**Stages of Development of Modern Methanol Production Technologies**

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**Abstract:** Methanol is a crucial product of the modern chemical industry, serving as the primary raw material for fuel, solvents, and organic synthesis products. This article analyzes the developmental stages of methanol production technologies, comparing traditional and modern approaches, with a focus on environmental sustainability. The research examines syngas synthesis using Cu/ZnO/Al2O3 catalysts, CO2-hybrid technologies, low-pressure processes, and the concept of green methanol. The work of Uzbek and global scientists is compared, presenting results on catalyst efficiency, process conditions, energy consumption, and carbon footprint reduction. Findings indicate that modern technologies are more efficient, environmentally sustainable, and energy-efficient compared to traditional methods. This article holds significant scientific and practical importance for the sustainable development of methanol production and in determining future research directions.

**Keywords:** Methanol synthesis, Cu/ZnO/Al2O3 catalysts, Syngas, CO2 utilization, Green methanol, Sustainable chemical technology, Low-pressure process

## ****INTRODUCTION****

Currently, methanol is one of the most important products in the modern chemical industry, serving as a crucial raw material for fuel, solvents, and numerous organic synthesis products. The increasing demand for methanol raises significant scientific and practical issues, such as improving production technologies, reducing energy consumption, and minimizing environmental impact. Traditional methanol synthesis is based on the catalytic process of obtaining methanol from a synthetic gas mixture, where catalysts like Cu/ZnO/Al2O3 play a leading role [1].

In recent years, considerable progress has been made in optimizing methanol production processes, implementing low-pressure synthesis conditions, and utilizing environmentally friendly raw materials such as CO2 and biomass sources. It is noted that the efficiency of methanol synthesis from synthetic gas depends on the catalyst structure and reactor configuration [1]. Furthermore, new research is being conducted on process kinetics and catalyst modification [2].

Additionally, the "Methanol Economy" concept promotes the possibility of obtaining methanol through CO2 processing, which serves as a foundation for creating sustainable and environmentally efficient systems in methanol production [3].

Scientific research on catalysts and synthesis processes is also being conducted in Uzbekistan. For instance, research centers focused on developing catalysts and synthesis technologies are being established in Central Asia, aiming to strengthen innovative developments related to improving synthesis gas and methanol production processes [4]. Furthermore, research on catalysts for synthetic gas in neighboring regions is directed towards increasing the energy efficiency of methanol synthesis processes [5].

## ****METHODS AND RESULTS****

Several approaches were applied. The main focus was on comparing **catalyst systems,** process conditions, and raw material sources. Studies have shown that **copper-based catalysts such as Cu/ZnO/Al2O3** play a leading role in the synthesis process [1]. The activity, selectivity, and thermal stability of the catalysts were studied in detail, confirming that surface copper centers and the auxiliary activity of ZnO play an important role in the mechanism of methanol formation. Concurrently, scientists in Uzbekistan conducted experiments to optimize the synthesis of catalysts based on regional raw materials, which allows for increasing the efficiency of the synthesis process [4].

In the analysis of process conditions, **syngas (CO + H2)** and CO2 hybrid technologies were compared. Traditional methanol synthesis occurs under high pressure and temperature conditions, while modern methods have shown that low-pressure processes and CO2 utilization are more environmentally and energy-efficient [2,3]. Studies have also shown that CO2 processing and obtaining methanol from biomass sources are important in creating carbon-neutral and sustainable systems based on the "green methanol" concept [5].

Through systematic analysis of literature and scientific sources, articles from the SCOPUS, Web of Science, and Google Scholar databases were studied. It was determined that the selected articles contain experiments on catalysts, reactors, process conditions, and energy efficiency, which were compared with regional studies in Uzbekistan. The influence of process conditions, particularly pressure, temperature, and reactor type (tubular reactors, film reactors) on the rate and selectivity of methanol formation was analyzed.

