

Article

Progress in Research on Coalbed Methane Purification Technology against the Background of Carbon Peak and Carbon Neutrality

Lu Xiao ^{1,2,*} , Houlin Liu ², Xuanping Gong ¹ and Cheng Cheng ¹¹ China Coal Energy Research Institute Co., Ltd., Xi'an 710054, China² Research Center of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang 212013, China

* Correspondence: xiaolu8317@126.com

Abstract: Coalbed methane is released externally due to coal mining activities. Given its low concentration, which renders utilization challenging, China annually vents approximately 285 billion cubic meters of coalbed methane into the atmosphere, leading to significant energy waste and greenhouse gas emissions. To enhance the utilization rate of coalbed methane, mitigate these emissions, and promote a “green and low-carbon” energy supply, this article investigates pressure swing adsorption technology for purifying coalbed methane and analyzes the advantages, disadvantages, and application scopes of three processes: separation based on equilibrium effects, kinetic effects, and steric hindrance effects. The research findings reveal that equilibrium effect-based adsorption is particularly advantageous for purifying low-concentration coalbed methane, effectively capturing methane (CH₄). Conversely, when dealing with medium- to high-concentration coalbed methane, methods leveraging kinetic effects prove more favorable. Within the context of equilibrium effects, activated carbon serves as a suitable adsorbent; however, achieving high-purity products entails substantial energy consumption. The methane saturation adsorption capacity of novel activated carbons has reached 2.57 mol/kg. Kinetic effect-based adsorbents, primarily carbon molecular sieves and zeolite molecular sieves, are characterized by lower energy demands. Currently, coal-based molecular sieves have achieved a CH₄/N₂ equilibrium separation factor of 4.21, and the amount of raw coal required to produce one ton of carbon molecular sieve has decreased to 2.63 tons. In light of the rapid advancement of intensive coal mining operations and the swift implementation of smart mine construction, there is an urgent need to intensify research on large-scale purification technologies for low-concentration coalbed methane. This will provide the technical foundation necessary for achieving “near-zero emission” of mine gas and facilitate the achievement of the goals of carbon peak and carbon neutrality.

Keywords: coalbed methane; carbon peak and carbon neutrality; coalbed gas purification; pressure swing adsorption; near-zero emission



Citation: Xiao, L.; Liu, H.; Gong, X.; Cheng, C. Progress in Research on Coalbed Methane Purification Technology against the Background of Carbon Peak and Carbon Neutrality. *Processes* **2024**, *12*, 1561. <https://doi.org/10.3390/pr12081561>

Academic Editor: Federica Raganati

Received: 15 June 2024

Revised: 22 July 2024

Accepted: 24 July 2024

Published: 25 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Coalbed methane is an associated gas which is adsorbed on the surface of coal particles or free in the space of coal particles. As an energy resource, its main component is methane. China is rich in coalbed methane resources, and in the current situation of “coal to gas” and the shortage of natural gas resources, coalbed methane can be used as an effective supplement to oil and gas resources [1]. In the process of coal mining, coalbed methane is usually drained in advance as a by-product using a water ring vacuum pump, and it is then determined whether it should be used according to its concentration and customer needs. According to statistics, the total amount of coalbed methane resources in the world [2] is about 2.4×10^{14} m³, and the proportion of natural gas in the world energy structure is gradually increasing [3–5]. At present, coalbed methane is mainly extracted underground

in China, and the concentration of CH_4 is mostly between 3% and 80%. According to survey data from the China Academy of Coal Science and Technology in 2022, which covered methane extraction volumes from 76 major coal mines in China, the volume of extracted coalbed methane with a methane concentration greater than 30% accounted for 43% of the total extraction volume, the volume of extracted coalbed methane with a methane concentration between 10% and 30% represented 29% of the total extraction volume, and the volume of extracted coalbed methane with a methane concentration below 10% constituted 28% of the total extraction volume. In addition, there is a large amount of ventilation air methane (CH_4 concentration is less than 1%) that cannot be used directly. Methane explosions occur in 5% to 15% of cases, and a large proportion of low-concentration coalbed methane is difficult to use and is directly discharged into the atmosphere, resulting in resource waste and environmental pollution [6].

In March 2024, the International Energy Agency (IEA) published the “Global Methane Tracker 2024” report, which indicated that global methane emissions from the energy sector amounted to approximately 120 million tons, with about 40 million tons stemming from the coal industry. Methane emissions during the process of coal mining in China account for 80% of the energy sector’s methane emissions, ranking first in China’s methane emission structure. From the perspective of greenhouse gas composition, carbon dioxide and methane remain the two primary greenhouse gases [7]. Considering that methane has an impact on the climate that is 25 times greater than that of carbon dioxide, it is a significant greenhouse gas contributing to global warming against the backdrop of carbon neutrality [8,9]. Therefore, vigorously promoting the utilization of coal mine gas is a critical technical pathway to maximally support the coal industry’s carbon peak and carbon neutrality targets. It has been reported that China’s methodology for utilizing coalbed methane in Certified Emission Reductions (CCER) is about to be released. Projects that utilize mine gas can not only achieve carbon reductions but also generate carbon sink assets through the trading of carbon reduction volumes. Medium- and low-concentration coalbed methane with a CH_4 concentration of 20% to 60% is the focus of future development and utilization; in order to utilize medium- and low-concentration coalbed methane, it is urgent to solve the problem of the concentration and purification of CH_4 in drained coalbed methane [10].

