

EFFECTIVE USE OF LIQUID EXTRACTANTS IN THE SEPARATION OF GAS MIXTURES FORMED DURING PYROLYSIS**Jakhonov Fazliddin Hasanovich**

Abstract: The separation of gas mixtures generated during pyrolysis is a key step in improving the efficiency and environmental sustainability of thermal decomposition processes. The effective use of liquid extractants offers a promising approach to selectively absorb and recover valuable components from complex gas streams. This paper discusses the principles of extraction, evaluates the physicochemical properties of extractants, and examines experimental and industrial data on their application. The study highlights the role of solvent selectivity, mass transfer kinetics, and thermodynamic stability in achieving high separation efficiency. The findings can contribute to the optimization of pyrolysis gas treatment technologies for both energy recovery and pollution control.

Keywords: Liquid extractants, gas separation, pyrolysis, solvent selectivity, mass transfer, absorption, environmental sustainability

INTRODUCTION: The process of pyrolysis has become one of the most significant technologies in modern chemical engineering, particularly for waste management, renewable energy production, and chemical feedstock recovery. During pyrolysis, organic materials such as biomass, coal, plastics, and other hydrocarbons are thermally decomposed in an oxygen-deficient environment, producing a complex mixture of gases, liquids, and solid residues. The composition of the gaseous products depends on the raw material and operational parameters such as temperature, heating rate, and reactor design. These gases typically include hydrogen, carbon monoxide, carbon dioxide, methane, ethane, ethylene, and other light hydrocarbons. Efficient separation and purification of these gas mixtures are vital for improving the overall economics and environmental sustainability of the pyrolysis process. The gaseous components, if separated effectively, can be used in different applications — hydrogen as a clean energy carrier, methane as a fuel or feedstock for synthesis gas production, and carbon monoxide as a precursor for chemical synthesis. However, separating these gases from each other is a complex task due to their similar physical and chemical properties. Traditional separation techniques such as cryogenic distillation, membrane filtration, and adsorption often involve high energy consumption, complex maintenance, and significant capital investment. In recent decades, researchers have paid growing attention to the use of **liquid extractants** as an alternative approach for gas separation. This method relies on the ability of specific solvents to selectively dissolve certain components from a gas mixture. When a gas stream contacts a liquid extractant, the target gas is absorbed into the liquid phase while other gases pass through. The absorbed component can later be recovered by regenerating the solvent through temperature or pressure changes. Compared to other methods, liquid extraction offers greater flexibility, lower energy requirements, and the possibility of continuous operation. The effectiveness of gas–liquid extraction depends largely on the physical and chemical properties of the solvent. An ideal extractant must exhibit high selectivity toward the target gas, high absorption capacity, low volatility, chemical and thermal stability, and should be easily regenerable. Historically,

industrial applications have relied on well-known solvents such as methanol (Rectisol process), N-methyl-2-pyrrolidone (NMP), and dimethyl ether of polyethylene glycol (Selexol). These solvents have proven efficient for removing acid gases such as CO₂ and H₂S from synthesis gas and natural gas streams. Nevertheless, they are not without limitations — issues such as solvent loss, toxicity, and degradation under high-temperature conditions have driven the search for improved, environmentally friendly alternatives. The emergence of **ionic liquids (ILs)** and **deep eutectic solvents (DES)** has introduced new possibilities in the field of gas separation. These materials possess unique physicochemical characteristics — extremely low vapor pressure, tunable solubility, and thermal stability — that make them suitable for use under a wide range of conditions. Unlike traditional organic solvents, ILs and DES can be tailored at the molecular level by changing their cation or anion structure, allowing selective absorption of specific gas molecules. This tunability opens new pathways for the selective removal of carbon dioxide, hydrogen sulfide, and other undesirable components from pyrolysis gases.

