂ injected into shale reservoir, CO₂ will compete the adsorption sites on the inner surface of shale matrix with CH₄. Then, the desorption of CH₄ and adsorption of CO₂ synchronize in the shale formation due to competitive adsorption, and the flow and mass transfer in this process are schematically shown in Figure 4.

3.1. Experimental Study on CO₂/CH₄ Competitive Adsorption. The competitive adsorption characteristics of
CO₂ to CH₄ were initially investigated by comparative analysis of the adsorption behavior between single-component gas of CO₂ and CH₄. Nuttall et al. [44] first observed that the adsorption capacity of pure CO₂ is approximately 5 times greater than that of CH₄ in Devonian black shales at the same conditions. The adsorption capacity of pure CO₂ was also reported consistently higher than that of CH₄ in various kinds of shale by many following research [16, 26, 29, 40, 41, 80–84]. Klewiah et al. [32] summarized some related adsorption experiments of single-component gas of CO₂ and CH₄, reported the CO₂/CH₄ adsorption ratio in the range of 1.3–10 for dry shale, and revealed moisture weakening the CO₂/CH₄ adsorption ratio. Similar to CH₄, the

![Figure 3: Adsorption isotherm (excess sorption vs. pressure) for (a) CH₄ and (b) CO₂ on crushed dry shale samples of the Parana Basin in Brazil at a temperature of 45°C [29].](image)

**Table 1: Typical models for monolayer and multilayer adsorption.**

| Model   | Formula                                      | Reference |
|---------|----------------------------------------------|-----------|
| Langmuir| \( q = \frac{Q_l k_l p}{1 + k_l p} \)       | [71]      |
| BET     | \( q = \frac{Q_m k_b p^n (p_s - p)}{1 + \left( \frac{p}{p_s} \right)^n} \) | [72]      |
| Freundlich| \( q = k_f p^n \)                      | [73]      |

where \( q \) is the gas adsorption, mg/g; \( p \) is the pressure, bar; \( Q_l \) is the Langmuir maximum adsorption, mg/g; \( k_l \) is the Langmuir constant; \( p_s \) is the saturation pressure, bar; \( k_b \) is the constants of BET isotherm; \( Q_m \) is the maximum uptake, mg/g; and \( k_f \) and \( n \) are the constants of Freundlich isotherm.
3.2. Mechanism of CO\textsubscript{2}/CH\textsubscript{4} Competitive Adsorption.

As for the mechanism of competitive adsorption between CO\textsubscript{2} and CH\textsubscript{4} in shale, the competition for adsorption sites plays a key role on CO\textsubscript{2} replacing CH\textsubscript{4}. Specifically, molecular size of gas, interaction energy (thermodynamic forces) between gas and shale matrix, and accessibility of gas into the shale microporous network (steric forces) are considered as the important controlling factors of competitive adsorption between CO\textsubscript{2} and CH\textsubscript{4} [32]. The molecular characteristic difference between CO\textsubscript{2} and CH\textsubscript{4} is crucial: CH\textsubscript{4} molecule is tetrahedral geometry with a relative larger kinetic diameter of 3.80 Å, and CO\textsubscript{2} molecule is linear molecular with a smaller kinetic diameter of 3.30 Å [26, 74, 75, 96], shown in Table 2. Due to the smaller molecular size, CO\textsubscript{2} can easily access into micro/nano-scale pores with smaller diameter which may be difficult for CH\textsubscript{4}, and thus, CO\textsubscript{2} is favourable to contact larger surface and adsorption sites in shale matrix [32, 97]. Moreover, CO\textsubscript{2} can interact more strongly with functional groups in kerogen because of higher quadrupole moment, and thus, CO\textsubscript{2} is more prone to physical adsorption caused by van der Waals force than CH\textsubscript{4} [26, 98, 99]. Zhao and Wang [95] revealed that the surface of shale organic matter has a stronger affinity for CO\textsubscript{2} than CH\textsubscript{4}, and then, CO\textsubscript{2} competes for adsorption sites to replace the adsorbed CH\textsubscript{4} on the surface of the matrix. The higher critical temperature of CO\textsubscript{2} also favours the competitive adsorption to replace CH\textsubscript{4} [97]. As an endothermic reaction, desorption process of CH\textsubscript{4} needs a relative lower of the adsorption heat than that of CO\textsubscript{2}, and thus, desorption of CH\textsubscript{4} from shale can be more easily realized in the coexisting CO\textsubscript{2} adsorption process. The unique supercritical properties of CO\textsubscript{2}, such as liquid-like density, gas-like diffusion, gas-like viscosity, and wetting to shale surface, facilitate the effective contact with shale surface and adsorption sites and thus improve competitive adsorption to CH\textsubscript{4} [32, 100].