After pretreatment, including desulfurization, drying, deoxidation, and decarbonization, etc., drained coalbed methane is mainly composed of CH_4 and N_2 , so the concentration and separation of coalbed methane mainly lies in the separation of CH_4 and N_2 . The main technologies for CH_4/N_2 separation in coalbed methane are cryogenic separation [11], pressure swing adsorption (PSA) separation [12], membrane separation, and gas hydrate separation, etc. Among these, the membrane separation method requires extremely expensive membrane materials and offers poor separation efficiency, while the gas hydrate separation method remains at the conceptual stage. Neither of these two separation methods has yet been applied in the field of gas purification. Both cryogenic distillation and PSA separation methods have practical applications, but the cryogenic method consumes a significant amount of latent heat during the liquefaction of gas components, resulting in much higher energy consumption compared to the PSA separation method. Therefore, the technology of PSA separation has developed rapidly, and its operating cost is low. It is suitable for enterprises of all sizes and is in the stage of industrial promotion. This study mainly introduces the progress in research on the technology of PSA purification of low-concentration coalbed methane. The applicable scopes of three coalbed methane separation principles based on equilibrium effects, kinetic effects, and steric hindrance effects are analyzed, providing technical support for methane emission reduction and the achievement of the goals of carbon peak and carbon neutrality.

2. The Principle of PSA Separation

The technology of PSA is a separation process that exploits differences in equilibrium adsorption capacities, kinetic rates of diffusion into and out of the adsorbent particles, or

steric effects of micropores on individual gas components within a mixture. By cyclically varying pressure, this technique enables both the adsorption and regeneration of the adsorbent, ensuring a continuous concentration or purification of the targeted components in the gas mixture.

Skarstrom designed the first PSA system and applied it to air separation in the 1960s. After decades of development, PSA has become one of the mainstream technologies in the field of gas separation, widely used in petrochemical processing, metallurgy, light industry and environmental protection and other fields. This process technology has been successfully applied and popularized in the following fields [13]: the purification of H_2 in coke oven gas and pyrolysis gas; the purification of CO in syngas, water gas, yellow phosphorus tail gas and other gases; the separation of N_2 and O_2 in the air.

Since the PSA process generally does not require external heating and can be operated at room temperature and low pressure (from 0.1 MPa to 3 MPa), it has the advantages of flexible operation, high degree of automation, and low energy consumption. The PSA separation of gas mixture (CH_4/N_2) has become a research hotspot in the past decade. The PSA separation of gas mixture (CH_4/N_2) is mainly based on the counterbalance effect and kinetic effect separation.

3. Separation Based on the Counterbalance Effect

Counterbalance effect-based separation achieves the separation of different components in a gas mixture by using the difference in equilibrium adsorbate loading on the adsorbent of different gas components. The strong adsorbent component is adsorbed in the adsorption column, and the weak adsorbent component is discharged from the cat head. If the strongly adsorbed molecule is the product gas, desorption is required to complete the recovery of the product. It is generally desired that the weakly adsorbed component forms the product gas, allowing for a high-purity product gas to be obtained at the top of the tower, which can then be directly recovered and utilized. This approach results in a high recovery rate and significantly reduces energy consumption.

The equilibrium adsorption quantity of typical gases on the adsorbent is in the following order [14]: $H_2 < O_2 < N_2 < CH_4 < CO < CO_2$. The horizontal axis P in the figure represents the operating pressure inside the adsorption tower, and the vertical axis Q_{ads} represents the static adsorption quantity of the gas. The equilibrium adsorption isotherm of the CH_4/N_2 single-component gas is shown in Figure 1. Therefore, the separation of CH_4/N_2 by the counterbalance effect is based on the fact that the adsorption density of methane on the adsorbent is greater than that of nitrogen. Methane is adsorbed preferentially, and nitrogen is discharged from the cat head. The product gas is extracted from the bottom of the tower by a vacuum pump. The process is vacuum pressure swing adsorption (VPSA). This PSA process flow chart is shown in Figure 2. Figure 3 is a schematic diagram of a two-stage PSA process based on PSA, with the numbers in the figure representing the molar fractions of methane at corresponding positions.

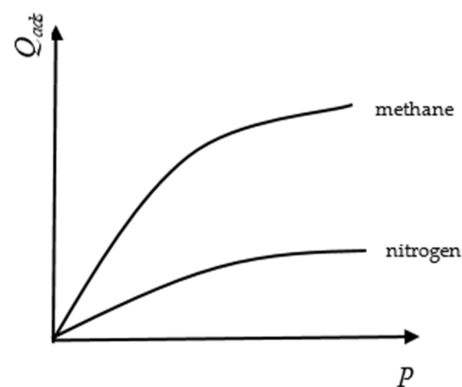


Figure 1. Schematic diagram of CH_4/N_2 equilibrium adsorption isotherm.

