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CLASSIFICATION AND COMPARATIVE ANALYSIS OF HYDROCARBON GAS PROCESSING METHODS

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Annotation. Hydrocarbon gases, particularly methane, represent an important feedstock for the modern chemical and energy industries. Their efficient conversion into value-added products is essential for improving resource utilization and reducing environmental impact. This study presents a comprehensive review and classification of the main methods used for hydrocarbon gas processing, including thermal, catalytic, oxidative, and non-oxidative approaches. The analysis is based on a systematic evaluation of scientific literature published between 2000 and 2025. The results show that thermal processes operate at high temperatures (800-1200 °C) and exhibit relatively low selectivity (20-40%), while catalytic methods demonstrate higher efficiency, with methane conversion reaching 70-98% and selectivity up to 95%. Oxidative processes provide faster reaction rates and lower energy consumption (100-200 MJ/mol CH_4) but are limited by over-oxidation and CO_2 formation. Non-oxidative methods, although promising for the direct production of high-value chemicals such as aromatics, are currently constrained by low conversion (10-30%) and catalyst instability. Overall, catalytic processes remain dominant in industrial applications, while emerging non-oxidative and low-emission technologies offer significant future potential. The study highlights the importance of developing advanced catalytic systems and energy-efficient processes to enhance the sustainability of hydrocarbon gas processing.

Keywords: Hydrocarbon gas processing, methane conversion, catalytic processes, oxidative conversion, non-oxidative conversion.

Аннотация. Углеводородные газы, в частности метан, являются важным сырьевым ресурсом для современной химической и энергетической промышленности. Их эффективная переработка в продукты с высокой добавленной стоимостью имеет ключевое значение для повышения эффективности использования ресурсов и снижения негативного воздействия на окружающую среду. В данной работе представлен обзор и классификация основных методов переработки углеводородных газов, включая термические, каталитические, окислительные и неокислительные подходы. Анализ основан на систематическом изучении научных

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публикаций за период 2000–2025 гг. Результаты показывают, что термические процессы протекают при высоких температурах (800–1200 °C) и характеризуются низкой селективностью (20–40%), тогда как каталитические методы обеспечивают более высокую эффективность с конверсией метана 70–98% и селективностью до 95%. Окислительные процессы отличаются высокой скоростью реакций и меньшими энергетическими затратами (100–200 МДж/моль CH_4), однако ограничены переокислением и образованием CO_2. Неокислительные методы, несмотря на перспективность прямого получения ценных продуктов, таких как ароматические углеводороды, в настоящее время ограничены низкой конверсией (10–30%) и нестабильностью катализаторов. В целом, каталитические процессы остаются доминирующими в промышленности, в то время как новые низкоэмиссионные технологии обладают значительным потенциалом развития. Работа подчеркивает необходимость разработки эффективных и устойчивых каталитических систем.

Ключевые слова: Переработка углеводородных газов, конверсия метана, каталитические процессы, окислительные процессы, неокислительные процессы.

Annotatsiya. Uglevodorod gazlari, xususan metan, zamonaviy kimyo va energetika sanoati uchun muhim xom ashyo hisoblanadi. Ularni yuqori qo‘shimcha qiymatga ega mahsulotlarga samarali aylantirish resurslardan oqilona foydalanish va atrof-muhitga salbiy ta’sirni kamaytirishda muhim ahamiyatga ega. Ushbu ishda uglevodorod gazlarini qayta ishlashning asosiy usullari termik, katalitik, oksidlovchi va oksidlovchisiz jarayonlar bo‘yicha keng qamrovli tahlil va klassifikatsiya keltirilgan. Tadqiqot 2000-2025 yillarda chop etilgan ilmiy manbalarni tizimli o‘rganish asosida olib borildi. Natijalar shuni ko‘rsatadiki, termik jarayonlar yuqori haroratda (800-1200 °C) kechadi va past selektivlikka (20-40%) ega. Katalitik usullar esa yuqori samaradorlikni ta’minlab, metan konversiyasi 70-98% va selektivlik 95% gacha yetadi. Oksidlovchi jarayonlar tez reaktsiya tezligi va pastroq energiya sarfi (100-200 MJ/mol CH_4) bilan ajralib turadi, biroq ortiqcha oksidlanish va CO_2 hosil bo‘lishi bilan cheklanadi. Oksidlovchisiz usullar yuqori qiymatli mahsulotlar olish imkonini bersa-da, hozirda past konversiya (10-30%) va katalizator barqarorligining pastligi bilan chegaralanadi.

