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Research on the Introduction and Localization Path of Carbon Adsorption Oil-Gas Recovery Technology

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Abstract: Volatile organic compound (VOC) emissions from oil-gas storage and transportation in China have long posed dual challenges of resource waste and environmental pollution. Prior to 2008, approximately 20,000 tons of oil-gas were lost annually due to volatilzation, with no mature engineering solutions available. Carbon adsorption oil-gas recovery technology, characterized by high recovery efficiency and strong adaptability, has become the core technology for addressing this issue. This paper reviews the principles and process characteristics of carbon adsorption oil-gas recovery technology, analyzes the background of its introduction from the United States, early promotion bottlenecks, and key localization pathways. Combining the development case of Bay Environment Enterprise, the introduction and localization path of carbon adsorption oil-gas recovery technology is systematically summarized.

1. Introduction

Oil-gas recovery is an environmental protection technology that collects, separates, and recycles VOCs volatilized during oil storage, transportation, loading/unloading, and refueling operations. It is widely applied in scenarios such as gas stations, oil depots, and refinery loading terminals. The implementation of oil-gas recovery carries economic, environmental, and safety value: it reduces oil-gas volatilization losses and enables hydrocarbon resource reuse, mitigates fugitive VOC emissions and atmospheric pollution risks, and eliminates flammable and explosive safety hazards. It constitutes an important means for energy conservation, carbon reduction, and atmospheric governance in the petrochemical industry.

The carbon adsorption method, based on the principle of activated carbon adsorption and vacuum desorption regeneration, offers advantages including mature process technology, high recovery efficiency (up to 95% or above), and strong adaptability to varying operating conditions. It has become the mainstream oil-gas recovery technology internationally. Foreign countries achieved industrialization of complete sets of equipment and specialized adsorbent materials as early as the 1980s, whereas China's VOCs control technology system lagged significantly before 2008, lacking mature engineering solutions, with annual oil-gas volatilization losses reaching approximately 20,000 tons. The introduction of mature foreign carbon adsorption technology can rapidly close domestic technology gaps, support environmental air quality assurance for major events, and provide a foundation for technology digestion, absorption, and independent innovation, thereby overcoming the application limitations of inefficient condensation methods and high-cost membrane separation methods.

After the early introduction of American carbon adsorption oil-gas recovery technology into China, the industry faced challenges including low recognition and poor adaptability to local operating conditions. Through technical demonstration, process optimization, and pilot verification at Beijing Changxindian Oil Depot, the technology was promoted via major events including the Olympic Games, World Expo, APEC, and G20, and gradually applied at scale in petrochemical central enterprises. The technology has preliminarily achieved localized adaptation and equipment/material localization; however, gaps remain in high-end adsorbents, core components, and intelligent integration. It is therefore necessary to systematically review the introduction history and clarify the localization development pathway.

2. Overview of Carbon Adsorption Oil-Gas Recovery Technology

Oil-gas recovery (Vapor Recovery) refers to the technology of collecting hydrocarbon gases volatilized during oil storage and transportation and converting them into liquid oil products for recycling. It is a key measure for controlling VOC emissions, achieving resource circulation, and preventing atmospheric pollution [1]. Among the four mainstream oil-gas recovery technology routes (absorption, adsorption, condensation, and membrane separation), the activated carbon adsorption method is widely adopted by European and American developed countries due to its high recovery rate (up to 95% or above), mature process technology, stable operation, and strong adaptability to low-concentration oil-gas, and has long dominated the tertiary oil-gas recovery market at gas stations [2]. The performance comparison of mainstream processes is shown in Table 1.