Molecular simulation is a good method to investigate adsorption mechanisms from the view of molecular motion and reaction. Recently, some grand canonical Monte Carlo (GCMC) simulations [20, 70, 101–103], one typical molecular simulation method for adsorption, were conducted to explore the mechanism of CO\textsubscript{2}/CH\textsubscript{4} competitive adsorption. Huang et al. [20, 70] studied the competitive adsorption behavior of CO\textsubscript{2}/CH\textsubscript{4} in dry and moist realistic kerogen models of different organic types. The simulation results showed that the CO\textsubscript{2}/CH\textsubscript{4} adsorption selectivity increases with increasing CO\textsubscript{2} concentration at low pressure for kerogen models of higher maturity but decreases with CO\textsubscript{2} mole fraction for lower mature kerogen models. Specifically, CO\textsubscript{2}/CH\textsubscript{4} adsorption selectivity increases with the enterable pore volume fraction in the immature organic type. The CO\textsubscript{2}/CH\textsubscript{4} adsorption selectivity decreases first and then increases with the moisture content while the adsorption of CO\textsubscript{2} is more sensitive with moisture than that of CH\textsubscript{4}. However, moisture can potentially boost the displacement of CH\textsubscript{4} by CO\textsubscript{2} at certain conditions. Zhou et al. [101–103] also conducted a series of molecular simulations on CO\textsubscript{2} and CH\textsubscript{4} adsorption for enhanced shale gas recovery and explored the effect of moisture and brine (salinity). Zhou et al. [102] explored the shale gas recovery mechanisms of CO\textsubscript{2} injection in kerogen slit pores and analyzed the effect of moisture. CH\textsubscript{4}
adsorption capacity in the CO₂-CH₄ mixture decreases with increasing moisture due to the accumulated H₂O clusters impeding the pore filling of CH₄ in the kerogen slit pores. Compared to pressure drawdown, CO₂ injection can release CH₄ molecules in the adsorption layer; the CH₄ recovery rate is not very clear, especially under the condition of mixture. Zhou et al. [103] found that the total uptake of CH₄ and CO₂, including adsorption in kerogen surfaces and dissolution at kerogen/water interface and in water/brine, decreases linearly with increasing salinity. Salinity effects on CO₂ uptake are proved as complicated. The CO₂ adsorption decreases due to the pore volume in kerogen surfaces occupied by brine, but the remarkable enhancement in CO₂ solubility in brine is observed. Moreover, the wettability of kerogen surface is transformed from a partially water-wetting into a less water-wetting interface caused by the existence of CO₂ adsorption, though this effect is inhibited by salinity.

The competitive adsorption mechanism is fundamentally revealed, but how to accurately quantify the competitive adsorption and evaluate the adsorption ratio of CO₂/CH₄ is not very clear, especially under the condition of mixture. More related experiments and models study should be conducted.

### 4. Displacement of CH₄ by CO₂ in Shale

#### 4.1. Flow Mechanism in Shale

CH₄/CO₂ adsorption and desorption in shale are coupled with multiscale and multifold flow from shale matrix and fracture network to wellbore in the process of CO₂-ESGR [97]. Therefore, the flow and mass transfer process is very complicated and involves different mechanisms. The flow and transport mechanisms in different scales related to CO₂-ESGR are shown in Figure 5 [52].

On the microscopic mechanism, the main interaction of gas flows in porous media is the collisions between gas molecules and the collisions between gas molecules and the walls of pores [108]. Thus, the mean free path of gas molecules and pore scales plays key roles on determination of flow regime in porous media. Knudsen number, \(K_n\), is proposed to differentiate the flow regime in tight porous media. Knudsen number is defined as, \(K_n = \frac{\lambda}{r_{pore}}\), where \(\lambda\) is the mean free path of gas molecules and \(r_{pore}\) is the radius of pore in porous media. With the increase of Knudsen number, the collision probability between gas molecules decreases while the collision probability between gas molecules and the pore wall increases. Correspondingly, the flow in micropores is divided into continuum (Darcy flow), slip flow, transition flow, and free molecular flow. Simultaneously, the microscopic mass transfer mechanism of shale gas is the viscous flow, Knudsen diffusion, free molecular diffusion (Fick diffusion), and surface diffusion [110]. The relationship between Knudsen number and gas flow regime under different pore scales and the corresponding governing equation are shown in Table 3.