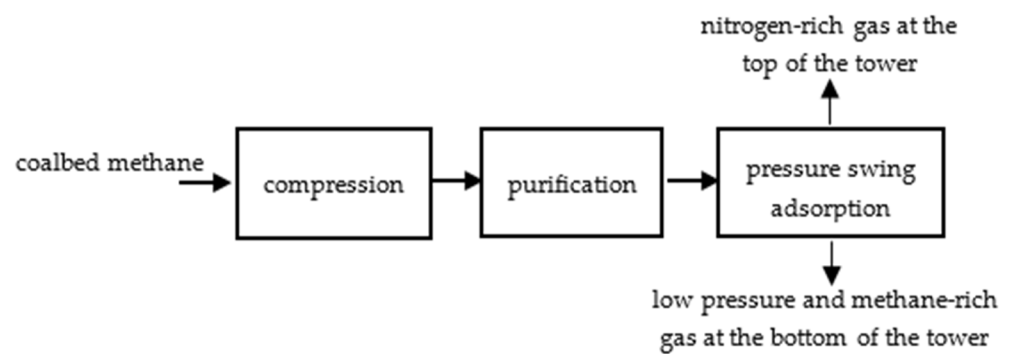


Figure 2. Process flow chart of methane enrichment by counterbalance effect.

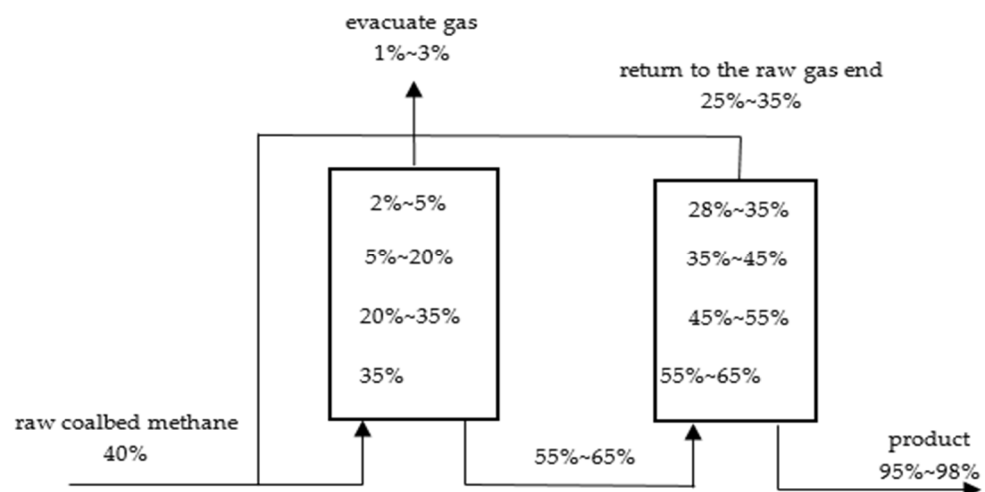


Figure 3. Schematic diagram of a two-stage PSA process based on equilibrium effect.

In 1986, Southwest Research Institute of Chemical Industry [15] first reported the patented method of PSA to enrich methane in coal mine gas. When the adsorption pressure increases to 1.0 MPa, the methane concentration in coalbed methane can be increased to more than 95% after several displacements. Using this process, the first set of coalbed methane PSA devices with a gas treatment capacity of 12,000 m³/d was established in Henan Jiaozuo Mining Bureau. However, due to uncertain market prospects and many displacements at that time, the cost recovery period was long, and it was not rapidly promoted and applied.

Davis M.M. et al., of UOP company, published a five-bed PSA process for purifying nitrogen-containing natural gas in 1992 [16]. Under the optimal conditions, the methane content of natural gas can be increased from 70% to 96.4%, and the methane recovery rate can reach 85%. In 1998, Huber M et al., of Nitrotec Company, disclosed a three-tower PSA process, in which the methane content of natural gas in the plant of this process was purified from 70% to 98%, and the recovery rate of hydrocarbons was maintained at about 70%.

The research group of Xian Xuefu of Chongqing University has carried out a lot of theoretical and experimental research on the purification of methane from coalbed methane using PSA based on the counterbalance effect in 2002. Gu Min used T103 activated carbon (the equilibrium separation coefficient of CH₄/N₂ is 2.9) as the adsorbent and tested an independently designed device of single-column PSA. When the adsorption pressure was 0.9 MPa, five procedure steps, including pressure charging, high pressure adsorption, parallel flow decompression, reverse decompression, and vacuum-pumping, were adopted to increase CH₄/N₂ from about 30% to about 49% based on the mechanism of the counterbalance effect [17].

