Journal of Renewable Energy, Electrical, and Computer Engineering
Volume 5, Number 2, September 2025. 150-155
eISSN 2776-0049
DOI: https://doi.org/10.29103/jreece.v5i2.19605
Research Original Article

Optimization of Cumene Production Through Reactive Distillation with Heat Integration

Galang Adi Saputra✉1, Amadeus Vincent Widjaja2, Kudrat Sunandar3
1Master of Chemical Engineering, Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung, 40132, Indonesia, galangadii@gmail.com
2 Master of Chemical Engineering, Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung, 40132, Indonesia, a.vincent.widjaja@gmail.com
3 Chemical Engineering, Institut Teknologi Indonesia, Jl. Raya Puspiptek, Tangerang Selatan, 15314, Indonesia, sundandar@gmail.com
✉Corresponding Author: **galangadii@gmail.com | Phone: +6285779791500**

Received: 17 April 2025 Revision: 11 July 2025 Accepted: 23 August 2025

Abstract

This study aims to optimize the cumene production process through reactive distillation by implementing heat integration to enhance energy efficiency and reduce operational costs. Cumene is produced via the alkylation reaction between benzene and propylene in a reactive distillation column, where reaction and product separation occur simultaneously. The research method involves process simulation using Aspen HYSYS software, comparing processes without and with heat integration. Simulation results indicate that heat integration reduces total energy requirements from 48,023 kW to 37,956 kW, achieving an energy saving of 10,067 kW. Additionally, this energy saving translates into an annual operational cost reduction of $377,309. While the amount of cumene produced remains constant at 7,055 kg/hour, heat integration proves effective in reducing costs and improving overall process efficiency. This study concludes that heat integration in reactive distillation is an economical and efficient solution for cumene production, with broad adoption potential in the chemical industry.

Keywords: Cumene, Reactive Distillation, Heat Integration, Energy Efficiency, Chemical Industry

Introduction

Cumene, also known as isopropyl benzene, is a highly significant chemical in the industry as it serves as the primary raw material to produce phenol and acetone—two products widely utilized in the manufacturing of resins, plastics, and various other industrial applications. The production of cumene generally involves the alkylation reaction of benzene and propylene with the aid of acid catalysts, such as zeolites (Hazmi, 2022). The primary challenge in this process lies in improving product separation efficiency and minimizing the formation of by-products like diisopropylbenzene (DIPB), which can complicate the separation process and increase energy requirements (Bouderbala et al., 2025). Therefore, optimizing the cumene production process is essential to address challenges in energy management and overall process efficiency (Shen et al., 2023).

The conventional cumene production process is typically carried out in a tubular reactor, followed by a series of separation processes using distillation columns (Jamshidi et al., 2025). However, this method is considered inefficient due to high energy consumption and the need for additional operational units for cumene purification and by-product separation (Kondamudi, 2015). To address these challenges, reactive distillation has emerged as an attractive alternative (Yadav et al., 2022). This approach combines chemical reaction processes with simultaneous product separation within a distillation column, thereby enhancing the efficiency of reactant conversion into the desired product and reducing the formation of by-products (Qiu, 2020).

In the context of energy optimization, heat integration emerges as a promising solution (Saxena et al., 2024). Heat integration utilizes the thermal energy generated during the process to be reused, such as in the preheating of reactants (Chen et al., 2022). This approach enables significant reductions in energy consumption while simultaneously lowering overall plant operational costs (Tayefeh et al., 2024). Several studies have shown that heat integration in reactive distillation processes can reduce energy requirements by up to 30% compared to processes without heat integration (Dimian, 2008). Therefore, simulating the cumene production process by combining reactive distillation with heat integration is a critical step toward achieving higher energy efficiency (Samad et al., 2023).

This study aims to optimize the cumene production process using a reactive distillation approach integrated with heat integration technology. Aspen HYSYS software-based simulation was utilized to model the alkylation reaction and simultaneous product separation, as well as to evaluate the energy-saving potential through heat integration. This research is expected to contribute significantly to reducing energy consumption, improving separation efficiency, and minimizing by-product formation. Furthermore, the study is anticipated to provide recommendations for the implementation of this technology on an industrial scale, supporting the development of more environmentally friendly and economical production processes (Kurniawan et al., 2023).

The benefits of this study encompass several key aspects, such as enhancing operational efficiency through energy savings, reducing production costs, and minimizing the environmental impact of the cumene production process. Additionally, the findings can offer valuable insights for the chemical industry to adopt reactive distillation and heat integration technologies to improve performance and competitiveness. As such, this study contributes to efforts toward more sustainable and efficient production processes.

Literature Review

Cumene, or isopropylbenzene, is an indispensable intermediate in the chemical industry, particularly as a precursor to phenol and acetone production. These downstream chemicals find extensive applications in the manufacture of resins, polycarbonates, and synthetic fibers, underpinning a significant share of industrial and consumer products. The production of cumene conventionally employs the alkylation of benzene with propylene, catalyzed by solid acid catalysts such as zeolites, under controlled thermodynamic and kinetic conditions as shown by figure 1. Despite its industrial maturity, the conventional cumene production process faces inherent inefficiencies, particularly in energy consumption, by-product management, and downstream purification.

