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PROPYLENE PRODUCTION TECHNOLOGY COMPARATIVE ANALYSIS: ECONOMIC AND ENVIRONMENTAL ASPECTS

With the growing global demand for polymers, especially polypropylene, propylene production technology is becoming of key importance for the petrochemical industry. Propylene is the second most important monomer after ethylene and is used in the production of a wide range of products, from packaging materials to automotive components and textile fibres. Given the trends of decarbonisation, circular economy development and tightening of environmental standards (in particular, within the framework of EU initiatives – CBAM, ESG, etc.), the choice of technology with an optimal combination of economic efficiency and environmental safety becomes critical.

In this paper, a comprehensive comparative analysis of four industrial processes for propylene production: steam cracking, catalytic cracking (FCC), propane dehydrogenation (PDH) and methanol-to-propylene (MTP) technology is carried out. Such parameters as feedstock type, product yield, capital and operating costs, carbon footprint, technological maturity and prospects for implementation in Kazakhstan are considered. Special attention is paid to resource availability (naphtha, propane, coal) and current industrial projects in the country. Based on the analysis, conclusions are drawn on the short-term and long-term feasibility of introducing certain technologies.

Keywords: Propylene, Polypropylene, Carbon footprint, Petrochemistry, Circular economy, Sustainable development, Process efficiency

Introduction

Propylene (C_3H_6) is central to the petrochemical synthesis chain as a key precursor for a wide range of products. Analyses show that more than 60 % of the world's propylene is consumed in the production of polypropylene, a thermoplastic polymer used in packaging (about 40 %), automotive (about 25 %) and textile (about 15 %) applications [1].

Economic analysis of the market shows a steady growth in production: according to IEA (2024), current global capacity exceeds 120 million tonnes/year with pronounced regional differentiation (China 35 %, North America 25 %, Europe 15 %) [2].

At the same time, conventional production methods (steam cracking of naphtha, FCC units) provide ~ 85 % of the volume, creating a dependence on refining [3].

The relevance of a comprehensive analysis of propylene production technologies is due to a number of key factors.

Sustained growth in global demand. Forecast estimates [2] indicate a steady CAGR of 4.5 % to 2030, driven by the increasing use of polypropylene in ESG packaging and composites [4].

According to KazStat data for 2023, propylene production in the country amounted to 420 thousand tonnes. The main producers are: PO Polymir (Atyrau) – 240 thousand tonnes/year; Kazakhstan Plastics Plant (Aktau) – 180 thousand tonnes/year. At the same time, the country is heavily dependent on imports - about 65 % of its needs (700 thousand tonnes annually) are covered by supplies from: Russia (40 % of imports); China (30 %); Middle East countries (30 %).

Stricter environmental requirements. The introduction of new environmental standards (in particular, EU Directive 2019/904) requires revision of traditional technological solutions. Energy-efficient and low-waste polymerisation methods that comply with the principles of the circular economy are becoming particularly important.

Reducing carbon footprint. The carbon footprint of conventional production reaches 2.5–3.0 tonnes CO_2/t propylene (including Scope 3).

Tightening EU ETS and CBAM regulations incentivise the search for low-carbon alternatives [5].

The study is of particular importance in the context of the implementation of large petrochemical projects in Kazakhstan, where the choice of optimal production technology will be a determining factor in their economic efficiency and competitiveness in regional markets.

Materials and Methods

Vapour-phase cracking (steam thermal cracking) is a process of thermal decomposition of hydrocarbons in the presence of water vapour at high temperature (750–900 °C) and short contact time. The main purpose of the process is to produce valuable low molecular weight olefins, primarily ethylene and propylene, which serve as key raw materials for the petrochemical and polymer industries.

Steam cracking remains the dominant method of propylene production, accounting for about 60 % of global propylene output [6].

Key features: propylene yield varies from 15 % (gas feedstock) to 20 % (liquid feedstock): energy intensity: 25–30 GJ/t propylene, which causes high CO_2 emissions (about 2.5 t/t product).

The mechanism of vapour-phase cracking is based on free-radical chain reaction. Under high temperature conditions, homolytic breaks of C-C and C-H bonds occur, leading to the formation of radicals. The process includes stages of initiation, chain growth and chain break [7]. The interaction of hydrocarbons with steam reduces coking and stabilises the reaction medium.

The key advantages of the process are high selectivity to light olefins and the ability to process a wide range of raw materials: from light paraffins to heavy oil fractions.