Table 1: Performance Comparison of Mainstream Oil-Gas Recovery Processes

Performance Indicator	**Carbon Adsorption**	**Condensation**	**Membrane Separation**	**Absorption**
Oil-gas recovery rate	95%–99%	90%–95%	85%–92%	80%–88%
Emission concentration (g/m^3)	≤5	≤10	≤15	≤20
Processing cost (Yuan/m^3)	0.15–0.25	0.30–0.40	0.20–0.30	0.10–0.15
Equipment investment (10,000 Yuan, 1000 m^3/h)	300–500	500–800	400–600	200–300
Applicable oil-gas components	C5–C8 mixed hydrocarbons	High-concentration oil-gas	Low-concentration oil-gas	Light-component oil-gas
Operational stability	High	Medium	Medium	Low

Since the implementation of GB 20952-2020 Emission Standard of Air Pollutants for Gas Stations [5], tertiary oil-gas recovery has entered a mandatory promotion period, and the introduction, digestion, and localization of carbon adsorption technology have become core issues urgentl

2.1 Fundamental Principles

The core mechanism of the activated carbon adsorption method is based on the selective adsorption of multi-component gases on solid surfaces. Hydrocarbon components in oil-gas (C_4–C_{12}) are captured by the enormous specific surface area of activated carbon (800–1500 m^2/g) via intermolecular dispersion forces (London forces), while inert gases such as N_2 and O_2, with extremely weak adsorption forces, pass directly through the carbon bed and are discharged into the atmosphere [3]. Research indicates that the isothermal adsorption behavior of activated carbon for oil-gas can be well described by the Langmuir model. The adsorption rate is extremely rapid in the initial stage, reaching near adsorption equilibrium in approximately 45 minutes. However, although elevated temperature accelerates the adsorption rate, it reduces the equilibrium adsorption capacity: the saturated adsorption rate of fresh activated carbon at 30 ℃ can reach 33.65%, but decreases to 29.79% at 50 ℃ [3]. Furthermore, relative humidity has a significant effect on adsorption performance: when relative humidity exceeds 60%, water vapor molecules compete with hydrocarbon molecules for adsorption in micropores, causing a 15%–25% reduction in oil-gas adsorption capacity [4]. Therefore, the optimal operating window must be sought between adsorption kinetics and thermodynamics in practical engineering applications.

2.2 Core Process Flow

A complete activated carbon adsorption oil-gas recovery system typically consists of three stages-adsorption, desorption (regeneration), and absorption-with two adsorption tanks operating alternately [4], as illustrated in Figure 1.

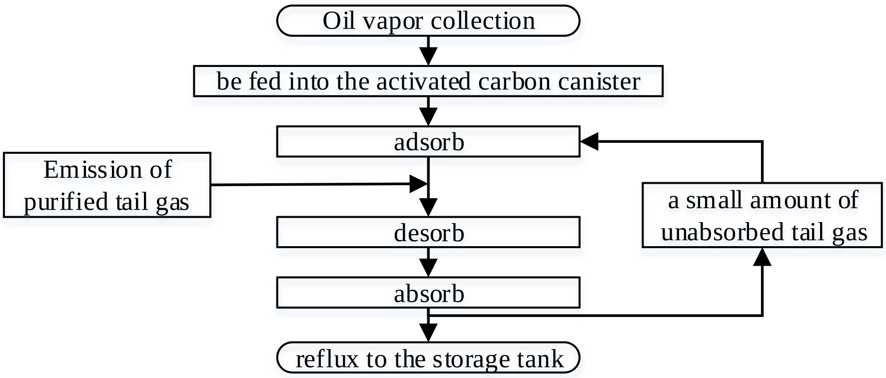

Fig. 1: Flow Chart of Carbon Adsorption Oil-Vapor Recovery Process

Adsorption stage: Oil-gas collected in a sealed manner from oil depots or loading terminals enters the activated carbon tank via pipeline, where approximately 95%–99% of oil vapor is adsorbed. The purified tail gas is discharged after online monitoring confirms compliance.

Desorption stage: When the activated carbon approaches saturation, a liquid ring vacuum pump is used to evacuate the carbon bed (typically to −85 to −95 kPa), causing the adsorbed hydrocarbons to desorb as high-concentration oil vapor. A small amount of air is simultaneously blown through for purging to ensure complete desorption [5].

