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Journal of Chemical Engineering Research Progress, 2 (2) 2025, 277-283

Research Article

Enhancing Energy Efficiency in Methanol-Based Formaldehyde Production through Heat Recovery Integration

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Received: 10th December 2025; Revised: 16th December 2025; Accepted: 17th December 2025
Available online: 28th December 2025; Published regularly: December 2025

Abstract

Formaldehyde is a key industrial chemical known for its high reactivity and broad applicability across sectors such as plastics, resins, textiles, and agrochemicals. Its production has evolved from early silver-catalyzed oxidation of methanol to the more efficient Formox process using iron molybdate catalysts. Despite these advancements, conventional production methods remain energy-intensive, prompting the need for sustainable alternatives. This study investigates the impact of process modification through internal heat recovery on the energy efficiency of methanol-based formaldehyde synthesis. By comparing conventional and modified process configurations, the results demonstrate that reusing reactor-generated heat to power auxiliary units significantly reduces external energy demand. The modified system achieved a 30.64% improvement in energy efficiency, underscoring the potential of heat integration strategies to enhance sustainability and reduce operational costs in formaldehyde manufacturing.

Keywords: formaldehyde; Methanol partial oxidation; Formox process; Energy efficiency; Heat recovery; Sustainable production

How to Cite: Malau, J. S., Hasby, A. M., Adelia, A. N., Khairunnisa, A., Novya, A. I., Amaanullah, D. (2025). Enhancing Energy Efficiency in Methanol-Based Formaldehyde Production through Heat Recovery Integration. *Journal of Chemical Engineering Research Progress*, 2 (2), 277-283 (doi: 10.9767/jcerp.20564)

Permalink/DOI: https://doi.org/10.9767/jcerp.20564

1. Introduction

Formaldehyde is one of the fundamental chemicals in the global industry, valued for its high reactivity and versatile properties. It serves not only as a primary feedstock in the production of plastics, polymers, resins, textiles, and pesticides, but also as a crucial component in a wide range of other value-added chemical products [1]. Its advantages lie in exceptional thermal stability, high purity, and the ability to interact with diverse organic substrates, making it indispensable within the modern chemical supply chain [2]. With these characteristics, formaldehyde supports the manufacture of functional materials ranging from wood adhesives and weather-resistant coatings to specialty chemicals for medical and cosmetic applications, thereby reinforcing its position as one of the most strategic chemical commodities in the global economy [3].

The history of formaldehyde dates to the mid-19th century, when Butlerov first reported its synthesis in 1859, followed by Hofmann in 1867, who successfully identified formaldehyde through the oxidation of methanol using a heated silver catalyst. Other early attempts in the 1870s included chemical, photochemical, and electrochemical experiments aimed at reducing carbon monoxide (CO) and carbon dioxide (CO_2) to formaldehyde, though the outcomes were highly limited due to thermodynamic constraints. Industrial-scale production of formaldehyde subsequently began in Europe in 1910 via the

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silver-catalyzed process, operating at high temperatures of around 600 °C [4]. This method became the industrial standard for several decades, but it was hindered by high energy demand and relatively low selectivity. In the 1930s, metal oxide catalysts particularly iron molybdate (Fe-Mo-O) were introduced, giving rise to the Formox process [5]. This technology proved safer by employing low methanol concentrations, operating at lower temperatures (300-400 °C), and achieving high selectivity toward formaldehyde (92–95%). Building on these technological advances, recent studies have emphasized the importance of integrating energy efficient reactor designs and renewable energy inputs into formaldehyde production, highlighting how process optimization and heat integration strategies can significantly reduce external energy demand and improve sustainability in large-scale operations [6,7]. To this day, formaldehyde production remains reliant on energy-intensive partial oxidation of methanol; however, modern research is increasingly directed toward sustainable approaches, including direct synthesis from CO_2, the utilization of biomass as feedstock, and the application of formaldehyde as a liquid organic hydrogen carrier (LOHC) for hydrogen energy storage [8].