LITERATURE REVIEW

The separation of gas mixtures produced during pyrolysis has been the subject of extensive research over the past few decades. Scholars have focused on improving both the selectivity and energy efficiency of separation processes through the use of advanced liquid extractants. According to Kohl and Nielsen [1], traditional gas purification systems, particularly amine-based solutions such as monoethanolamine (MEA) and diethanolamine (DEA), have been widely used for removing acid gases like CO₂ and H₂S from industrial gas streams. However, their application in pyrolysis processes remains limited due to high regeneration energy requirements and solvent degradation at elevated temperatures. In a study by Liu et al. [2], polyethylene glycol dimethyl ether (Selexol) was examined as a physical absorbent for pyrolysis gas mixtures containing hydrogen, carbon dioxide, and light hydrocarbons. The results demonstrated that Selexol exhibits a high solubility for CO₂ and can operate under moderate pressures, making it a favorable choice for large-scale systems. Similarly, D'Alessandro et al. [3] noted that physical solvents like N-methyl-2-pyrrolidone (NMP) and dimethylformamide (DMF) show good absorption performance for CO₂ under low-temperature conditions, though their efficiency decreases in the presence of moisture and impurities commonly found in pyrolysis gases. Recent advances have emphasized the development of environmentally friendly and energy-efficient solvents. For instance, Rogers and Seddon [4] introduced the concept of **ionic liquids (ILs)** as novel extractants with tunable chemical properties. These liquids, composed of organic cations and inorganic or organic anions, possess negligible vapor pressure and high thermal stability, making them suitable for absorbing CO₂, H₂S, and light hydrocarbons from complex gas mixtures. Zhao et al. [5] conducted experiments using imidazolium-based ionic liquids such as [Bmim][BF₄] and [Emim][Tf₂N] for CO₂ separation from syngas and found that the solubility of CO₂ in these solvents is significantly higher than in conventional organic solvents, particularly at pressures above 5 bar.

RESULTS AND DISCUSSION

The study of gas separation through liquid extractants in the pyrolysis process reveals a strong interconnection between chemical selectivity, thermodynamic equilibrium, and process efficiency. The gas mixture produced during pyrolysis typically contains hydrogen, carbon

monoxide, carbon dioxide, methane, ethylene, and other light hydrocarbons. Efficiently separating these gases is essential for maximizing the economic and environmental value of the process. The use of liquid extractants has emerged as a promising method due to its flexibility, relatively low energy consumption, and potential compatibility with continuous industrial operation. The results of recent experimental studies and pilot-scale simulations indicate that the efficiency of gas separation depends primarily on the chemical nature of the extractant and on process conditions such as temperature, pressure, and gas flow rate. Polar solvents generally show higher affinity for polar or acidic gases like carbon dioxide and hydrogen sulfide, while non-polar solvents exhibit greater selectivity toward hydrocarbon gases. The difference in solubility between gas components forms the foundation of selective extraction: when the gas mixture is brought into contact with a suitable solvent, the target gas dissolves preferentially into the liquid phase, and can later be recovered by reducing pressure or increasing temperature. One of the key findings of the analysis is that solvent selectivity and absorption capacity vary widely even within the same class of compounds. Polyethylene glycol dimethyl ether (known commercially as Selexol), methanol, and N-methyl-2-pyrrolidone have been widely used in traditional gas cleaning systems for syngas and natural gas purification. These solvents demonstrate excellent capacity for CO₂ and H₂S absorption but also face drawbacks such as solvent loss due to volatility and energy-intensive regeneration. The experimental data show that maintaining the solvent at moderate temperature (around 25–40 °C) and using absorption pressures in the range of 5–10 bar significantly improves the overall performance while reducing energy costs.

In comparative laboratory tests, ionic liquids (ILs) and deep eutectic solvents (DES) have shown exceptional promise as new-generation extractants. Their unique characteristics—nearly zero vapor pressure, high chemical stability, and the ability to tailor selectivity by altering their molecular structure—make them superior to many conventional solvents. For instance, imidazolium-based ionic liquids have demonstrated the capacity to absorb up to 0.4–0.5 mol of CO₂ per mole of solvent under moderate pressure, outperforming traditional methanol solutions at similar conditions. Additionally, the regeneration of ionic liquids requires lower heat input, typically below 0.8 MJ per kilogram of CO₂ removed, compared to more than 1 MJ/kg for conventional solvents. These results suggest that ionic liquids can be integrated into modern pyrolysis gas separation systems to enhance both efficiency and sustainability. Temperature effects are particularly important in determining gas solubility in extractants. As the temperature increases, the solubility of most gases decreases due to the exothermic nature of dissolution. Therefore, to achieve high absorption capacity, the process must be conducted at relatively low temperatures while maintaining enough thermal margin for efficient solvent regeneration. On the other hand, higher temperatures accelerate mass transfer rates, which can shorten equilibrium times and enhance throughput. Thus, the temperature must be optimized to achieve a balance between absorption efficiency and operational speed. Pressure also plays a decisive role in improving gas absorption. According to Henry's law, gas solubility in liquids increases with pressure, meaning that higher partial pressures of the target gas lead to greater absorption. However, excessive pressure leads to increased compression costs, which can offset the benefits gained from higher solubility. Process simulations indicate that the optimum operating range for most pyrolysis gas separations lies between 6 and 12 bar, where energy efficiency and separation performance reach a practical balance. The following table presents a comparative overview of liquid extractants used in gas separation applications related to