Absorption stage: The high-concentration oil vapor enters the absorption tower, where it contacts gasoline spray liquid from the storage tank in countercurrent flow. The vast majority of oil-gas is dissolved and absorbed, converted into liquid gasoline that returns to the storage tank. A small amount of unabsorbed tail gas is returned to the adsorption tank for reprocessing, achieving closed-loop recovery [4].

3. Technology Introduction and Localization Pathway

The development history of carbon adsorption oil-gas recovery technology in China is essentially an industrial evolution from "introduction–digestion–re-innovation" to "independent breakthrough." Since Sinopec Huangcun Oil Depot first introduced a complete set of equipment from the American Jordan Company in the mid-1990s, the technology has undergone nearly three decades of introduction, digestion, and localization in China.

3.1 Overview of Technology Introduction

Currently, the sources of introduced carbon adsorption oil-gas recovery technology in China are highly concentrated, primarily from two global giants: the American Jordan Company and the Danish Kureha (WuYu Chemical) Company. Taking Sinopec Huangcun Oil Depot as an example, the depot introduced an internationally advanced activated carbon adsorption oil-gas recovery system from the American Jordan Company in March 2003, employing mechanical desorption (vacuum desorption) technology, configured with two adsorption tanks operating alternately, along with vacuum pumps, an absorption tower, and a gasoline circulation system, solving the problem of direct oil-gas emissions during refined oil loading [14]. Qilu Petrochemical Storage and Transportation Plant invested over 800,000 yuan in 1996 to build an activated carbon fiber (carbon blanket) adsorption oil-gas recovery device, with each adsorption column loaded with 90 kg of activated carbon fiber and automated switching between adsorption and steam regeneration controlled by PLC [14].

From the perspective of technology routes, introduced installations generally adopt a three-stage "adsorption + desorption + absorption" process. During adsorption, approximately 95%–99% of oil vapor in the oil-gas is adsorbed by activated carbon. During desorption, a liquid ring vacuum pump evacuates the carbon bed to −85 to −95 kPa, and hot nitrogen at 120–150 ℃ is used for purging to desorb the oil-gas, with a desorption rate requirement of no less than 95%. During absorption, the high-concentration oil vapor enters the absorption tower for countercurrent contact with gasoline spray liquid, where the vast majority of oil-gas is dissolved and recovered [4].

3.2 Localization Bottlenecks

In practice, localization faces three major technical barriers.

First, the fundamental research remains underdeveloped. The core bottleneck of localization lies in the severe insufficiency of basic theoretical research. Domestic enterprises have invested limited resources in areas such as pore structure regulation, surface chemical modification, and adsorption mechanism research of activated carbon, with product development relying predominantly on empirical accumulation rather than scientific guidance. At present, the majority of enterprises in the industry remain at the stage of optimizing and improving traditional production processes, with extremely limited mastery of advanced preparation techniques including template method, chemical vapor deposition, and sol-gel method. Fewer than 15% of enterprises above designated size possess relevant technological reserves[2].

More critically, there is a severe talent shortage. According to statistics from the China Activated Carbon Industry Association, technical R&D personnel holding doctoral degrees account for merely 2.3% of the entire industry, while those with master's degrees account for only 8.7%. In contrast, internationally advanced enterprises report corresponding proportions of 12% and 25%, respectively. The acute scarcity of high-end technical talent has become the most significant impediment to breakthroughs in the performance of domestically produced activated carbon.

Second, significant gaps persist in key equipment and control systems. Beyond the activated carbon itself, the precision control of vacuum desorption systems constitutes another major obstacle to localization. Imported equipment achieves vacuum control precision of ±1 kPa and desorption temperature uniformity of ±2 ℃, whereas domestic devices exhibit notable deficiencies in vacuum sealing integrity and temperature field uniformity, resulting in incomplete desorption and low activated carbon regeneration efficiency. Furthermore, insufficient system automation is a pervasive issue-conventional domestic installations lack adequate automated control capabilities, making it difficult to precisely regulate critical parameters such as temperature and flow rate, thereby substantially compromising recovery efficiency[2].

