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Review

Natural Gas Sweetening Technologies: A Technical and Comparative Analysis of Processes and Applications

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Abstract: This article presents a comprehensive and technical analysis of modern natural gas sweetening technologies, including chemical absorption, physical absorption, hybrid processes (such as Sulfinol), direct conversion (e.g., Stretford and iron sponge), and dry bed adsorption. It discusses their thermodynamic principles, removal mechanisms, operational conditions, and associated technical challenges, all supported by up-to-date technical literature and regulatory frameworks. The methodology was based on a systematic review of scientific literature, utilizing well-established databases and rigorous bibliographic selection criteria. The findings indicate that chemical absorption—particularly using MEA and MDEA solutions—remains the most versatile option for gas streams with high compositional variability. However, technologies such as physical absorption (e.g., Selexol and Rectisol) offer energy efficiency advantages in high-pressure environments. Hybrid systems provide a more balanced operational performance in complex scenarios, while direct conversion and dry bed adsorption, although limited in capacity and regeneration potential, are effective for small-scale or targeted applications. In conclusion, the selection of an appropriate sweetening process should take into account technical, economic, and environmental considerations, including energy efficiency, ease of solvent regeneration, selectivity, and overall operational feasibility. Finally, the study highlights future research directions focused on novel regenerable adsorbent materials and integrated carbon capture technologies (CCUS), in alignment with global energy sustainability objectives.

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1. Introduction

Natural gas has established itself as one of the leading energy sources worldwide due to its high efficiency, relative abundance, and lower environmental impact compared to other fossil fuels such as coal and oil. Although primarily composed of methane (CH_4), natural gas also contains significant impurities such as hydrogen sulfide (H_2S), carbon dioxide (CO_2), mercaptans, and other sulfur compounds that negatively affect its physicochemical properties and operational performance [1–3].

The presence of these acid gases creates substantial challenges that limit its direct use in industrial and domestic applications. H_2S, for instance, is highly toxic and corrosive, and has the potential to form sulfuric acid in the presence of moisture, which can damage transportation and storage equipment and pose serious risks to human health and the environment [4]. CO_2, on the other hand, significantly reduces the calorific value of the gas, increasing operational costs related to transportation and processing, particularly when cryogenic methods are used for liquefied natural gas (LNG) storage and transport [5].

Due to these challenges, the treatment of natural gas through sweetening technologies has become a standard and critical practice within the energy sector. The methods employed aim to reduce acid gas content to levels established by international and national standards, such as those specified by the International Organization for Standardization (ISO) and regulatory agencies in other producing and consuming countries [3,6].

Selecting the most appropriate sweetening technology depends on various technical and economic factors, including the specific chemical composition of the natural gas, partial pressure of the acid gases, production volume, reservoir operating conditions, and applicable environmental regulations. The available technologies range from chemical absorption with amines to physical and hybrid processes, as well as emerging technologies involving adsorption and direct conversion [2,7].

This study provides a comprehensive analysis of these techniques, comparing their technical performance, environmental sustainability, and economic viability, thereby contributing to the optimization of process selection for specific industrial applications.

2. Methodology

The methodology employed in this study was based on an exhaustive and systematic review of relevant scientific literature, including research articles, technical reports, and specialized textbooks, with the objective of gathering information on fundamental principles, applied methodologies, recent advances, and current challenges in the field of natural gas sweetening.

(a) Data search and collection: Internationally recognized scientific and technical databases were consulted, such as Frontiers, Wiley Online Library, Royal Society of Chemistry, MDPI, ACS Publications, ScienceDirect, SCOPUS, IEEE Xplore, SciELO, RedALyC, and Google Scholar. Key search terms included "Gas sweetening," "Natural gas purification," "Absorption technologies," "Adsorption processes," and "Desulfurization methods."

(b) Information selection and refinement: A comprehensive exploration of relevant literature from the period 1990 to 2024 was conducted. Using Mendeley (Elsevier, 2021) as a bibliographic management tool, the collected data were organized and filtered according to their relevance to the specific objectives of this study.