Olajossy used activated carbon as an adsorbent to purify CH₄ from coalbed methane and conducted experiments and computer simulation studies on the VPSA process in 2003. The results show that the CH₄ concentration in coalbed methane can be increased from 55.2% to the range of 96% to 98% at an operating temperature of 278 K, and the methane reflux ratio can reach 86% to 91% when the methane reflux ratio is 1.8 to 2.12 in the displacement step.

In 2008, Japan Gas & Electric Investment Co., Ltd., built a PSA pilot plant at Fuxin Coal Mine in Liaoning Province for purifying low-concentration coalbed methane with gas volume of 1000 m³/h. The adsorbent was highly selective activated carbon produced by Osaka Gas, and the two-bed VPSA process increased the methane concentration from 21% to 48% with a recovery rate of 93%. In 2014, Shanghai Hanxing Energy Technology Co., Ltd., used activated carbon as an adsorbent and the technology of VPSA to purify low-concentration gas in an industrial trial operation in Chengzhuang Mine, Jincheng, Shanxi Province. The CH₄ concentration of coal mine gas was purified from 12% to 30% for gas power generation [18].

Table 1 outlines the timeline of the development of PSA technology based on equilibrium effect-based separation. At present, the technology of PSA based on counterbalance effect-based separation has encountered certain bottlenecks in terms of its practical application. First of all, the equilibrium separation coefficient of the existing adsorbent is too small, and it is difficult to achieve an efficient separation of the two gases, so the purification of methane is limited. Secondly, CH₄ is preferentially adsorbed as a strong adsorption component under the counterbalance effect, and the product gas must be desorbed by vacuum-pumping. If you want to obtain high-concentration CH₄, you must take multistage compression and increase the displacement step, so the energy consumption is relatively high. The existing equilibrium separation adsorbents are mainly activated carbon. The methane saturation adsorption capacity of novel activated carbons can reach 2.57 mol/kg, and both the regeneration energy consumption of the adsorption tower and the usage amount of activated carbon have significantly decreased, making the costs largely acceptable to coal mining enterprises. Developing new adsorbents or modifying activated carbon to improve the CH₄/N₂ equilibrium separation coefficient of adsorbents will be the future research direction.

Table 1. Research timeline for PSA technologies based on equilibrium effects.

Timeline	R&D Entity	Technology	Effect
1986	Southwest Chemical Industry Research Institute	Multi-stage adsorption and desorption	Methane concentration increased to 95%
1992	UOP	Five-bed PSA process	Methane concentration increased from 70% to 96.4% with a methane recovery rate of 85%
1998	Nitrotec Company	Three-bed PSA process	Methane concentration increased from 70% to 98% with a hydrocarbon recovery rate of 70%
2002	Chongqing University	Single-tower PSA experiment	Methane concentration increased from 30% to 49%
2003	Olajossy	VPSA	Methane concentration increased from 55.2% to 96% with a methane recovery rate of 86%
2008	Japan Gas and Power Company	Dual-bed VPSA process	Methane concentration increased from 21% to 48% with a recovery rate of 93%
2014	Shanghai Hanxing	VPSA	Methane concentration increased from 12% to 30%

4. Separation Based on the Dynamic Effect

Kinetic effect-based PSA can also be used to separate CH₄/N₂ and is mainly based on the difference in the molecular kinetic diameters of CH₄ and N₂ (the kinetic diameter of CH₄ is 0.382 nm and that of N₂ is 0.364 nm) and the differences in diffusion rate on an adsorbent with a relatively uniform pore size to achieve the separation of the gas mixture. Adsorbents are generally carbon molecular sieves (CMS) and zeolite molecular sieves. Figure 4 shows the adsorption kinetics curves of CH₄ and N₂ on the adsorbent. The

horizontal axis t represents the residence time of the gas on the adsorbent, and the vertical axis Q_{ads} represents the static adsorption quantity of the gas.

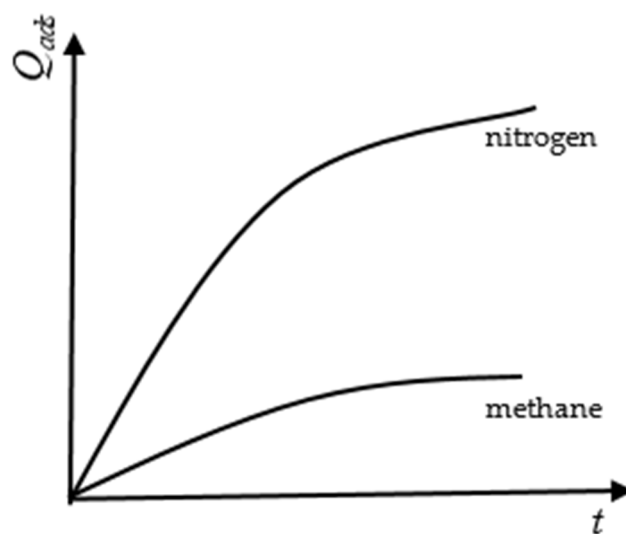


Figure 4. Adsorption kinetics curves of CH₄ and N₂ on the adsorbent.