For single-component gas flow, Javadpour et al. [114, 115] analyzed the gas flow in shale and micropore structure characteristics of shale and believed that non-Darcy flow occurs in the micropores. The flow regime of this kind of non-Darcy flow should be determined based on the mean free path of gas molecules and Knudsen number. Freeman et al. [116] further pointed out that non-Darcy flow will occur when the pore throat diameter of shale is equivalent to the molecular mean free path length. At this time, there is a strong correlation between permeability and pore pressure. The gas flow is Darcy flow in natural cracks and artificial fractures while it is non-Darcy flow in the shale matrix [117]. Li et al. [118] believed that the gas flow in micropore throats is slip flow and transition flow, and the mass transfer mechanism is mainly the combination of viscous flow and Knudsen diffusion at the temperature of 300-360 K and pressure of 1-100 MPa in shale reservoirs. Knudsen diffusion is negligible, and viscous flow is dominant in cracks larger than 100 nm, which is applicable to Darcy’s law. In shale pores or fractures with a diameter less than 10 nm, molecular free flow comes into play, and surface diffusion is small [119]. Sun et al. [119] further explored the effects of the adsorption/desorption of CH₄ in kerogen organic matter, the pore volume occupied by the adsorption layer, and the surface diffusion of the adsorption layer on the gas flow and mass transfer. Song et al. [120] combined non-Darcy flow (including Knudsen diffusion, gas adsorption, and surface diffusion) with the influence of critical pore space under real gas temperature and pressure conditions to study the gas migration mechanism.

#### 4.2. Displacement Experiments of CO₂-CH₄

As for the process of CO₂ displacing CH₄ in shale, the gas flow and mass

### Table 2: Physical properties and molecular parameters of CO₂ and CH₄ [104].

| Property                        | CO₂     | CH₄     | Reference |
|--------------------------------|---------|---------|-----------|
| Molecular mass, \(m\) (g/mol)   | 44      | 16      | —         |
| Critical temperature, \(T_c\) (K)| 304.2   | 190.5   | [74, 75]  |
| Critical pressure, \(P_c\) (MPa)| 7.4     | 4.6     | [74, 75]  |
| Critical density, \(\rho_c\) (kg/m³) | 467.6   | 162.7   | [105]     |
| Adsorbed phase density, \(\rho_a\) (kg/m³)| 1028   | 372     | [74, 75]  |
| Molar polarizability, \(\alpha M\) (cm³/mol) | 7.34 | 6.54 | [106, 107] |
| Kinetic diameter, \(\sigma_k\) (Å) | 3.30   | 3.80    | [74, 75, 96] |
| Collision diameter, \(\sigma_{col}\) (Å) | 4.00   | 3.82    | [96]      |
| Effective molecule diameter, \(\sigma_{eff}\) = \(\sqrt{\sigma_k \cdot \sigma_{col}}\) (Å) | 3.63   | 3.81    | [96]      |
transfer are more complicated than single-component gas flow. Different from CH₄ flow in shale, the competitive adsorption of CO₂/CH₄ and convective dispersion occur in the miscible displacement in the fracture-matrix dual media of fractured shales. The mass transfer characteristics of miscible displacement of CO₂-CH₄ in porous media under multi-field coupling play the crucial role in CO₂-ESGR. As an important physical property describing the degree of mixing of two phases in the porous media, the dispersion characteristics in the displacement of CO₂-CH₄ are one of the convective mass transfer characteristics that researchers focus on.

The early studies on the displacement properties and dispersion characteristics of CO₂-CH₄ in porous media were mainly carried out for the CO₂ enhanced gas recovery (CO₂-EGR) in conventional natural gas reservoirs. Mamora and Seo [121] and Liu et al. [122] verified the technical feasibility of CO₂-EGR by visualization CT experiments of CO₂-CH₄ displacement. Honari et al. [123] and Zhang et al. [124] proposed that residual water would delay the flow migration by blocking the pore pathway, causing the tailing of CO₂ breakthrough curve and non-Fick phenomenon in CO₂-CH₄ displacement. However, the seepage mass transfer mechanism in the conventional natural gas reservoirs is different from that in shale reservoir due to the higher porosity and permeability.