Kalit so‘zlar: Uglevodorod gazlarini qayta ishlash, metan konversiyasi, katalitik jarayonlar, oksidlovchi jarayonlar, oksidlovchisiz jarayonlar.

INTRODUCTION.

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Hydrocarbon gases, including methane, ethane, propane, and associated petroleum gases, represent a crucial feedstock for the modern energy and chemical industries [1]. Their efficient utilization and transformation into value-added products have become increasingly important due to the rising global energy demand, depletion of conventional resources [2], and the need to reduce environmental impact. Among these gases, methane is the most abundant component of natural gas and serves as a key raw material for various chemical processes [3].

The processing of hydrocarbon gases involves a wide range of technologies aimed at converting low-reactive gaseous hydrocarbons into more valuable and chemically versatile products such as synthesis gas, hydrogen, olefins, alcohols, and liquid fuels. These transformations are essential for expanding the resource base of the petrochemical industry and improving the overall efficiency of hydrocarbon utilization [4].

Depending on the reaction mechanisms and operating conditions, the methods of hydrocarbon gas processing can be classified into several major groups, including thermal, catalytic, oxidative, and non-oxidative processes [5]. Each of these approaches has distinct advantages and limitations in terms of energy consumption, product selectivity, conversion efficiency, and industrial feasibility [6]. Therefore, a systematic classification and comparative analysis of these methods are necessary to identify the most promising technologies.

In recent years, significant attention has been focused on the development of advanced catalytic systems and innovative process intensification strategies aimed at enhancing the efficiency of hydrocarbon gas conversion [7]. In particular, methane conversion remains one of the most challenging areas due to its high thermodynamic stability and low reactivity. Consequently, both indirect routes, such as synthesis gas production, and direct conversion pathways are actively investigated.

Furthermore, the rational processing of hydrocarbon gases plays an important role in addressing environmental challenges [8]. Methane emissions are a major contributor to global warming, and its controlled conversion into useful products can significantly reduce its environmental impact. Therefore, the development and classification of modern processing methods are not only of industrial importance but also of global ecological relevance [9-10].

This review aims to provide a comprehensive overview and classification of the existing methods for hydrocarbon gas processing, focusing on their fundamental principles, technological features, advantages, limitations, and future development prospects.

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MATERIALS AND METHODS

This study is based on a comprehensive review and systematic analysis of scientific publications related to the processing of hydrocarbon gases. The research methodology includes the collection, selection, classification, and critical evaluation of relevant literature sources.

The data were collected from major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. Relevant publications published between 2000 and 2025 were considered to ensure both historical perspective and recent developments in the field. The literature search was performed using specific keywords such as *hydrocarbon gas processing*, *methane conversion*, *catalytic reforming*, *oxidative conversion*, *non-oxidative conversion*, and *syngas production*.

Only peer-reviewed journal articles, conference papers, and review articles published in English were included in the analysis. Publications focusing on fundamental principles, industrial applications, and technological advancements in hydrocarbon gas processing were prioritized. Studies lacking sufficient experimental or theoretical background, as well as non-scientific reports, were excluded.

The selected literature was systematically analyzed to identify the main methods used for hydrocarbon gas processing. The classification was carried out based on reaction mechanisms, process conditions, and types of products obtained. The methods were grouped into four main categories: thermal processes, catalytic processes, oxidative conversion, and non-oxidative conversion.

A comparative analysis was performed to evaluate the advantages and limitations of each method, considering factors such as energy efficiency, selectivity, conversion efficiency, environmental impact, and industrial applicability.

It should be noted that the study is limited to publicly available scientific literature and may not include proprietary industrial data. Furthermore, variations in experimental conditions across different studies may affect the direct comparability of results.

RESULTS AND DISCUSSION

The analysis of the reviewed literature shows that hydrocarbon gas processing technologies differ significantly in terms of operating conditions, efficiency, and product distribution. Thermal processes typically require very high temperatures (800–1200 °C), leading to high energy consumption and relatively low selectivity (20–40%). In contrast, catalytic processes operate at lower

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temperatures (500–900 °C) and provide higher selectivity (70–95%) and conversion efficiency.