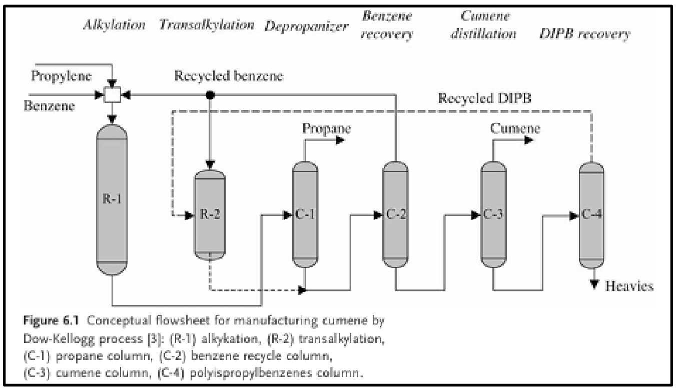

Figure 1. Block Flow Diagram of Cumene Process

The alkylation process can be summarized by the following primary reaction:

$$C_6H_6\ (\text{gas}) + C_3H_6\ (\text{gas}) \rightarrow C_9H_{12}\ (\text{gas}) \quad (1)$$

However, secondary alkylation reactions often lead to the formation of diisopropylbenzene (DIPB), a less desirable by-product:

$$C_9H_{12}\ (\text{gas}) + C_3H_6\ (\text{gas}) \rightarrow C_{12}H_{18}\ (\text{gas}) \quad (2)$$

DIPB not only reduces the yield of the desired product but also introduces significant complexities in separation and recycling, requiring additional operational units and elevating energy demands.

The traditional tubular reactor setup followed by distillation columns, though established, has several drawbacks. The separation stages are energy-intensive, as they rely on high-temperature operations to achieve the requisite product purity. Moreover, the design of sequential unit operations introduces inefficiencies in heat recovery, exacerbating operational costs. The need to recycle unreacted benzene and DIPB adds to the complexity of the process. Consequently, innovations in process intensification, particularly reactive distillation and heat integration, have emerged as viable strategies to address these challenges.

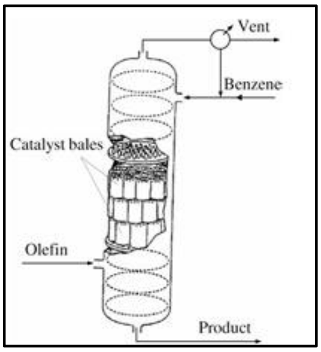

Figure 2. Reactive Distillation

Reactive distillation integrates chemical reaction and product separation into a single unit operation, leveraging the thermodynamic and kinetic interplay of reaction and distillation. This approach optimizes the contact time of reactants with the catalyst while simultaneously removing the cumene product from the reaction zone to drive the equilibrium forward. Additionally, the differential boiling points of benzene, cumene, and DIPB facilitate the efficient separation of these compounds within the same column. Reactive distillation minimizes the formation of by-products, such as DIPB, and eliminates the need for downstream separation units, significantly reducing the energy footprint of the process. Furthermore, the continuous removal of cumene prevents catalyst deactivation caused by high concentrations of alkylated products, extending catalyst life and maintaining process efficiency.

The incorporation of heat integration into reactive distillation further enhances the energy efficiency of the process. Heat integration utilizes surplus thermal energy generated in high-temperature regions of the system, such as the condenser and bottom streams, to preheat incoming reactants or maintain optimal operating temperatures. Advanced configurations, such as heat exchangers strategically positioned within the reactive distillation column, recycle thermal energy, reducing external heat input requirements. This synergistic integration of reaction, separation, and heat recovery can lower energy consumption by up to 30%, as reported by Dimian (2008). Moreover, it stabilizes the thermal profile within the column, mitigating the risks of thermal degradation of reactants and catalysts, and improving reaction selectivity.

Simulations and modeling tools like Aspen HYSYS and Aspen Energy Analyzer have proven instrumental in optimizing these advanced processes. Detailed thermodynamic modeling allows for precise quantification of heat and mass transfer dynamics within the column, enabling fine-tuning of operational parameters such as reflux ratio, feed stage location, and reboiler duty. For instance, studies have demonstrated that incorporating heat integration into the reactive distillation process can reduce the total energy requirement for producing cumene from 48,023 kW to 37,956 kW. This reduction translates to an operational cost saving of approximately $377,309 annually, without compromising product purity or production capacity, which remains consistent at 7,055 kg/h. Such simulations underscore the feasibility and economic viability of integrating heat recovery systems into reactive distillation setups.