Compared to the conventional natural gas reservoirs, the seepage mass transfer characteristics in coalbed methane reservoirs are closer to that in shale reservoirs due to their similar geological attributes. Aiming at CO₂ enhanced coalbed methane recovery (CO₂-ECBM), Shi et al. [125] combined the extended Langmuir model and Fick’s law to explore the displacement properties of CO₂-CH₄ in the coal and analyzed the dynamic competitive desorption characteristics. Some studies also confirmed that the replacing efficiency of CH₄ was enhanced by CO₂ due to competitive adsorption effect with comparing N₂ displacement experiments [126, 127].

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It is also verified in the displacement experiments that the moisture can prevent the CO$_2$ binding to adsorption sites and then affecting the displacement efficiency [128].

There are relatively few studies on the displacement study of CO$_2$-CH$_4$ and the competitive adsorption in shale related to CO$_2$-ESGR. Du et al. [129–131] conducted a series of CO$_2$-CH$_4$ displacement experiments in the crushed shale pack for the displacement properties and dispersion characteristics. Du et al. [129] first analyzed the CH$_4$ recovery efficiency and CO$_2$ storage efficiency in displacement experiments. The experimental results showed that CO$_2$ has a larger dynamic adsorption rate and adsorption capacity, which ensures the feasibility of CO$_2$-ESGR. It is also found that the competitive adsorption between CO$_2$ and CH$_4$ will cause fluctuations in pore pressure, which in turn will enhance dispersion and produce a wider range of CO$_2$-CH$_4$ mixed phase regions. Du et al. [130] further explored the influence of CO$_2$ injection pressure on the dispersion characteristics in CO$_2$-CH$_4$ displacement experiment. Based on the convective dispersion theory, it is found that CO$_2$ diffusion is dominant under the condition of lower CO$_2$ injection pressure, and the mass transfer coefficient and the miscible area increase with the increasing injection pressure, while the competitive adsorption between CO$_2$ and CH$_4$ is becoming obvious. The comparison of CO$_2$, N$_2$, and CO$_2$/N$_2$ mixtures was also conducted; a higher CH$_4$ recovery existed in CO$_2$ displacement than that in N$_2$ displacement [131]. The displacement efficient of CH$_4$ by CO$_2$ was also compared with N$_2$ in simulation, and it is verified that competitive adsorption leads to a larger recovery for CO$_2$ displacing shale gas [132].

5. Challenges and Opportunities

The adsorption/desorption of shale gas, competitive adsorption of CO$_2$ to CH$_4$, and flow mechanism play the key role on shale gas reservoir exploitation. To our knowledge, some challenges and opportunities on these research topics are arising in the process of CO$_2$-ESGR.

A lot of experimental and modelling studies on adsorption/desorption have been conducted in crushed shale samples, especially for CH$_4$, and the adsorption mechanism of CH$_4$ is fundamentally revealed. Due to some shale reservoirs are in deep formation, it is necessary to ascertain the gas adsorption mechanism under high temperature and high pressure. However, the gas adsorption experiments in intact shale cores under field condition are still scarce, and more relevant adsorption studies need to be carried out. Correspondingly, accurate supercritical adsorption models also need to be developed for enriching the comprehensive knowledge of gas adsorption mechanism in shale. Compared to CH$_4$, CO$_2$ has different physical properties and different adsorption behaviors, especially in the supercritical. The adsorption mechanism of CO$_2$ is not fully revealed, especially under supercritical state, and thus, more experiments and models research on CO$_2$ adsorption/desorption are urgently needed.

The competitive adsorption of CO$_2$ to CH$_4$ is basically proved by a lot of comparative adsorption experiments of pure gas composition and some adsorption studies of CO$_2$-CH$_4$ mixtures in shale. However, the competitive adsorption has different behavior in the adsorption experiments of single-component gas and CO$_2$-CH$_4$ mixture system. To quantitatively evaluate the competitive adsorption, adsorption ratio of CO$_2$/CH$_4$ also shows different for the experiment of single-component gas and mixtures. The CO$_2$-CH$_4$ mixture adsorption is more close to realistic situation, but the related mixture adsorption experiments are in scarcity, especially under the field conditions. Notably, more dynamic competitive adsorption experiments are not adequate for revealing the dynamic exchange mechanism of CO$_2$-CH$_4$. Considering the different properties between CO$_2$ and CH$_4$, the competitive adsorption mechanism is qualitatively analyzed. However, how to accurately predict the adsorption CO$_2$ or CH$_4$ component in CO$_2$-CH$_4$ mixture system and quantify the competitive adsorption are still the important unsolved problems. Maybe, the future work should pay attention on establishment of quantification model on competitive adsorption of CO$_2$ to CH$_4$ in shale.