Formaldehyde can be produced through several methods, including the oxidation of light hydrocarbons, partial oxidation of alcohols, or dehydrogenation of specific organic compounds. The most widely applied industrial route is methanol oxidation. In this process, methanol is converted into formaldehyde via two primary mechanisms direct dehydrogenation and partial oxidation both of which are strongly influenced by catalyst properties and reaction conditions [9]. In this process, methanol is converted into formaldehyde via silvercatalysed partial oxidation, which is typically operated adiabatically at nearatmospheric pressure and high temperatures in the range of 600–700 °C. A methanolrich mixture containing methanol, steam, and air is passed over a shallow bed of metallic silver particles, yielding formaldehyde with high selectivity, while a minor fraction of methanol undergoes nonselective oxidation to carbon monoxide and carbon dioxide [10]. The partial oxidation of methanol to produce formaldehyde is an exothermic reaction as shown in Equation (1). Because the reaction is exothermic, this reaction requires catalysts with high activity, excellent thermal stability, and strong selectivity toward formaldehyde to withstand the substantial heat release and suppress nonselective oxidation pathways leading to carbon monoxide and carbon dioxide [11,12].

$$CH_3OH + \tfrac{1}{2}\,O_2 \rightarrow CH_2O\ (g) + H_2O\ (g) \quad \Delta H^{o}_{298} = -159\ \text{kJ/mol} \tag{1}$$

Formaldehyde production has advanced through the development of improved catalysts and reactor designs. However, conventional processes remain highly energy intensive. Most previous studies have concentrated on catalyst selectivity or the use of renewable feedstocks, while relatively little attention has been directed toward internal heat recovery strategies. Therefore, this research aimed to enhance the energy efficiency of methanol-based formaldehyde production through heat recovery by reusing the reactor energy stream (Q-103) from the PFR-100 to drive the methanol circulation pump. The objective of this study was to evaluate how this integration of heat recovery could reduce external energy demand and improve the sustainability and overall performance of formaldehyde manufacturing, with particular focus on quantifying the efficiency improvement achieved.

2. Method

To enhance energy efficiency in the methanol partial oxidation process, system modifications were simulated using Aspen HYSYS V11. The process utilizes a plug flow reactor operating under non-isothermal conditions, where the highly exothermic reactions release substantial amounts of energy. Such non-isothermal behavior strongly influences reactor design and energy management, requiring precise control of temperature profiles to achieve optimal conversion and process stability [13]. The energy released during the reaction is subsequently recovered through a heat exchanger system which facilitates internal heat recycling and thereby reduces external energy demand [9]. In the modified configuration, methanol is gradually preheated before entering the reactor to ensure favorable reaction conditions [14,15].

The output from the plug flow reactor (Q-103) is directed to the pump (P-100) and subsequently reused through an internal energy loop system. Utilizing the reactor output (Q-103) enables more efficient energy recovery, reduces external energy requirements, and enhances the overall thermal efficiency of the process. The effectiveness of this modification can be evaluated through net energy calculations, which compare the energy generated and consumed within the system. With this new configuration, the process not only supports improved energy efficiency but also contributes to the sustainability of formaldehyde production.

$$NE = Ep - Ec \tag{2}$$

As shown in Equation (2) the calculation of net energy within a process or system. In this formulation, *NE* (Net Energy) denotes the amount of energy available after accounting for the energy consumed. The first component, *Ep* (Energy Produced), refers to the total energy generated by the process, such as energy derived from fuel combustion, chemical reactions, or biomass conversion. The second component, *Ec* (Energy Consumed), indicates the total energy required to sustain the process, including inputs for heating, pumping, separation, or material transportation.