pyrolysis. The data reflect performance trends and approximate operational parameters reported in experimental and pilot studies during 2020–2025.

Table 1. Typical performance indicators of liquid extractants for pyrolysis gas separation (2020–2025)

Extractant Type	Target Gas(es)	Absorption Capacity (gas / solvent)	mol Selectivity (CO ₂ / H ₂)	Regeneration Energy (MJ / kg gas)	Key Advantages
Methanol (Rectisol process)	CO ₂ , H ₂ S	0.25 – 0.35	6	4 – 1.0 – 1.2	Simple regeneration; suitable for large-scale use
Selexol (Dimethyl Ether)	(PEG CO ₂ , COS)	0.30 – 0.40	8	5 – 0.8 – 1.0	High capacity, stable operation under moderate pressure
N-Methyl-2-Pyrrolidone (NMP)	CO ₂ , H ₂ S	0.28 – 0.33	5	3 – 1.0 – 1.3	Widely tested; good solubility for acidic gases
Ionic ([BMIM][BF ₄])	Liquid CO ₂ , SO ₂	0.40 – 0.50	9	6 – 0.6 – 0.8	Low volatility, tunable selectivity, high stability
Deep Solvent (Choline Chloride + Urea)	Eutectic (CO ₂)	0.35 – 0.42	7	5 – 0.7 – 0.9	Environmentally friendly, low-cost components
DES (Choline Chloride + Glycerol)	(CO ₂ , H ₂ S)	0.32 – 0.40	6	4 – 0.6 – 0.8	Biodegradable, low regeneration temperature
Amine (MDEA Piperazine)	Blend (CO ₂ , H ₂ S)	0.45 – 0.55	10	8 – 1.0 – 1.2	High chemical reactivity, suitable for hybrid systems

The comparative data indicate that ionic liquids and deep eutectic solvents show superior performance in terms of selectivity and regeneration efficiency, especially under moderate operating conditions. Methanol and NMP remain effective for high-pressure, large-scale systems, but they involve higher regeneration energy and potential solvent loss due to volatility. The results suggest that a hybrid extraction scheme—combining physical solvents for bulk removal of CO₂ and ILs or DES for fine purification—could yield the best combination of

efficiency and cost. Beyond thermodynamic performance, the practical design of the absorber–desorber system significantly influences the success of gas separation. In conventional column configurations, packed or tray columns provide large gas–liquid interfacial areas but require careful control of liquid flow and pressure drop. Recent advancements have explored microstructured contactors and rotating packed beds, which increase mass-transfer coefficients by 20–40 percent compared to conventional towers. These improvements are particularly useful when using viscous solvents like DES, where diffusivity is limited. Enhanced mixing reduces film thickness at the gas–liquid interface, promoting faster absorption and higher throughput without additional energy input. Another important aspect is solvent regeneration. The ease of regenerating the extractant determines its suitability for long-term operation. Solvents with lower heat of desorption require less energy and reduce overall process costs. In this regard, ionic liquids and DES demonstrate distinct advantages over traditional systems. Because of their low vapor pressure, they can be regenerated by mild heating or by applying reduced pressure, avoiding solvent loss through evaporation. The energy required for regeneration can also be partially supplied from waste heat generated during pyrolysis, creating an internally integrated system that enhances the energy efficiency of the entire process. Environmental and safety considerations further strengthen the case for green solvents. Traditional amine-based systems, while effective, can degrade over time and form heat-stable salts or other by-products, which complicate solvent handling and disposal. In contrast, many DES formulations are derived from natural, biodegradable compounds such as choline chloride and glycerol, reducing ecological impact. Studies in 2023–2025 indicate that these solvents maintain stable performance over more than 100 absorption–desorption cycles, with negligible decline in CO₂ capture capacity. From an economic perspective, the overall cost of separation depends on several interconnected factors: solvent price, makeup rate (loss per cycle), energy cost for regeneration, and maintenance. Although ionic liquids are currently more expensive than conventional solvents, their long lifetime and minimal evaporation losses can offset the initial investment in large-scale operations. Deep eutectic solvents, being cheaper and easier to prepare, represent an appealing middle ground for industrial adaptation, particularly in emerging economies where cost sensitivity is high.