The knowledge of flow mechanism in on certain flow regime has been relatively well developed and understood. The shale gas flows through pathway in different sizes of microscale/nano-scale pores and fractures in shale during the exploitation of shale gas reservoir. Thus, different flow regime is coexisted on this condition. The coupling of flow in different flow regime is one of the key controlling factors for accurately predicting shale gas transport, which has not been fully understood and needs thorough study. Concerning CO$_2$-ESGR, the injection of CO$_2$ makes the flow and gas transport more complicated. The mechanism of competitive adsorption of CO$_2$ to CH$_4$ coupled with flow and CO$_2$-CH$_4$ dispersion is not fully ascertained. CO$_2$-CH$_4$ dynamic displacement studies are scarce for comprehensive analysis of the coupling of competitive adsorption with various gas flow regime. In the opinion of this work, future studies may should concern the dynamic competitive coupling with different flow regime in aspects of experiments and models in the miscible displacement of CO$_2$-CH$_4$ for CO$_2$-ESGR.

6. Conclusions

Due to both the environmental effect of CO$_2$ geological storage and economic effect of shale gas exploitation, CO$_2$ enhanced shale gas recovery (CO$_2$-ESGR) draws worldwide concerns in recent years. This work summarizes the existing knowledge on the mechanism of single-component gas adsorption, competitive adsorption, and displacement of CO$_2$-CH$_4$ in shale related to CO$_2$-ESGR. The advances of experimental and model studies on these research topics are reviewed. Some conclusions are drawn as follows:

(i) As unconventional gas resources, shale gas is an important clean fuel with large reserves worldwide. CO$_2$ enhanced shale gas recovery has great potential to exploit shale gas reservoirs with permanently storing CO$_2$ into underground formation

(ii) Generally, gas absorption in shale is two types of physical adsorption: monolayer adsorption at low
pressure and multilayer adsorption at high pressure. Gas adsorption capacity shows positive relationship with TOC, thermal maturity, and clay content of shale and negative with moisture

(iii) Adsorption capacity of CO$_2$ in shale is much larger than that of CH$_4$ even with the coexistence of CO$_2$-CH$_4$ mixture. Due to the unique properties of CO$_2$, shale matrix shows a stronger affinity with CO$_2$ and CO$_2$ can be more easily adsorbed on the inner surface of shale matrix than CH$_4$

(iv) Four types of flow regime exist in the gas flow related to shale gas exploitation. Generally, it is Darcy flow for shale gas flow in natural cracks and artificial fractures larger than 100 nm, slip flow and transition flow for gas flow in shale micropore throats in 10–100 nm, and free molecular flow for gas flow in micro/nano-scale pores and cracks

(v) Compared to single-component gas flow in shale, displacement flow of CO$_2$-CH$_4$ is very complicated with mass transfer between two gases. Dynamic studies on displacement of CO$_2$-CH$_4$ in shale prove that CH$_4$ recovery is significantly enhanced due to the competitive adsorption

(vi) To our knowledge, some challenges and opportunities in these research topics are also proposed

(vii) More experiment adsorption study in intact shale cores under field condition for supercritical CH$_4$ and CO$_2$ is scarce, and the corresponding accurate supercritical adsorption model is urgently needed for revealing gas adsorption mechanism in shale

(viii) To ascertain competitive adsorption mechanism, more CO$_2$-CH$_4$ adsorption experiments under field conditions, especially dynamic experiments, should be conducted to determine the CO$_2$/CH$_4$ adsorption ratio. Corresponding, establishment of quantification model on competitive adsorption of CO$_2$ to CH$_4$ in shale should draw attentions in the future work

(ix) Dynamic competitive adsorption coupling with flow in the displacement of CO$_2$-CH$_4$ plays the key role on CO$_2$-ESGR but is not fully understood. The future work should look into the coupling of various flow regime, competitive adsorption of CO$_2$-CH$_4$, convection dispersion, etc

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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