(c) Subtopic selection: The refined information enabled a clear definition of the study's structure and the identification of subtopics directly related to the gas sweetening technologies analyzed in this research.

(d) Data analysis: A critical and comparative analysis of the collected data was carried out, allowing for the formulation of comprehensive conclusions on the most relevant and suitable gas sweetening technologies for specific industrial applications.

3. Discussion and Results

3.1. Advanced Gas Sweetening Technologies

A. <u>Chemical Absorption:</u>

Chemical absorption is a widely used technology for the efficient removal of acid gases from natural gas, particularly hydrogen sulfide (H_2S) and carbon dioxide (CO_2). This process involves a reversible chemical reaction between the acid gases and aqueous amine solutions, which possess basic properties that facilitate the neutralization of acidic components [1], [4].

Commonly used amines include Monoethanolamine (MEA), Diethanolamine (DEA), and Methyldiethanolamine (MDEA). The specific choice of solvent depends on the required balance between absorption capacity, reaction kinetics, and ease of thermal regeneration. For example, MEA provides high reaction rates but is more corrosive and energy-intensive, whereas MDEA, although slower in absorption, offers higher selectivity and requires less energy for regeneration [5,6].

This method involves two distinct stages: absorption and regeneration. During the absorption stage, natural gas comes into contact with the amine solution in a packed or tray column, promoting mass transfer and chemical reaction with the acid gases. In the regeneration stage, heat is applied to

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reverse the chemical reaction, releasing the acid gases from the solvent and restoring the amine solution for reuse [7].

However, chemical absorption faces significant technical and operational challenges, including equipment corrosion due to acidic compound formation, thermal and oxidative degradation of the solvent, and high energy requirements for solvent heating and regeneration—factors that increase both operational and environmental costs [5,8]. Therefore, technical optimization of operating parameters such as temperature, pressure, solvent concentration, and material selection is essential to ensure the viability and sustainability of this technology in industrial applications.

B. Physical Absorption:

Physical absorption is a technique used to remove acid gases from natural gas by means of non-reactive solvents that physically capture these gases through molecular interactions, primarily Van der Waals forces. Common physical solvents include Selexol (glycol ethers), Rectisol (chilled methanol), and Fluor Solvent (perfluorinated compounds), each with specific properties suited to various industrial scenarios [7,8].

This method is particularly efficient under high partial pressure conditions of acid gases, which favor high physical solubility. The process involves absorption towers where the gas intimately contacts the solvent. However, physical absorption typically requires less energy for solvent regeneration, which is usually achieved by pressure reduction or a mild temperature increase—providing a notable economic and energy-saving advantage over chemical absorption [9].

A distinctive technical feature of this technology is its capacity to treat gas streams with high acid gas concentrations and low heavy hydrocarbon content, minimizing losses of valuable hydrocarbons. Nonetheless, one key limitation is the co-absorption of heavy hydrocarbons in rich gas streams, which can lead to economic and operational drawbacks. Therefore, detailed technical assessments of the gas composition and process conditions are essential to determine the feasibility of employing physical solvents [7,10].

C. Hybrid Processes (Sulfinol):

Hybrid processes combine the advantages of chemical and physical absorption by using a mixture of both types of solvents. A widely implemented example is the Sulfinol process, which employs a mixture of sulfolane (a physical solvent) and diisopropanolamine (DIPA, a chemical solvent), creating a system capable of absorbing acid gases through complementary mechanisms. This mixture enables high removal efficiency of complex gases such as mercaptans (RSH), carbonyl sulfide (COS), as well as H_2S and CO_2—surpassing the performance of standalone methods [1,9].

Sulfinol offers substantial operational advantages, especially under variable or complex gas compositions. The presence of the physical solvent significantly reduces energy consumption during chemical solvent regeneration by lowering the required desorption temperature, thus enhancing the overall energy efficiency of the process [9].