Since the diffusion rate of N₂ on the molecular sieve adsorbent is greater than that of CH₄, N₂ will be preferentially adsorbed in a short time, while CH₄ gas is excluded due to competitive adsorption; purified methane can be obtained directly from the exhaust port at the cat head by controlling the reasonable adsorption time through the adjustment of the PSA program and it can be directly used as product gas. This process does not require additional steps to obtain high-pressure product gas, which is conducive to the operation of further PSA purification, and does not require additional pressurization, which is conducive to reducing energy consumption. The process of coalbed methane PSA achieved in this way is shown in Figure 5. Figure 6 illustrates a four-tower coalbed methane separation device using PSA.

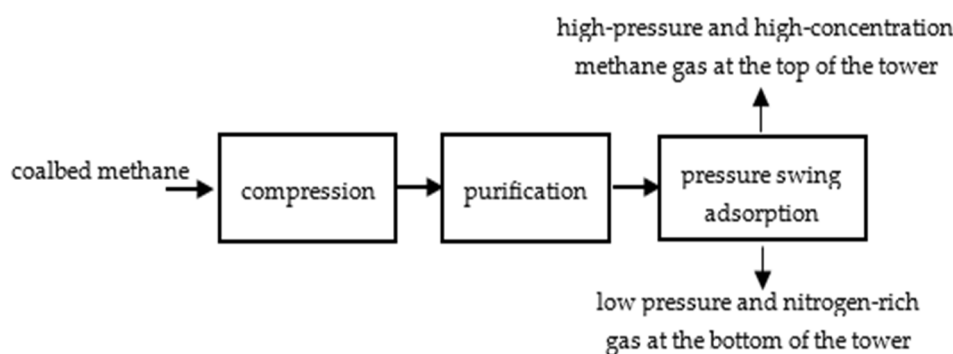


Figure 5. Process flow chart of methane enrichment based on counterbalance effect.

Molecular sieves are materials featuring precise and uniform micropores, endowed with homogeneous pore sizes and exceptionally high specific surface areas. Their pore size distribution is remarkably uniform. Through their unique pore structure and adsorption properties, molecular sieves enable the selective adsorption and separation of gas molecules, thereby conferring distinct advantages over other types of adsorbents. The selection of molecular sieve material is critical for efficiency and effectiveness in the adsorption process. Commonly used carbon molecular sieve materials in China include coal-based carbon molecular sieves, coconut shells, and graphene. Due to coal being an excellent natural adsorbent that is inexpensive and readily available, it has become a mainstream material for molecular sieves in recent years. After raw coal undergoes processes such as crushing,

grinding, kneading into shape, drying, controlled carbonization, activation, and pore adjustment, it is transformed into a high-quality adsorbent with good selectivity, specifically for coalbed gas separation.



Figure 6. Four-tower coalbed methane separation device using PSA.

Ackley et al. used CMSs produced by the company BF (Bergbau-Forschung) in Germany as an adsorbent and used the Skarstrom cycle to study the CH_4/N_2 binary gas separation process [19]. PSA was based on the kinetic effect of q carbon molecular sieve, and CH_4 was directly enriched at the cat head as product gas. The results show that the diffusion rate of N_2 is significantly higher than that of CH_4 , and the ratio of the N_2/CH_4 diffusion time constant is up to 27. By using this commercial CMS, the CH_4 concentration in the gas mixture can be purified from 50% to 80% with a recovery rate of 55% by using the technology of pressure swing separation based on the dynamic effect.

Fatehi et al. used a two-tower device based on PSA to study the CH_4/N_2 separation performance of CMS produced by BF Company in Germany [20]. The results show that in the separation process, the adsorbent is affected by both potential energy resistance on the crystal surface and diffusion resistance inside the crystal. Two kinds of coalbed gas with 60% and 92% methane volume fraction can be purified to 76% and 96%, respectively.

Zhang Chuanquan et al. at Shanghai Jiaotong University used a ZTCMS-185 carbon molecular sieve produced by Zhejiang Changxing Zhongtai Molecular Sieve Co., Ltd., which contained 40% methane and 60% nitrogen, as an adsorbent [21] to study the separation of coalbed methane. The feasibility of coalbed methane separation at low temperatures was discussed. The results indicate that the adsorption and separation characteristics of CH_4/N_2 at low temperature are significantly different from those at room temperature. Under three different adsorption pressures of 1.0 MPa, 2.0 MPa, and 3.0 MPa, the methane concentration of feedstock gas can be increased by more than 65% at room temperature, while the methane concentration cannot be increased to more than 50% at low temperature.

Yang Ying et al. at East China University of Science and Technology evaluated in detail the static and kinetics properties of a carbon molecular sieve produced by Changxing Shanli Chemical Materials Technology Co., Ltd. in China [22]. The results show that the adsorption densities of methane and nitrogen are 1.91 mol/kg and 1.01 mol/kg at 303 K and 700 kpa, respectively. The adsorption rate is controlled by both the potential resistance at the micropore orifice and the diffusion resistance inside the micropore. The kinetic separation contrast is obvious, and the separation coefficient reaches 5.3. It can be seen

from the breakthrough curve of the fixed bed that the adsorbent can increase the methane concentration from 30% to 45%.