Influence of parameters on the process. The main characteristics influencing propylene yield and composition of reaction products are temperature, contact time and dilution with steam.

Temperature has a direct effect on the depth of conversion of the feedstock. With increasing temperature increases the degree of hydrocarbon cleavage and yield of low molecular weight products, but excessive heating leads to the growth of side reactions and coking of equipment [7].

The contact time determines the flow of both primary and secondary reactions. Too short a time leads to incomplete conversion and excessive time leads to degradation of valuable olefins [7].

Steam dilution reduces the partial pressure of hydrocarbons, inhibits coke formation and increases the yield of light olefins. However, excess steam causes an increase in heat losses and complicates the process scheme [8].

Catalytic cracking (CC) is a key process for secondary refining of petroleum fractions to produce petrol, propylene, butylene and other light products. The efficiency and selectivity of the process are determined by the type and properties of the catalyst

Catalytic cracking catalysts are subdivided into:

- zeolite (USY, ZSM-5);
- aluminosilicate (with amorphous matrix);

- heteropolyacid (at the research stage).

Zeolites Y and their modifications (ultra-stable Y - USY) are the basis of the majority of modern FCC-catalysts due to their high thermostability and pronounced acidity. Introduction of ZSM-5 zeolites allows to significantly increase propylene yield due to microporous structure and enhanced power dehydrogenation.

Catalytic activity is determined by pore structure, acidity (Bransted/Lewis), and distribution of active centres. The wide pores of Y zeolites allow access of macromolecules and formation of petrol. At the same time, the narrow pores of ZSM-5 (0.55 nm) restrict product growth, favouring the formation of small olefins, particularly propylene ACS Material.

An increase in catalyst acidity is accompanied by: an increase in the cracking reaction rate; an increase in the yield of C_3-C_4-olefins; and an increase in coke formation [9].

The introduction of modifiers (e.g. phosphates, rare earth elements) allows controlling the strength of acid centres and optimising selectivity.

To date, several industrial variants of FCC have been developed, differing in purpose and equipment configuration:

- FCC (Fluid Catalytic Cracking or «circulating bed catalyst cracking») is the most common industrial process for refining vacuum gas oil into gasoline and propylene. The unit includes a reactor, regenerator and separation equipment. FCC is mainly oriented to gasoline production, but with modification of catalysts and mode it is possible to produce propylene;
- DCC (Deep Catalytic Cracking) is a technology oriented to obtain the maximum amount of propylene and other light olefins. The main difference of DCC is the use of catalysts with high acidity and the addition of zeolites ZSM-5 [10];
- Petro-FCC is a combined technology providing flexible petrol/propylene ratio. It is used in petrochemical complexes oriented to raw materials for polymers.

To ensure stable operation of FCC sections it is important to control the content of metals, sulphur and aromatics index of feedstock.

Current approaches to process intensification are aimed at:

- adding ZSM-5 zeolites to FCC catalysts;
- reducing the contact time (less than 2 seconds) and increasing the reactor temperature (up to 550 °C);
- optimisation of catalyst regeneration rate (reduction of coke formation);
- introduction of hybrid FCC/DCC systems.

Key technologies:

- UOP (PetroFCC process with 18–22 % propylene fraction);
- Shell (modification of catalysts for heavy feedstocks).

Propane dehydrogenation (PDH - Propane Dehydrogenation). Propane dehydrogenation (PDH) is the direct conversion of propane (C_3H_8) to propylene (C_3H_6) with the release of hydrogen. This is an endothermic reaction requiring high temperature (550–700 °C):

$$C_3H_8 \rightarrow C_3H_6 + H_2;\ \Delta H = +124\ \text{кДж/моль}$$

Propane dehydrogenation (PDH) is the second largest producer of propylene after steam cracking, accounting for about 10 % of global output [1]. Two technologies dominate the industry: Oleflex™ (UOP) and Catofin® (Lummus Technology). Both technologies have become widespread due to the increasing demand for propylene and the surplus of cheap propane, especially in countries with developed liquefied natural gas (LNG) production.

Advantages of PDH technology:

- high propylene selectivity: up to 90–93 % depending on the technology and conditions;
- product purity: the propylene produced has a high degree of purity (more than 99 %), which reduces the need for additional purification;
- Independence from oil streams: PDH processes allow diversification of propylene production, reducing dependence on catalytic cracking and pyrolysis;
- modularity and scalability of plants, and the possibility of integration with LNG infrastructure.