Equation (3) expresses the aggregate of all heat flows in the conventional system, establishing a baseline for subsequent comparison. In this formulation, $EP_{\text{Unmodified}}$ (Energy Produced in the unmodified system) represents the total energy output generated by the process prior to heat recovery integration. The individual terms Q-100, Q-101, Q-102, Q-103, and Q-104 correspond to distinct energy streams released at various stages of the methanol oxidation system, including reactor heat, exchanger duties, and auxiliary thermal outputs. By summing these contributions, Equation (3) provides a comprehensive measure of the overall energy produced in the conventional configuration, serving as the reference point against which the modified process is evaluated.

$$EP_{\text{Unmodified}} = \text{Q-100} + \text{Q-101} + \text{Q-102} + \text{Q-103} + \text{Q-104} \tag{3}$$

Within the framework, Equation (4) defines $EC_{\text{Unmodified}}$ as the total energy demand required to operate the system in the absence of heat recovery. Within this formulation, *U1* represents the energy consumption of auxiliary equipment such as pumps and compressors that ensure fluid circulation and maintain system pressure. In parallel, *H11* denotes the heating duty essential for sustaining thermal operations, including feed preheating and the maintenance of reaction conditions. Collectively, these two components capture the external energy requirements of the conventional process, establishing a baseline against which efficiency gains from heat recovery can be assessed.

$$EC_{\text{Unmodified}} = U1 + H11 \tag{4}$$

Equation (5) defines the net energy of the unmodified process using the same principle as Equation (2), where net energy (*NE*) is expressed as the difference between energy produced (*EP*) and energy consumed (*EC*), while Equation (2) presents the general formulation applicable to any system, Equation (5) applies this definition specifically to the conventional configuration without heat recovery. In this context, *EP* denotes the cumulative energy output of the process, encompassing reactor heat and auxiliary thermal streams, whereas *EC* represents the total energy demand required to sustain operations such as pumping, heating, and circulation. Accordingly, Equation (5) quantifies the effective energy balance of the unmodified system, establishing a benchmark for assessing efficiency gains in the modified configuration.

$$NE_{\text{Unmodified}} = EP - EC \tag{5}$$

In contrast to Equation (3), the modified process omits Q-100 since a portion of the reactor heat stream (Q-103) is repurposed to power the circulation pump. This integration reduces reliance on external energy inputs, thereby lowering the overall energy demand of the system.

$$\text{EP}_{\text{Modified}} = \text{Q-101} + \text{Q-102} + \text{Q-103} + \text{Q-104} \tag{6}$$

Equation (7) defines EC_{Modified} as the total energy demand of the system following heat recovery integration. The first term, *U1*, represents the energy consumption of auxiliary equipment such as pumps and compressors required to maintain circulation and system pressure. The second term, *H11*, denotes the heating duty essential for sustaining thermal operations, including feed preheating and the maintenance of reaction conditions. Although the structure of Equation (7) mirrors that of Equation (4) for the unmodified process, its values are reduced because a portion of the reactor heat stream is internally recycled. Consequently, Equation (7) demonstrates the lowered external energy requirement achieved through the modified configuration.

$$EC_{\text{Modified}} = U1 + H11 \tag{7}$$

Equation (8) defines the net energy of the modified process using the same principle as Equation (2), where net energy (*NE*) is expressed as the difference between energy produced (*EP*) and energy consumed (*EC*). Similar to Equation (5), it represents the system's energy balance; however, in this case it applies to the configuration with heat recovery. Here, *EP* corresponds to the total energy output excluding Q-100, since a portion of the reactor heat stream (Q-103) is repurposed to drive the circulation pump, thereby reducing external demand. Meanwhile, *EC* denotes the energy required for operations such as heating and auxiliary units, with lower values achieved through internal recycling. Accordingly, Equation (8) quantifies the usable energy in the modified system and underscores the efficiency improvements relative to the unmodified baseline.

$$NE_{\text{Modified}} = EP - EC \tag{8}$$

Equation (9) illustrates the *Energy Efficiency* (%) gain achieved through heat recovery. In this formulation, the numerator captures the difference between the net energy of the conventional system and that of the modified system, while the denominator normalizes this difference against the unmodified baseline. The resulting ratio provides a clear measure of the reduction in external energy demand compared to the original configuration. This metric is particularly valuable for assessing energy feasibility, process efficiency, and the sustainability of technological applications, with strong relevance to chemical engineering and renewable energy systems [16].