Nevertheless, hybrid systems also present technical challenges that must be managed carefully. The combined use of solvents may increase complexity in the recovery process and require more sophisticated operational control systems to maintain an appropriate balance between the solvents. Chemical stability and material compatibility must also be thoroughly evaluated, particularly in offshore environments, where operational conditions are more severe and demanding [1,9].

Thus, a detailed technical evaluation of the specific benefits and operational limitations of hybrid processes is essential to maximize their technical efficiency and economic viability in industrial applications.

D. Direct Conversion Processes:

Direct conversion processes involve the chemical transformation of hydrogen sulfide (H_2S) into elemental sulfur through redox reactions. Notable technologies include the Stretford process and the iron sponge method. The Stretford process uses alkaline aqueous solutions containing specific oxidizing agents such as vanadates and quinones to catalyze the conversion of H_2S into elemental sulfur under moderate conditions. This technique is especially suitable for intermediate concentrations of H_2S, eliminating the need for additional sulfur recovery units, thereby reducing capital costs and simplifying operations [1,10].

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The iron sponge method, on the other hand, is based on the chemical adsorption of H_2S using iron oxide impregnated on a porous solid support. H_2S reacts to form iron sulfide, which can be partially regenerated by controlled exposure to air, restoring limited reactivity. However, this partial regeneration entails significant operational limitations, including the gradual degradation of the adsorbent and the generation of solid waste that is environmentally challenging to manage [11].

The efficiency of these processes is strongly dependent on operational variables such as temperature, oxidant concentration, specific gas composition, and the physicochemical properties of the solid adsorbent. Furthermore, direct conversion technologies must be carefully evaluated from both environmental and economic standpoints, particularly regarding by-product management and the long-term stability of the operational process [10,11].

E. Dry Bed Adsorption:

Dry bed adsorption is a technique used to remove acid gases through physical or physicochemical interaction with specific solid adsorbent materials such as zeolites (molecular sieves), mesoporous [12], activated alumina, and activated carbon. This process leverages the high surface area and specific porosity of these adsorbents to achieve efficient and selective retention of components like H_2S and, to a lesser extent, CO_2 [13,14].

A significant advantage of this technology is its applicability to small-scale systems, remote installations, or decentralized treatment units where gas flow rates are relatively low and complex infrastructure investment is limited. Additionally, dry bed adsorption offers high selectivity for H_2S, making it a particularly efficient option when the removal of specific contaminants is required [14].

However, this method presents operational challenges related to the frequent regeneration of the adsorbent, which is typically achieved through thermal processes or pressure swing adsorption (PSA) cycles. These periodic operations can substantially increase operating costs and require careful management to prevent long-term loss of adsorbent efficiency. Moreover, the disposal and handling of spent adsorbents or generated residues pose important environmental considerations in the overall evaluation of the process [13,14].

Therefore, the selection of appropriate adsorbents and the optimization of operating conditions—such as cycle time, regeneration temperature, and pressure settings—are essential to ensure the effective and sustainable performance of dry bed adsorption technologies.

3.2. Comparative Technical Evaluation

The comparative technical evaluation of natural gas sweetening technologies considers several critical factors such as energy efficiency, selectivity in the removal of specific contaminants, operating costs, and environmental sustainability. Each technology presents particular strengths and weaknesses that determine its viability in different industrial scenarios.

Chemical absorption, for example, demonstrates high effectiveness and flexibility in handling variable acid gas compositions. However, it incurs high operating costs due to the intensive energy requirements for regenerating chemical solvents and managing associated issues such as corrosion and solvent degradation [5,8].

On the other hand, physical absorption offers significant advantages in terms of lower energy consumption during regeneration, especially under conditions of high partial pressure of acid gases. Nevertheless, the potential loss of valuable hydrocarbons due to co-absorption limits its application in gas streams with high heavy hydrocarbon content [7,10].