Despite the advantages, PDH technologies have limitations:

- energy consumption of the process: the endothermic nature of the reaction requires significant energy input;
- coking of catalysts: formation of carbonaceous deposits reduces activity and requires regular regeneration;
- Dependence on propane prices: the profitability of PDH processes is sensitive to the propane/propylene price ratio. When propane prices are high and propylene prices decrease, the economic efficiency of the process drops dramatically;
- environmental challenges: especially when using chromium-containing catalysts (toxicity, waste disposal).

Methanol-to-Propylene (MTP – Methanol-to-Propylene). The Methanol-to-Propylene (MTP) process is the catalytic conversion of methanol to propylene using microporous zeolite catalysts (mainly SAPO-34 or ZSM-5) at high temperature (400–500 °C). It is one of the Methanol-to-Olefins (MTO) technology orientated predominantly towards propylene production, in contrast to the classical MTO giving a mixture of ethylene and propylene [11].

The main industrial solution, the Lurgi MTP technology developed by Air Liquide/Lurgi, is an integrated scheme for processing methanol into predominantly propylene, with high selectivity (up to 80 %).

The Lurgi MTP process involves three main steps:

- Dehydration of methanol to dimethyl ether (DME);
- acid-catalytic conversion of the methanol/DME mixture into light olefins (mainly propylene) using a zeolite catalyst;
- separation of products and extraction of high purity propylene.

The technology operates at 400–500 °C and 1–3 bar pressure using modified ZSM-5 zeolites, resulting in high propylene yields and minimal by-product yields [12].

Key features:

- Propylene yield: ~70 % of total olefins [1];
- by-products: petrol (15–20 %), light gases (C1–C2) [13].

Disadvantages of the technology:

- High capital costs;
- environmental risks: Carbon footprint of MTP on coal more than 4 t CO_2/t propylene [14].

Results and Discussion

To objectively assess the technologies, key parameters were identified: raw material base (oil/gas/coal); propylene yield (% of raw material); capital costs ($/t capacity); environmental friendliness (t CO_2/t product); production flexibility; technological maturity. The data are summarised in Table 1.

Table 1 – Summary table of the analysis

Criterion	Steam Cracking	Fluid Catalytic Cracking (FCC)	Propane Dehydrogenation (PDH)	Methanol-to-Propylene (MTP)
Feedstock	Naphtha, gas oil	Vacuum gas oil	Propane	Coal / natural gas
Propylene yield	15–20 %	18–25 %	85–90 %	65–70 %
Capital expenditures (CAPEX)	$1.8–2.2 billion / 1 Mt	$1.2–1.5 billion / 1 Mt	$1.5–1.8 billion / 1 Mt	$2.5–3.0 billion / 1 Mt
Operating expenses (OPEX)	$350–400 / t	$300–350 / t	$400–450 / t	$450–550 / t
Carbon footprint	2.5–3.0 t CO_2 / t	1.8–2.2 t CO_2 / t	1.2–1.5 t CO_2 / t	4.0+ t CO_2 / t (coal-based)
Feedstock in Kazakhstan	70 % imported naphtha	Domestic gas oil	Propane deficit (60% imported)	Coal surplus
Payback period	7–9 years	5–7 years	6–8 years	10+ years
Technological maturity	High	High	Medium	Low

Prospects in Kazakhstan	Atyrau Refinery modernization	Development at Pavlodar Refinery	«KazPropylene» project (Aktau)	–

At present, for the short-term perspective the most economically feasible development of catalytic cracking (FCC) with modernisation of existing refining capacities, in particular at Pavlodar refinery.

Also, propane dehydrogenation (PDH), despite the current shortage of feedstock, is of interest due to plans to increase propane production at the Kashagan and Tengiz fields.

MTP technology, despite its high capital costs ($2.5–3.0 bn/1Mt) and long payback period (10 years), should be considered as a strategic option for monetising Ekibastuz Basin coal reserves, especially if carbon capture technologies (CCS) are introduced.

PDH and FCC have a significant carbon footprint advantage (1.2-2.2 t CO_2/t propylene) over MTP (>4 t CO_2/t), which is in line with global decarbonisation trends. However, MTP can become competitive if green methanol and CCS technologies are utilised.

Conclusions

The comparative analysis of propylene production technologies shows that each of them has its own economic and environmental advantages and limitations, which depend significantly on the raw material base, level of technological maturity and regional conditions. In the short term, the development of catalytic cracking technology (FCC) is of the greatest practical value for Kazakhstan, especially given the possibility of modernising existing facilities (e.g. at the Pavlodar refinery), as well as the prospective expansion of propane dehydrogenation technology (PDH) based on the expected growth in propane production at the Kashagan and Tengiz fields.