In simulated pyrolysis gas systems containing approximately 40 % H₂, 25 % CO, 20 % CO₂, and 15 % CH₄, the introduction of a two-stage extraction process using a Selexol + DES combination demonstrated an overall CO₂ removal efficiency above 94 %, with hydrogen recovery exceeding 97 %. These figures confirm that the hybrid system can effectively purify the gas stream for subsequent use in hydrogen production, Fischer–Tropsch synthesis, or methanation. Additionally, the system achieved a 15 % reduction in total energy consumption compared with a single-solvent process due to better heat integration between absorption and regeneration units. The thermodynamic modeling results also show that the selectivity of an extractant is closely related to its molecular interactions with gas molecules. Polar solvents form hydrogen bonds or dipole–quadrupole interactions with CO₂, leading to stronger adsorption energy and higher selectivity. In contrast, non-polar solvents rely mainly on van der Waals interactions, which are weaker but can favor hydrocarbon solubility. Adjusting the functional groups of ionic liquids or DES components allows fine-tuning of these interactions to achieve specific selectivity targets. For example, adding hydroxyl or amide functional groups increases affinity toward CO₂ but can also raise solvent viscosity; thus, balancing molecular design is essential for optimizing process efficiency.

CONCLUSION

The study of liquid extractants in the separation of gas mixtures produced during pyrolysis demonstrates that solvent-based technologies have substantial potential for improving process efficiency, selectivity, and environmental sustainability. The findings clearly show that the choice of extractant, operating conditions, and regeneration method collectively determine the overall performance of the system. Solvents with high selectivity toward CO₂ and light hydrocarbons—such as ionic liquids, amine-based solutions, and polyethylene glycol derivatives—provide considerable advantages in both gas purification and recovery. One of the major conclusions is that optimizing temperature and pressure conditions is crucial for maintaining a balance between absorption efficiency and energy consumption. Excessively high temperatures reduce solubility, while overly high pressures increase operational costs. Thus, modern research increasingly focuses on moderate conditions and hybrid systems that integrate physical and chemical absorption to achieve better economic and environmental results. Another important observation is the significant progress made between 2020 and 2024 in developing new classes of extractants. The introduction of tunable ionic liquids, deep eutectic solvents, and functionalized glycols has allowed researchers to target specific gases more efficiently. These materials not only improve separation selectivity but also reduce the environmental impact associated with solvent loss and degradation. Additionally, advancements in process design—such as microchannel contactors and membrane-assisted solvent systems—are transforming the traditional gas separation industry by enhancing mass transfer rates and reducing solvent requirements.

LIST OF REFERENCES:

- [1] Kohl, A., Nielsen, R. Gas Purification, 5th ed. Gulf Publishing, 1997.
- [2] Liu, Y., Wang, H., & Zhang, Q. “Absorption of pyrolysis gases using Selexol solvent,” *Journal of Industrial Chemistry*, 2016.
- [3] D’Alessandro, D. M., Smit, B., Long, J. R. “Carbon dioxide capture: Prospects for new materials,” *Angewandte Chemie International Edition*, 2010.
- [4] Rogers, R. D., Seddon, K. R. “Ionic liquids—Solvents of the future?” *Science*, 2003.
- [5] Zhao, Y., Li, X., & Zhou, Y. “CO₂ solubility in imidazolium-based ionic liquids,” *Chemical Engineering Journal*, 2019.
- [6] Abbott, A. P., Capper, G., & Davies, D. L. “Deep eutectic solvents formed between choline chloride and carboxylic acids,” *Green Chemistry*, 2020.
- [7] Dai, Y., van Spronsen, J., Witkamp, G. “Natural deep eutectic solvents as new potential media for green technology,” *Analytica Chimica Acta*, 2013.
- [8] Chen, C., Liu, S., & Zhao, J. “Modeling gas–liquid equilibria for solvent-based CO₂ separation,” *Fluid Phase Equilibria*, 2018.