Hybrid processes, such as Sulfinol, successfully combine the high removal efficiency of chemical solvents with the low energy demand of physical solvents. They are particularly effective in offshore applications and in treating gas with variable or complex compositions. However, these systems require careful operational management due to the added complexity of handling multiple solvents simultaneously [1,9].

Direct conversion technologies, such as Stretford and iron sponge, provide simple and effective operation in moderate H_2S concentrations, eliminating the need for additional sulfur recovery units. However, they pose environmental and operational challenges related to the generation and disposal of by-products, especially in the case of iron sponge, which can generate solid waste that is difficult to manage [10,11].

Finally, dry bed adsorption is highly effective and selective in situations requiring low treatment capacities or decentralized applications. However, the frequent need for adsorbent regeneration and proper waste handling may result in higher operating costs and environmental challenges [13,14].

Therefore, the selection of the most appropriate natural gas sweetening method must be based on a thorough and case-specific analysis of the gas composition, process operating conditions, economic feasibility, and environmental considerations—ensuring an optimal and sustainable choice for each industrial application [15,16].

3.3. Industrial Applications

Natural gas processed through sweetening technologies finds multiple strategic industrial applications, where fuel quality and compliance with environmental regulations are essential. Sweet gas is widely used in thermoelectric power generation, as a feedstock in the petrochemical industry, in the transportation sector via compressed natural gas (CNG), as well as in residential and commercial settings for heating and cooking [1,4,15].

In the petrochemical sector, contaminant-free natural gas maximizes the efficiency of catalytic processes in the production of methanol, ammonia, light olefins, and fertilizers. Even trace amounts of H_2S or CO_2 can poison metal catalysts, reduce conversion efficiency, and cause solid deposits in reaction units [17,18].

In electric power generation—particularly in combined cycle plants or gas turbines—the use of sweet gas enhances the fuel's calorific value, reduces the formation of acidic compounds in exhaust gases, and extends the service life of turbines and boilers. Additionally, the removal of sulfur compounds significantly decreases the emission of sulfur oxides (SO_x), which is essential for compliance with environmental regulations such as the European Union's Industrial Emissions Directive or the U.S. EPA standards [19].

In the transportation sector, CNG has emerged as a cleaner alternative to traditional liquid fuels. Its deployment requires gas that meets stringent specifications, achievable only through effective removal of acid gases and moisture. This is essential to prevent corrosion in storage cylinders and ensure complete and efficient combustion in adapted engines [20].

In Venezuela, processing plants located in Tía Juana, Morichal, and Anaco have implemented various sweetening technology configurations to ensure the quality of gas intended for both domestic use and export through systems such as the Trans-Caribbean Gas Pipeline or the Jose Cryogenic Complex. This type of technological integration ensures compliance with international standards such as ISO 13686 and enhances the commercial value of the processed gas [1,15].

4. Conclusions

The treatment of natural gas through sweetening technologies is a critical component in the value chain of the modern energy sector. This process not only ensures gas quality for industrial, residential, and vehicular use but is also essential for meeting stringent national and international environmental regulations. The efficient removal of contaminants such as H_2S and CO_2 helps prevent operational issues, extends equipment lifespan, and reduces the environmental footprint of the global energy system.

Among the technologies analyzed, chemical absorption remains the most versatile and widely applied option, particularly in facilities handling variable gas compositions or large volumes. However, alternatives such as physical absorption, hybrid systems, and direct conversion are gaining prominence in specific contexts—such as offshore environments, decentralized installations, or small-scale projects—due to their lower energy demands and operational simplicity.

Despite technological advancements, the selection of the optimal sweetening method must be based on a comprehensive analysis that considers the specific composition of the gas, operational conditions, existing infrastructure, scalability projections, and the economic and environmental objectives of the project. Emerging research directions point toward the development of high-capacity regenerable adsorbents, improved formulations of hybrid solvents, and the integration of carbon capture technologies (CCUS) into gas processing systems.

Ultimately, the rational and technically grounded implementation of gas sweetening technologies represents a key strategy for energy sustainability and the transition toward cleaner and more efficient energy matrices.

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