$$\%Energy\ Efficiency\ = \frac{NE_{\text{Unmodified}} - NE_{Modified}}{NE_{\text{Unmodified}}} \times 100\% \tag{9}$$

3. Results and Discussion

3.1. Performance Comparison Between Basic and Modified Process

The production of formaldehyde from methanol was simulated using both the unmodified and modified processes. The Aspen HYSYS V11 simulation with Non-Random Two-Liquid (NRTL) and process flow diagrams of the modified process are presented in Figures 1 and 2, respectively, while those of the unmodified processes are shown in Figures 3 and 4. The main difference between the modified and unmodified processes lies in the utilization of heat recovery in the system. The P-100 pressure converter is used to flow methanol to the heat exchanger. The pump requires a significant amount of energy to increase the pressure. Considering that the mass flow of fluid that must be pumped is quite large, namely 2884 kg/h. In the unmodified configuration, the heat flow (Q-103) from the PFR-100 is simply allowed to exit the reactor and is not effectively reused. According to Maulana [12], reusing the heat generated by the reactor will increase energy efficiency and even operational

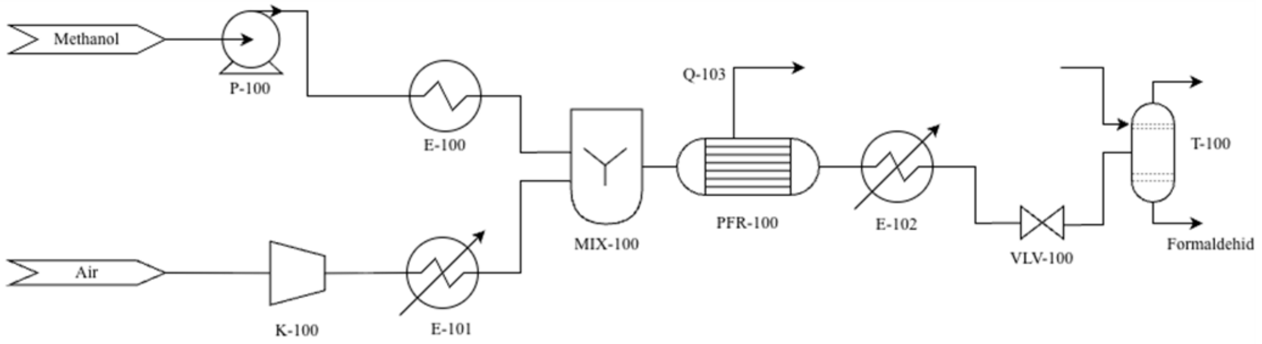

Figure 1. Process Flow Diagram (PFD) of unmodified process.

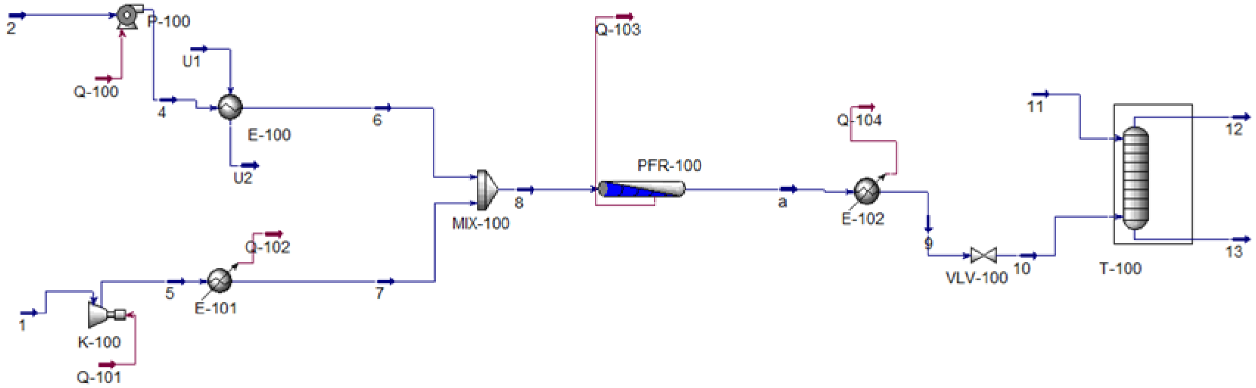

Figure 2. Process simulation of unmodified process.

cost efficiency. Therefore, in the modified process system, the energy in the form of Q-103 generated by the PFR-100 reactor is reused to operate the P-100 pump. The simulation results show that the pump can work to flow methanol and achieve the desired pressure. The reuse of this energy provides a significant increase in energy efficiency in the overall process [10].