Researchers led by Guo Haoqian from the Coal Science & Technology Research Institute used a self-made carbon molecular sieve as the adsorbent and conducted experimental studies using a four-column PSA process on coalbed methane with a methane concentration of 25%. They examined the impact of process parameters such as adsorption pressure, adsorption time, and others on the effect of concentration and extraction [23]. The results show that the methane concentration can be increased to 62.8% under the optimal process conditions. In 2018, the adsorbent was used to extract low-concentration coalbed methane by a three-stage PSA process based on kinetic effect separation. A compressed natural gas (CNG) production project was built in Shentangzou, Xinjing Mine, by the Shanxi Huayang New Materials Technology Group. The methane concentration in the feedstock gas of the equipment was 35%, and the methane concentration was increased by a three-stage PSA. The calorific value of the product gas reached 33.47 MJ/m³, and the capacity of the device reached 2119 m³/h. The methane concentration of the product gas could be flexibly controlled between 88% and 95%.

Table 2 outlines the development timeline for PSA technology based on kinetic effect-based separation. Given the presence conditions of coalbed methane within coal seams, the main impurities in coalbed methane are water, carbon dioxide, and hydrogen sulfide, all of which molecular sieves have a strong affinity for. Hydrogen sulfide, being a reductive gas, is present in negligible amounts in coalbed methane and does little harm to molecular sieves; thus, its influence on the system's adsorption capacity is typically not considered. Coalbed methane is extracted using a water-ring vacuum pump and contains saturated moisture; additionally, the content of carbon dioxide is approximately 0.5% (usually considered as 1%). In the PSA apparatus, there is a purification step before the molecular sieve adsorption system, mainly to eliminate oil and most of the water. The residual small amounts of water and carbon dioxide are predominantly removed by silica gel and activated alumina placed at the bottom of the adsorption tower. When designing the adsorption apparatus, the loading quantities of silica gel and activated alumina are calculated based on constraints of water content and carbon dioxide content. As such, the presence of these impurities has little impact on the adsorption capacity of the molecular sieve for the primary gas components in coalbed methane within the main body of the adsorption tower.

Table 2. Research timeline for PSA technologies based on kinetic separation effects.

Timeline	R&D Entity	Technology	Effect
1990	BF	Skarstrom Cycle	Methane concentration increased from 50% to 80%, with a recovery rate of 55%
1995	Fatehi	Dual-Tower PSA Experiment	Methane concentration increased from 60% to 76%
2008	Shanghai Jiao Tong University	Utilizing ZTCMS-185 Carbon Molecular Sieve	Methane concentration at room temperature increased from 40% to 65%
2014	Shanghai Jiao Tong University	General Carbon Molecular Sieve	Methane concentration increased from 30% to 45%
2016	Coal Science and Technology Research Institute Co., Ltd.	Four-Column PSA Process	Methane concentration increased from 25% to 62.8%
2018	Coal Science and Technology Research Institute Co., Ltd.	Three-Level PSA Process	Methane concentration increased from 35% to 88%, enabling flexible control of product concentration

The enriched high-pressure product gas can be obtained directly at the top of the tower by the dynamic effect-based PSA separation process. It has high purity and does not consume much energy due to multi-stage compression. Compared with counterbalance effect-based separation, it has significant advantages. It has been widely used by researchers in China and abroad. Many studies have been carried out in foreign countries on the separation of CH₄/N₂ based on kinetic effects, but most of them are based on medium- and high-concentration gas mixtures with high CH₄ content. There are few studies on coalbed methane with low concentration of about 30%, and the corresponding studies are

mainly concentrated in China. There are still few research reports on dynamic separation in China, and only a few institutions are making technical breakthroughs. The reported kinetic adsorbents are mainly carbon molecular sieves and zeolite molecular sieves, which are expensive and their industrial use is limited. Further development of efficient and cheap kinetic selective adsorbents will be an important direction for PSA separation of CH_4/N_2 in the future.

Separation based on kinetic effects primarily relies on the differential diffusion rates of different components of coalbed methane on the surface of molecular sieves to enhance the concentration of methane. The CH_4/N_2 equilibrium separation factor reaches 4.21, and the overall energy consumption is lower than that of separation based on equilibrium effects (the specific energy consumption figures are contingent upon the methane concentration in the feed gas and the purity of the product methane). This approach is currently the mainstream method for PSA separation in the field of coal mine gas utilization. During the implementation of this technology, the core science and technology are manifested in the preparation of the adsorbent. The cost of carbon molecular sieves constitutes a significant proportion of the initial investment and operational expenses in coalbed methane separation equipment. With advances in molecular sieve preparation technology, the material consumption for coal-based carbon molecular sieves has also decreased. Currently, the amount of raw coal required to produce 1 ton of carbon molecular sieves has been reduced to 2.63 tons.