Third, the standard system lags behind. For a prolonged period, China has lacked dedicated standards for activated carbon specifically designed for oil and gas recovery. Although GB 20952-2020 Emission Standard of Air Pollutants for Gas Station prescribes emission concentration limits, the performance requirements for core materials have remained relatively ambiguous. Notably, the draft of GB 20952-2025 has introduced dedicated VOCs adsorption efficiency indicators for activated carbon, mandating an adsorption efficiency of ≥90% for benzene-series compounds (e.g., toluene). Meanwhile, ASTM D6646-2022 has revised the breakthrough curve plotting methodology by incorporating the mass transfer zone length (MTZ ≤ 0.3 times bed height) as a key evaluation parameter. These standard upgrades will further elevate the technical threshold for localization[6].

3.3 Localization Breakthrough Pathway-A Case Study of Bay Environment

3.3.1 Company Profile and Technology Route

Bay Environment, founded in 1994, is a national high-tech enterprise. Its technology route can be summarized as "introduction of American technology-digestion and absorption-independent innovation." The core team predominantly holds overseas academic backgrounds, and the company has established joint R&D programs with the University of Southern California, along with technical cooperation with the U.S. EPA and the California Air Resources Board (CARB) [7]. The company explicitly proposed the technology strategy of "introducing the most mature international VOCs recovery experience into China and conducting localized adaptation on that basis" [7].

In March 2006, Bay Environment signed and completed China's first onshore oil depot oil-gas recovery project-Sinopec Changxindian Oil Depot, which was designated as a Beijing oil-gas recovery demonstration project [8]. Subsequently, the company established two national-level R&D platforms: the "National Environmental Protection Petroleum and Petrochemical Industry VOC Pollution Control Engineering Technology Center" and the "National Engineering Laboratory for Volatile Organic Pollution Control Technology and Equipment" [8], building a complete innovation chain from fundamental research to engineering application.

3.3.2 Evolution of Key Localization Indicators

Based on the company's publicly disclosed information [7][8][9], the localization progress can be quantified through the changes in key indicators as shown in Table 2.

Table 2: Key Indicators of Bay Environment's Technology Evolution (2006–2024)

INDEX	**2006 (INTRODUCTION PHASE)**	**2015 (DIGESTION PHASE)**	**2024 (INDEPENDENT INNOVATION PHASE)**
OIL DEPOT PROJECTS	1 (CHANGXINDIAN)	~80	~250
ANNUAL VOCS PROCESSED	<1,000 TONS	~20,000 TONS	>40,000 TONS
CORE TECHNOLOGY SOURCE	100% IMPORTED	PRIMARILY IMPORTED SUPPLEMENTED BY SELF-DEVELOPED	PRIMARILY INDEPENDENT IP
NATIONAL R&D PLATFORMS	0	1	2 NATIONAL+1 PROVINCIAL
INDUSTRY STANDARD PARTICIPATION	NONE	1 STANDARD	MULTIPLE STANDARDS (LED/PARTICIPATED)
REPRESENTATIVE PRODUCT	IMPORTED AS SERIES	IMPROVED AS SERIES	AS-100 INDEPENDENT PRODUCT

At the product level, the independently developed AS-100 tertiary oil-gas recovery system has reached international levels in key indicators such as hydrocarbon removal rate and system energy consumption [8]. In 2024, the R&D team obtained two national patents: "Oil-Gas Recovery Device and Condensation System Thereof" (CN220990223U) and "An Explosion-Proof Hydrocarbon Remover" (CN110935310B). The condensation system achieves energy self-recovery under low load through cascade circulation, improving system energy efficiency by approximately 18% compared to conventional solutions [10].

At the standard level, Bay Environment participated in compiling the Ministry of Transport's Technical Specification for Terminal Oil-Gas Recovery. Its terminal oil-gas recovery technology became one of China's first large-scale application projects conforming to international standards, with typical projects including the Sinochem Xingzhong 5,000 m^3terminal and Sinochem Quanzhou 1,200 m^3chemical terminal [11].