3.2. Improving Energy Efficiency by Heat Recovery

The simulation provides data on the total energy required by the system, expressed through the heat flows within the process. This representation serves as a model for quantifying the potential energy savings relative to the unmodified configuration. Based on this framework, the energy conserved in the modified process can then be calculated mathematically, offering a clear measure of efficiency improvement. The results, derived from the formulations in Equations (3) through (9), are summarized as follows:

$EP_{\text{Unmodified}} = 1.4887\times10^{7}$ kJ/h
$EC_{\text{Unmodified}} = -1{,}520{,}623{,}057$ kJ/h
$NE_{\text{Unmodified}} = 1{,}535{,}510{,}840$ kJ/h
$EP_{\text{Modified}} = 1.3105\times10^{7}$ kJ/h
$EC_{\text{Modified}} = -1{,}051{,}791{,}326$ kJ/h
$NE_{\text{Modified}} = 1{,}064{,}896{,}345$ kJ/h
%Energy Efficiency = 30.64%.

Energy efficiency is improved by reusing energy (Q-103) from the PFR-100 reactor to drive the pump that increases pressure and circulates methanol. This reuse of energy has been proven to reduce the energy required by the pump to increase pressure and circulate methanol to E-100. Before reusing energy Q-103 from the PFR-100 reactor, the energy requirement in the P-100 pump was 3,000.5387 kJ/h and the total net energy of the process was 1,535,510,840 kJ/h. while after reusing the Q-103 energy from the PFR-100 reactor, the total net energy of the process became 1,064,896,345 kJ/h. This wise step has resulted in an increase in energy efficiency of 30.64%.

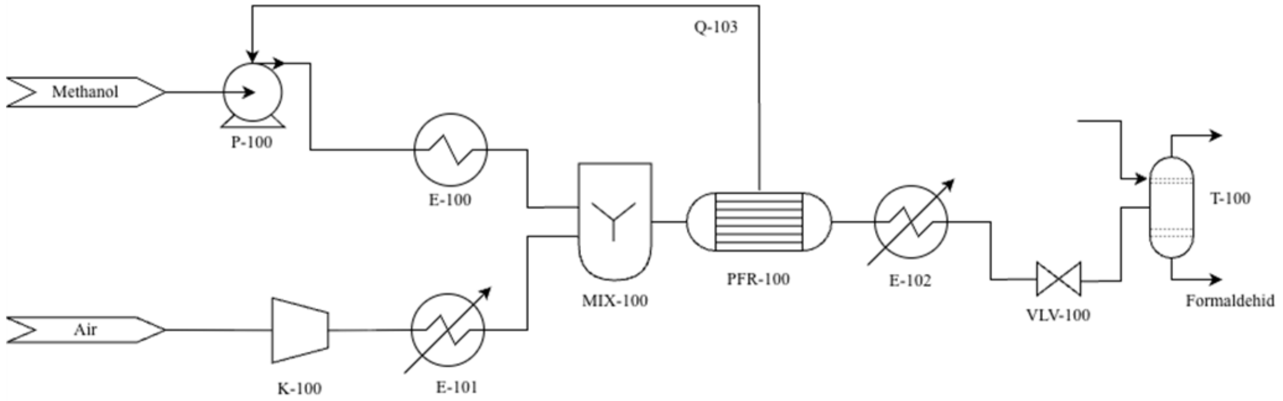

Figure 3. Process Flow Diagram (PFD) of modified process.