5. Separation Based on Steric Hindrance Effects

The steric hindrance effect has high requirements for adsorbents. The selection of adsorbents should meet the requirement of uniform pore size distribution of the adsorbent, with a diameter size between that of the target gas and other gas molecules. Only molecules smaller than the adsorbent pore size can diffuse into the adsorbent particles, while other larger molecules are blocked [24]. At present, titanium silicon molecular sieve adsorbents meet the conditions of the steric hindrance effect for gas separation, mainly because the internal pore size of the molecular sieve can be adjusted by changing the cation content inside the titanium silicon molecular sieve. Reference [25] used ETS-4 as an adsorbent to separate CH_4/N_2 gas mixtures. The results show that by controlling the pore size of the adsorbent within the range of 3–4 angstroms, the concentration of CH_4 in the CH_4/N_2 mixture can be purified from 80% to 90% through PSA, while N_2 concentration can be reduced from 18% to below 5%.

6. Conclusions

- (1) PSA technology can increase the concentration of methane in coalbed methane, reduce the emission of greenhouse gases, and minimize energy wastage, thereby offering a solution for carbon emission reduction in the coal industry. Current PSA separation processes are often solely based on equilibrium effects or kinetic effects. For coalbed methane with low methane content, the equilibrium effect-based adsorption of CH_4 presents a significant advantage. In cases of medium- to high-concentration coalbed methane, where the nitrogen content to be removed is relatively small, a kinetic effect-based N_2 -selective adsorption process is more advantageous. If, in the future, the goal is to purify low-concentration coalbed methane to above 90% purity, it should involve a combination of separation processes based on both equilibrium and kinetic effects.
- (2) In the equilibrium effect scenario, activated carbon is commonly utilized as an adsorbent. Methane, being a strongly adsorbing component, is preferentially adsorbed. The product gas must be obtained from the bottom of the tower through vacuum withdrawal. To achieve a high-concentration product, the number of stages must be increased, leading to higher overall energy consumption. Currently, the methane saturation adsorption capacity of newly developed activated carbons has reached 2.57 mol/kg, and there has been a significant reduction in the regeneration energy consumption of the adsorption tower and the amount of activated carbon used.

Modifying activated carbon to enhance the equilibrium separation coefficient of the adsorbent is a direction for future research.

- (3) Adsorbents operating on kinetic effect principles primarily consist of carbon molecular sieves and zeolite molecular sieves, which feature lower energy consumption and are suitable for medium- to high-concentration coalbed methane with higher methane content. Due to the high cost of carbon molecular sieves and zeolite molecular sieves, developing efficient and cost-effective selective adsorbents represents a future research direction. Currently, significant advancements have been made in the technology of producing molecular sieves from coal, with the CH_4/N_2 equilibrium separation factor reaching 4.21, and the amount of raw coal required to produce 1 ton of carbon molecular sieve has been reduced to 2.63 tons.
- (4) With the rapid advancement of intensive and high-intensity mining in coal mines and the rapid implementation of intelligent mining construction, research on large-scale purification technology for low-concentration coalbed methane should be strengthened, especially in the study of mixed adsorption materials [26] and highly selective adsorbents [27], increasing the adsorption capacity of molecular sieves, reducing costs, providing technical and equipment support for “zero emission” coal mine gas, and helping to achieve the goals of “carbon peak and carbon neutrality”.

Author Contributions: Resources, H.L.; data curation, C.C.; writing—original draft, L.X.; funding acquisition, X.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research study was funded by the National Key Research and Development Program of China Project (2023YFF0615404) and the National Natural Science Foundation Joint Key Project of China (U23B2093). The APC was funded by the National Key Research and Development Program of China Project (2023YFF0615404).

Data Availability Statement: The data that support the findings of this study are available from the corresponding author.