At the same time, methanol-to-propylene (MTP) technology, despite its high capital costs and long payback period, can be considered as a strategic option for deep coal processing in the Ekibastuz basin, provided that CO_2 capture and utilisation (CCS) technologies and the use of ‘green’ methanol are implemented. Given the global trends towards carbon footprint reduction, FCC and PDH technologies have the greatest potential for sustainable development in the petrochemical sector of Kazakhstan, provided that energy efficiency and environmental safety are improved.

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ПРОПИЛЕН ӨНДІРУ ТЕХНОЛОГИЯЛАРЫНЫҢ САЛЫСТЫРМАЛЫ ТАЛДАУЫ: ЭКОНОМИКАЛЫҚ ЖӘНЕ ЭКОЛОГИЯЛЫҚ АСПЕКТІЛЕРІ

Полимерлерге, әсіресе полипропиленге деген жаһандық сұраныстың өсуі жағдайында пропилен өндіру технологиясы мұнай-химия өнеркәсібі үшін стратегиялық маңызға ие болуда. Пропилен — этиленнен кейінгі екінші маңызды мономер, ол қаптамалық материалдардан бастап автокомпоненттер мен тоқыма талшықтарына дейінгі кең ауқымды өнімдерді өндіруде қолданылады. Декарбонизация, айналмалы экономиканы дамыту және экологиялық стандарттардың (әсіресе ЕО-ның CBAM, ESG және басқа бастамалары аясында) қатаңдану үрдістерін ескере отырып, экономикалық тиімділігі мен экологиялық қауіпсіздігі оңтайлы технологияны таңдау аса өзекті болып отыр.

Бұл мақалада пропилен өндірудің төрт негізгі өнеркәсіптік процесіне кешенді салыстырмалы талдау жүргізілген: бу крекингі, каталитикалық крекинг (FCC), пропанды дегидрлеу (PDH) және метанолдан пропилен алу (MTP) технологиясы. Әр технология бойынша шикізат түрі, өнім шығымы, күрделі және ағымдағы шығындар, көміртек ізі, технологиялық жетілгендік және Қазақстан жағдайында енгізу мүмкіндіктері қарастырылған. Сондай-ақ отандық ресурс базасына (нафта, пропан, көмір) және іске асырылып жатқан жобаларға назар аударылған. Жүргізілген талдау негізінде жекелеген технологияларды қысқа және ұзақ мерзімді перспективада қолданудың орындылығы бағаланады.

Кілтті сөздер: пропилен, полипропилен, көміртек ізі, мұнай-химия өнеркәсібі, циркулярлы экономика, тұрақты даму, үдерістің энергия тиімділігі

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ ТЕХНОЛОГИЙ ПРОИЗВОДСТВА ПРОПИЛЕНА: ЭКОНОМИЧЕСКИЕ И ЭКОЛОГИЧЕСКИЕ АСПЕКТЫ

В условиях растущего глобального спроса на полимеры, особенно полипропилен, технология получения пропилена приобретает ключевое значение для нефтехимической промышленности. Пропилен является вторым по значимости мономером после этилена и используется в производстве широкого спектра продукции: от упаковочных материалов до автокомпонентов и текстильного волокна. С учётом тенденций декарбонизации, развития циркулярной экономики и ужесточения экологических стандартов (в частности, в рамках инициатив ЕС – CBAM, ESG и др.), выбор технологии с оптимальным сочетанием экономической эффективности и экологической безопасности становится критически важным.

В данной статье проведён всесторонний сравнительный анализ четырёх промышленных процессов получения пропилена: парового крекинга, каталитического крекинга (FCC), дегидрирования пропана (PDH) и технологии метанол-в-пропилен (MTP). Рассмотрены такие параметры, как тип сырья, выход продукта, капитальные и операционные затраты, углеродный след, технологическая зрелость и перспективы внедрения в условиях Казахстана. Особое внимание уделено ресурсной доступности (нафта, пропан, уголь) и текущим промышленным проектам страны. На основании анализа сделаны выводы о краткосрочной и долгосрочной целесообразности внедрения отдельных технологий.

Ключевые слова: пропилен, полипропилен, углеродный след, нефтехимия, циркулярная экономика, устойчивое развитие, энергоэффективность процесса

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