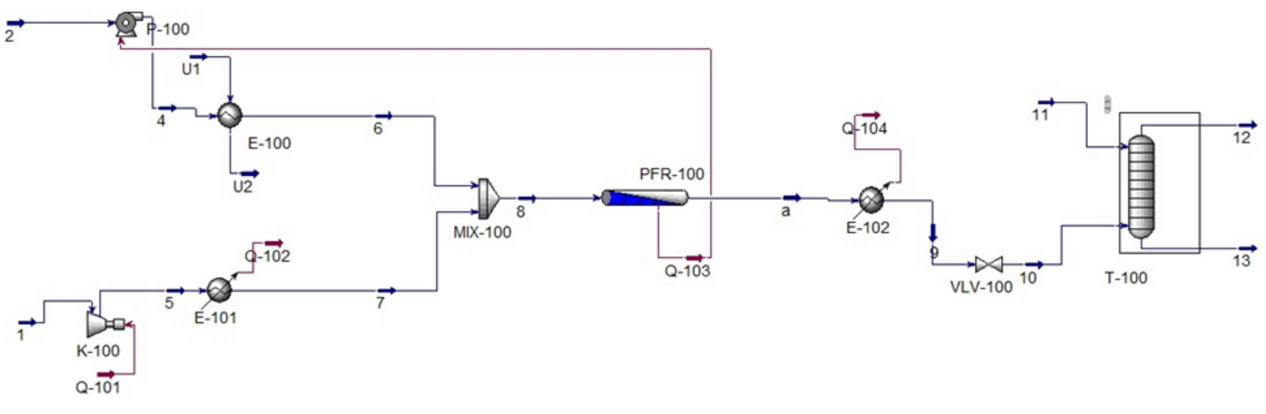

Figure 4. Process simulation of modified process.

4. Conclusions

This study highlights the effectiveness of heat recovery integration in improving the energy efficiency of formaldehyde production from methanol. By redirecting the reactor's thermal output to support auxiliary operations, particularly the methanol circulation pump, the modified process configuration substantially reduces net energy consumption. The comparative analysis revealed a 30.64% increase in energy efficiency relative to the conventional setup. These findings emphasize the importance of process optimization and energy reuse in advancing sustainable chemical manufacturing. Future work may explore further integration with renewable energy sources and alternative feedstocks to enhance the environmental performance of formaldehyde production systems.

CRedit Author Statement

Author Contributions: J. S. Malau: Conceptualization, Methodology, Investigation, Resources, Data Curation, Writing, Review, Software and Editing, Supervision; A. M. Hasby: Conceptualization, Methodology, Formal Analysis, Data Curation, Writing Draft Preparation, Visualization, Software, Project Administration; A. N. Adelia: Validation, Writing Draft, Review and Editing, Data Curation; A. Khairunnisa: Validation, Investigation, Resources, Writing Draft, Review and Editing, Validation; A .I. Novya: Validation, Investigation, Resources, Data Curation, Writing Draft, Review and Editing. D. Amaanullah: Investigation, Resources, Data Curation, Review and Editing. All authors have read and agreed to the published version of the manuscript.

References

[1] Shakeel, K., Javaid, M., Muazzam, Y., Naqvi, S.R., Taqvi, S.A.A., Uddin, F., Niazi, M.B.K. (2020). Performance comparison of industrially produced formaldehyde using two different catalysts. *Processes*, 8(5), 571. DOI: 2227-9717/8/5/571.

[2] Deng, X., Liu, Z., Wang, Z., Wu, Z., Li, D., Yang, S., Ji, N. (2025). Mechanical Properties, Thermal Stability, and Formaldehyde Emission Analysis of Nanocellulose-Reinforced Urea–Formaldehyde Resin and Its Mechanism. *Polymers*, 17(10), 1402. DOI: 10.3390/polym17101402.

[3] Malik, M.I., Abatzoglou, N., Achouri, I.E. (2021). Methanol to formaldehyde: an overview of surface studies and performance of an iron molybdate catalyst. *Catalysts*, 11(8), 893. DOI: 10.3390/catal11080893.