The results showed that traditional Cu/ZnO/Al2O3 catalysts work effectively at high pressures (50-100 bar) and temperatures of 200-300 °C. Modern low-pressure processes and CO2 hybrid technologies reduce energy consumption by 15-20% and increase the environmental efficiency of the process [2,3]. Experiments on obtaining methanol from biomass and industrial waste are also important in implementing the "green methanol" concept.

Research conducted by Uzbek scientists is aimed at developing catalysts and CO2 hybrid technologies in the Central Asian region, which will serve to increase the energy efficiency of the methanol production process and ensure environmental sustainability [4,5]. The results show that modern technologies have advantages over traditional methods in terms of efficiency, energy saving, and environmental protection.

**DISCUSSION**

Methanol production technologies have historically developed since the mid-20th century with the traditional synthesis of syngas based on Cu/ZnO/Al2O3 catalysts. Although this process is effective under conditions of high pressure (50-100 bar) and temperature (200-300 °C), it has weaknesses such as high energy consumption and a large carbon footprint. At the same time, modern technologies, in particular low-pressure synthesis processes, CO2-hybrid technologies, and the green methanol concept, increase environmental sustainability, reduce energy consumption, and significantly reduce the carbon footprint [2,3,5].

**TABLE 1.** New catalyst systems, reactor architectures, and process optimization

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Technology Type** | **Pressure and temperature** | **Catalyst** | **Energy efficiency** | **Ecological aspect** | **Advantage** | **Disadvantage** |
| Traditional syngas | 50-100 bar, 200-300 °C | Cu/ZnO/Al2O3 | Average | Low | Widely used, technologically reliable | High energy consumption, CO2 emissions |
| Low-pressure processes | 20-50 bar, 180-250 °C | Modified Cu/ZnO/Al2O3 | High | Medium | Energy saving, low operating costs | In some cases, selectivity may decrease |
| CO2-hybrid technologies | 20-60 bar, 200-250 °C | Cu/ZnO/Al2O3 + modifications | High | High | Carbon neutral, environmentally clean | Process complexity, new reactor design required |
| Green methanol (biomass) | 10-50 bar, 180-240 °C | Cu/ZnO/Al2O3 + additional catalysts | High | High | Sustainable raw materials, waste utilization | Raw material supply is complex, efficiency is variable |

As can be seen from Table 1, modern technologies have advantages over traditional approaches in increasing environmental sustainability and energy efficiency. At the same time, they require new catalyst systems, reactor architectures, and process optimization. Research conducted by scientists in Uzbekistan is aimed at developing innovative approaches to regional raw materials and catalyst modifications, which align with global trends [4,5].

From this perspective, the "Methanol Economy" concept promotes opportunities for CO2 processing and environmentally clean methanol production. This concept not only creates carbon-neutral systems but also paves the way for using methanol as a sustainable energy source and raw material for organic synthesis [3]. The scientific and practical significance of the research lies in the fact that modern technologies allow for increased energy efficiency, reduced carbon footprint, and optimized use of regional resources.

**CONCLUSION**

Methanol production technologies have evolved from traditional syngas synthesis to modern low-pressure processes, CO2-hybrid technologies, and green methanol concepts. The study showed that:

Although traditional technologies are reliable and widely used, they have high energy consumption and carbon emissions. Modern technologies excel in increasing energy efficiency, environmental sustainability, and carbon neutrality. The work of Uzbek scientists has presented important results on catalyst optimization and the use of regional raw materials. In the future, sustainable raw materials, environmentally friendly technologies, and low-pressure processes will play a key role in methanol production. It is also advisable to focus future scientific research in the following areas: Enrichment of catalyst systems with new materials and identification of mechanisms.

Expansion of CO2-hybrid technologies in industrial conditions. Development of technologies for the highly efficient conversion of biomass and waste into methanol. Study of low-pressure and stable production processes under Uzbekistan's conditions.

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