3.3.4 Stage Characteristics of the Localization Pathway

Based on Bay Environment's practice, China's carbon adsorption oil-gas recovery technology localization pathway can be condensed into a "three-stage model":

Stage 1 (2006–2012): Technology Digestion. Starting from the Changxindian Oil Depot project, engineering verification and operational data accumulation of the introduced technology were completed, addressing the question of "whether it works."

Stage 2 (2013–2020): Independent Innovation. Leveraging national-level R&D platforms, independent products such as AS-100 were developed, with the core technology localization rate increasing from below 20% to over 60% [9], addressing the question of "how well it works." The company was selected for the "Global Cleantech 100" in 2015 (the sole Chinese enterprise that year) [12] and was recognized as a national-level specialized and new "Little Giant" enterprise in 2024 [13], indicating that localized products have achieved international recognition.

Stage 3 (2021–present): Standards Output. The company has transitioned from a technology user to a standard setter. Cooperation with the University of Southern California has upgraded from one-way introduction to bidirectional joint R&D, promoting "Chinese solutions" to participate in international competition [8], addressing the question of "whether it can lead."

3.3.5 Pathway Analysis and Recommendations

Bay Environment's case demonstrates that technology introduction is not the endpoint of localization but rather the starting point for independent innovation. Currently, China's carbon adsorption oil-gas recovery technology localization has entered a "deep-water zone." It is recommended to adopt a "three-step" pathway: Step 1 (2025–2027): Focus on the industrial-scale production of specialized activated carbon with benzene adsorption capacity ≥350 mg/g; Step 2 (2027–2029): Promote standardization and modularization of combined processes such as "condensation + adsorption"; Step 3 (2029–2030): Fully deploy digital twin and intelligent O&M systems to achieve core technology self-reliance.

4. Conclusion

Carbon adsorption oil-gas recovery technology, as a key supporting technology for China's total VOCs emission reduction and "dual carbon" goals, has undergone nearly three decades of introduction, digestion, and localization. From the perspective of technology principles, the activated carbon adsorption method, with its recovery rate exceeding 95% and strong adaptability to low-concentration oil-gas, remains the irreplaceable mainstream technology route in the tertiary oil-gas recovery field at gas stations [1]. However, the performance gap in core materials-specialized activated carbon for oil-gas recovery-insufficient precision control of key equipment, and lagging standard systems constitute three structural barriers constraining the deepening of localization [6][5].

Localization pioneers represented by Bay Environment provide a replicable breakthrough pathway: starting from introduced technology, supported by national-level R&D platforms, and culminating in standard formulation, progressing through the three stages of "technology digestion-independent innovation-standards output," achieving a leap from "follower" to "peer" [8][13]. As of 2024, its independent products such as AS-100 have been deployed at approximately 250 oil depots nationwide, processing over 40,000 tons of VOCs annually, with a core technology localization rate exceeding 60% [8][9]. This practice demonstrates that localization is not simple import substitution, but systematic re-innovation built upon introduction.

Looking ahead, the localization of carbon adsorption oil-gas recovery technology should continue along the "material breakthrough-system integration-intelligent upgrade" three-step pathway [6]. At the material level, there is an urgent need to achieve scale production of specialized activated carbon with high specific surface area (≥ 1400 m^2/g) and high adsorption capacity (benzene adsorption ≥ 350 mg/g). At the system level, standardization and modularization of combined processes such as "condensation + adsorption" will become key directions for reducing operating costs and extending activated carbon service life [2]. At the intelligent level, deployment of digital twin and AI lifecycle prediction systems is expected to raise the operating efficiency of domestic installations to over 90% of imported equipment levels [6].

It is foreseeable that with the implementation of new standards such as GB 20952-2025 and the continuous tightening of total VOCs emission reduction assessments [5], the localization of carbon adsorption oil-gas recovery technology will shift from an "option" to a "necessity." Only by deeply integrating technology introduction with independent R&D can true core technology self-reliance be achieved, providing solid technical support for China's atmospheric pollution prevention and green low-carbon transition.

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