[4] Van Leeuwen, J.A., Hartog, N., Gercite, J., Gallacher, C., Helmus, R., Brock, O., Parsons, J.R., Uassaricadeh, S.M. (2020). The dissolution and microbial degradation of mobile| aromatic hydrocarbons from a Pintsch gas tar DNAPL source zone. *Science of the Total Environment*. 722,137797. DOI: 10.1016/j.scitotenv.2020.137797.

[5] Thrane, J., Mentzel, U.V., Thorhauge, M., Høj, M., Jensen, A.D. (2021). A review and experimental revisit of alternative catalysts for selective oxidation of methanol to formaldehyde. *Catalysts*, 11(11), 1329. DOI: 10.3390/catal11111329.

[6] Van Valen, Y., Bergh, T., Skrzydło, T., Emanuelli, M., Gramazio, P., Bjørkedal, O.H., Venvik, H.J. (2025). Sub-reactions of the Silver Catalysed Conversion of Methanol to Formaldehyde. *Topics in Catalysis*, 1-16. DOI: 10.1007/s11244-025-02158-0.

[7] Chen, L., Long, Y., Huang, B., Sun, C., Kang, S., Wang, Y. (2025). Technological innovations review in reducing formaldehyde emissions through adhesives and formaldehyde scavengers for building materials. *Environmental Research*, 273, 121242. DOI: 10.1016/j.envres.2025.121242.

[8] Heim, L.E., Konnerth, H., Prechtl, M.H. (2017). Future perspectives for formaldehyde: pathways for reductive synthesis and energy storage. *Green Chemistry*, 19(10), 2347-2355. DOI: 10.1039/C6GC03093A.

[9] Jouhara, H. (2023). Advanced Heat Exchangers for Waste Heat Recovery Applications. *ChemEngineering*, 7(1), 3. DOI: 10.3390/chemengineering7010003.

[10] Klemeš, J. J., Varbanov, P.V., Ocłoń, P., Chin, H.H. (2019) Towards efficient and clean process integration: utilisation of renewable resources and energy-saving technologies. *Energies,* 12 (21) 4092. DOI: 10.3390/en12214092.

[11] Lervold, S., Lødeng, R., Yang, J., Skjelstad, J., Bingen, K., Venvik, H.J. (2021). Partial oxidation of methanol to formaldehyde in an annular reactor. *Chemical Engineering Journal*, 423, 130141. DOI: 10.1016/j.cej.2021.130141.

[12] Maulana, E.I., Tarikh, A., Widaranti, R.D. (2024). Minimizing Energy Usage in the Production of Benzene through Hydrodealkylation Toluene Process by Optimizing Heat Transfer Unit in Reactor System. *Journal of Chemical Engineering Research Progress*, 1(2), 97-107. DOI: 10.9767/jcerp.20167.

[13] Nestler, F., Müller, V.P., Ouda, M., Hadrich, M.J., Schaadt, A., Bajohr, S., Kolb, T. (2021). A novel approach for kinetic measurements in exothermic fixed bed reactors: advancements in non-isothermal bed conditions demonstrated for methanol synthesis. *Reaction Chemistry & Engineering*, 6(6), 1092-1107. DOI: 10.1039/d1re00071c.

[14] Alarifi, A. (2016). Modeling, Analysis and Optimization of the Gas-Phase Methanol Synthesis Process. *Ph.D. Dissertation*, Department of Chemical Engineering, University of Waterloo, Waterloo, Ontario, Canada.

[15] Tavalatifi, F., Sami, S., Bashipour, F. (2025). Integrated Simulation and Improvement of the Multi-bed Methanol Synthesis Process with Syngas Recycling and Energy Recovery in Aspen HYSYS. *Iranian Journal of Chemical Engineering (IJChE)*, 22(3), 18-33. DOI: 10.22034/ijche.2025.535892.1566.

[16] Wang, Y., Liu, Y., Xu, Z., Yin, K., Zhou, Y., Zhang, J., Zhu, Z. (2024). A review on renewable energy-based chemical engineering design and optimization. *Renewable and Sustainable Energy Reviews*, 189, 114015. DOI: 10.1016/j.rser.2023.114015.