Conflicts of Interest: Authors Lu Xiao, Xuanping Gong and Cheng Cheng were employed by the China Coal Energy Research Institute Co., Ltd. The remaining author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Zhang, Z.; Huo, C. Research progress of CBM utilization technology in mining areas. *Min. Saf. Environ. Prot.* **2022**, *4*, 59–64.
- Yang, M. Climate change and energy policies, coal and coalmine methane in China. *Energy Policy* **2009**, *3*, 2858–2869. [\[CrossRef\]](#)
- Ju, L.; Xu, H.; Liu, Y.A.; Li, X.X. Risk assessment of natural gas development project based on fuzzy matter—Element analysis. *J. Xi'an Shiyou Univ. (Soc. Sci. Ed.)* **2019**, *28*, 1–5.
- BP Company. *BP Review of World Energy 2002*; BP Company: London, UK, 2002; pp. 10–15.
- Harbit, G.K. The LNG market for the world. *Oil Gas J.* **2000**, *98*, 36–38.
- Zhang, T. Simulation study on thermal energy regulation of coal bed methane thermal storage and oxidation. *Min. Saf. Environ. Prot.* **2021**, *48*, 18–22.
- Khan, M.K.; Butolia, P.; Jo, H.; Irshad, M.; Han, D.; Nam, K.W.; Kim, J. Selective conversion of carbon dioxide into liquid hydrocarbons and long-chain α -olefins over Fe-Amorphous AlO_x bifunctional catalysts. *ACS Catal.* **2020**, *10*, 10325–10338. [\[CrossRef\]](#)
- Ahmed, S.; Irshad, M.; Yoon, W.; Karanwal, N.; Sugiarto, J.R.; Khan, M.K.; Kim, S.K.; Kim, J. Evaluation of MgO as a promoter for the hydrogenation of CO_2 to long-chain hydrocarbons over Fe-based catalysts. *Appl. Catal. B Environ.* **2023**, *338*, 123052. [\[CrossRef\]](#)
- Ahmed, S.; Bibi, S.S.; Irshad, M.; Asif, M.; Khan, M.K.; Kim, J. Synthesis of long-chain paraffins over bimetallic Na-FeO . $9\text{MgO} \cdot 10\text{Ox}$ by direct CO_2 hydrogenation. *Top. Catal.* **2024**, *67*, 363–376. [\[CrossRef\]](#)
- Shen, B.; Liu, J.; Lei, Y. Present status and prospects of coalbed methane development and utilization technology of coal mine area in China. *Coal Sci. Technol.* **2015**, *43*, 1–4.
- Xiao, L.; Chen, J. Experimental study on heat transfer caused by feed gas concentration fluctuation in low concentration CBM utilization unit. *Heat Mass Transf.* **2022**, *58*, 355–363. [\[CrossRef\]](#)
- Chen, J. Study progress of concentrating technology of low-concentration oxygen-containing coalbed methane. *Min. Saf. Environ. Prot.* **2017**, *44*, 94–97.
- Sircar, S.; Golden, T.C. Purification of hydrogen by pressure swing adsorption. *Sep. Sci. Technol.* **2000**, *35*, 667–687. [\[CrossRef\]](#)
- The Technology of Adsorption Separation*; Chemical Industry Press: Beijing, China, 2000.

15. Gong, Z.; Wang, B.; Tao, P. Enrichment of Methane in Coal Mine gas by Pressure Swing Adsorption. China Patent 85103557, 29 October 1986.
16. Davis, M.M.; Gray, R.L., Jr.; Patel, K. Process for the Purification of Natural Gas. U.S. Patent 5,174,796, 29 December 1992.
17. Gu, M.; Xian, X.; Zhang, D. Separation of CH₄/N₂ gas mixture by pressure swing adsorption processes. *J. China Coal Soc.* **2002**, *27*, 197–200.
18. Libo, Z. The selection of gas purification technology and the analysis of application benefit in Chengzhuang Mine. *China Pet. Chem. Stand. Qual.* **2014**, *7*, 261–262.
19. Ackley, M.W.; Yang, R.T. Kinetic separation by pressure swing adsorption: Method of characteristics model. *Aiche J.* **1990**, *36*, 1229–1238. [[CrossRef](#)]
20. Fatehi, A.I.; Loughlin, K.F.; Hassan, M.M. Separation of methane—Nitrogen mixtures by pressure swing adsorption using a carbon molecular sieve. *Gas Sep. Purif.* **1995**, *9*, 199–204. [[CrossRef](#)]
21. Zhang, C.; Lin, W.; Gu, A. The experimental research of cryogenic adsorption separation of CH₄/N₂ on carbon molecular sieve(CMS). *Cryog. Supercond.* **2008**, *36*, 9–12.
22. Yang, Y.; Ribeiro, A.M.; Li, P.; Yu, J.G. Adsorption equilibrium and kinetics of methane and nitrogen on carbon molecular sieve. *Ind. Eng. Chem. Res.* **2014**, *53*, 16840–16850. [[CrossRef](#)]
23. Guo, H.; Li, X.; Che, Y.; Liu, C.; Zhang, J.; Wang, P. Experimental study of low concentration coalbed methane by pressure swing adsorption. *Clean Coal Technol.* **2016**, *22*, 132–136.
24. Mohammadreza, G.F.; Milad, V.; Shima, N.N.; Fateme, S. Investigation of the MOF adsorbents and the gas adsorptive separation mechanisms. *J. Environ. Chem. Eng.* **2021**, *9*, 30–42.
25. Qi, B.; Chen, Y.; Li, Y.; Ma, L. Study on the removal of hydrogen sulfide from natural gas by titanosilicite zeolite. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *657*, 012034.
26. Salih, H.A.; Alkhatib, I., II; Zahra, M.A.; Vega, L.F. Diamine based hybrid-slurry system for carbon capture. *J. CO₂ Util.* **2023**, *68*, 102383. [[CrossRef](#)]
27. Yang, M.; Yang, B.; Yue, W.; Zhang, N.; Li, X.; Du, M.; Guo, L. Tunable gas absorption capability for graphene doped silica aerogel by wrinkle structure: Effects of gas absorption, mechanical properties and thermal insulation. *Sep. Purif. Technol.* **2024**, *336*, 126325. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.