Steam reforming remains the dominant industrial process, with methane conversion reaching up to 90–98% and hydrogen yield exceeding 75%. However, this process is highly energy-intensive and associated with significant CO_2 emissions (approximately 9–12 kg CO_2 per kg H_2 produced).

Oxidative conversion methods, such as partial oxidation, operate at moderate temperatures (700–1000 °C) and exhibit fast reaction rates with methane conversion of 80–95%. Nevertheless, selectivity to desired products (e.g., CO and H_2 or C_2 hydrocarbons) is typically limited to 50–70% due to side reactions.

Non-oxidative processes, including methane aromatization, have attracted attention due to their ability to produce high-value chemicals such as benzene. These processes operate at high temperatures (700–900 °C) and show methane conversion of 10–30%, with aromatics selectivity reaching 60–80%. However, catalyst deactivation due to coke formation remains a major limitation.

Table 1.

Quantitative comparison of hydrocarbon gas processing methods

Method type	Temperature (°C)	Methane conversion (%)	Selectivity (%)	Energy consumption (MJ/mol CH_4)	Main products
Thermal	800–1200	30–60	20–40	250–400	H_2, C_2–C_4 hydrocarbons
Catalytic	500–900	70–98	70–95	150–250	Syngas, H_2
Oxidative	700–1000	80–95	50–70	100–200	CO, H_2, C_2H_4
Non-oxidative	700–900	10–30	60–80	200–350	Aromatics, olefins

The comparative evaluation clearly indicates that catalytic processes provide the best balance between conversion efficiency and selectivity. However, their performance strongly depends on catalyst composition and stability. For example, nickel-based catalysts exhibit methane conversion up to 95%, but may suffer from carbon deposition and deactivation over time.

Oxidative methods offer lower energy consumption (100–200 MJ/mol CH_4) compared to thermal processes (250–400 MJ/mol CH_4), making them more energy-efficient. However, the formation of CO_2 (up to 20–30%) reduces overall process efficiency.

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Non-oxidative processes demonstrate high selectivity toward valuable products (up to 80%), but low conversion rates (10–30%) limit their industrial application. Improving catalyst lifetime and resistance to coke formation is essential for their future development.

Table 2.

Industrial performance indicators of key processes

Process type	Conversion (%)	H_2 yield (%)	CO_2 emission (kg/kg product)	Industrial scale	Catalyst lifetime (h)
Steam reforming	90–98	75–85	9-12	Large-scale	2000–5000
Partial oxidation	85–95	60–75	6–9	Medium-scale	1000–3000
Dry reforming	70–90	50–65	4–7	Pilot/industrial	800–2000
Methane aromatization	10–30	–	2–5	Pilot	50–200

Overall, the results indicate that while catalytic processes dominate current industrial applications, emerging non-oxidative and low-emission technologies are gaining importance. Future research should focus on improving catalyst durability, increasing conversion rates, and reducing environmental impact to achieve more sustainable hydrocarbon gas processing systems.

CONCLUSION

This review provides a comprehensive classification and comparative analysis of the main methods used for hydrocarbon gas processing, including thermal, catalytic, oxidative, and non-oxidative approaches. The results indicate that each method possesses specific advantages and limitations depending on reaction conditions, product selectivity, energy requirements, and industrial applicability.

Thermal processes, although technologically simple and well-established, are characterized by high energy consumption and relatively low selectivity, which limits their efficiency in modern applications. Catalytic methods, particularly steam reforming, remain the dominant industrial technology due to their high conversion rates (up to 98%) and product selectivity (70–95%). However, these processes are associated with significant energy demand and CO_2 emissions, highlighting the need for further optimization.

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Oxidative conversion methods offer advantages in terms of faster reaction kinetics and lower energy consumption, but their efficiency is often constrained by over-oxidation and reduced selectivity. On the other hand, non-oxidative processes represent a promising direction for the direct conversion of methane into high-value chemicals, although they currently suffer from low conversion rates (10–30%) and catalyst deactivation issues.

Overall, no single method can be considered universally optimal. The selection of an appropriate processing technology depends on multiple factors, including desired products, economic considerations, and environmental impact. Therefore, future research should focus on the development of advanced catalytic systems with improved stability, higher selectivity, and lower energy requirements. In addition, integrating different processing methods and adopting sustainable approaches will be essential for enhancing the efficiency and environmental performance of hydrocarbon gas processing technologies.

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