At a mechanistic level, the interplay of chemical kinetics and thermodynamics within reactive distillation and heat-integrated systems enables superior process performance. The reaction zone is maintained under optimal conditions for alkylation, while the distillation stages prevent the back-mixing of products, thereby enhancing conversion and selectivity. The introduction of heat exchangers not only improves the thermal efficiency of the column but also ensures the recycling of latent heat, transforming potential energy losses into operational savings. This integrated approach aligns with principles of sustainable process engineering, addressing both economic and environmental objectives.

In conclusion, the combination of reactive distillation and heat integration represents a paradigm shift in cumene production, offering a high degree of process intensification. By consolidating reaction and separation into a single unit and integrating thermal energy recovery, this approach achieves substantial reductions in energy consumption, by-product formation, and operational costs. As global industries shift towards sustainable manufacturing practices, these advancements provide a scalable and environmentally responsible framework for chemical process design, with the potential for broader application beyond cumene production.

Materials & Methods

This study employs an experimental design based on simulations to optimize cumene production through reactive distillation integrated with heat recovery. The simulations were conducted using Aspen HYSYS software, accessed in the computer laboratory of the Master's Program in Chemical Engineering at Institut Teknologi Bandung. The study encompasses the modeling of the alkylation reaction between benzene and propylene, along with an energy consumption analysis. Heat integration simulations were performed using Aspen Energy Analyzer to evaluate energy savings. Quantitative analysis was carried out by comparing the simulation results of processes with and without heat integration. The data analyzed included reactant conversion rates, separation efficiency, and energy consumption. The results were presented in graphical and tabular formats to illustrate the potential for energy savings and improvements in process efficiency.

Results and Discussion

The formation of cumene in this simulation was conducted using reactive distillation without heat integration. Initially, benzene and propylene were supplied as the primary reactants. The alkylation reaction occurred within the reactive distillation column (T-100), where a catalyst facilitated the formation of cumene. During the process, cumene was separated from the reaction mixture based on boiling point differences, with the heavier cumene accumulating at the bottom of the column. By-products such as diisopropylbenzene (DIPB) were separated and recycled through a loop system to be converted back into cumene via transalkylation reactions, as depicted in Figure 3.

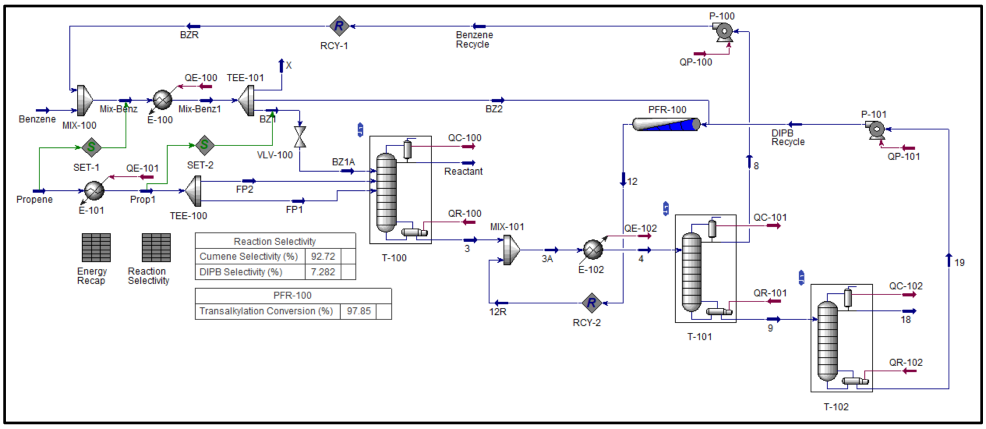

Figure 3. Cumene HYSYS Process Without Heat Integration

The energy requirements for this process vary significantly depending on operational conditions. In the simulated report, the energy demand for the condensers and reboilers in the main distillation columns (T-100, T-101, and T-102) without heat integration totaled 48,023 kW. This energy is essential for maintaining optimal temperatures and pressures for the separation of cumene, benzene, and DIPB, as well as supporting the alkylation reaction within the distillation system.

The reactive distillation process produces high-purity cumene after three stages of distillation across columns T-100, T-101, and T-102. At the end of the process, the simulation indicated that the amount of cumene produced reached 7,055 kg/hour. This output is a result of an efficient alkylation reaction and optimal product separation achieved using reactive distillation technology. With the integration of heat recovery, not only is energy consumption significantly reduced, but the overall process efficiency is also improved, making this technology more advantageous in terms of economic and operational viability for cumene production.

Heat integration in the cumene production process using reactive distillation aims to reutilize the energy generated during reaction and distillation stages, thereby reducing the dependency on external energy sources. In the updated simulation diagram, several heat exchangers (such as E-100, E-101, E-102, E-103, and E-104) are strategically incorporated at various stages of the process to enhance energy efficiency. These heat exchangers capture heat from product or gas streams, which would otherwise be wasted, and repurpose it to preheat incoming reactants. As a result, the energy requirements for heating are significantly reduced, as illustrated in the simulation presented in Figure 4.

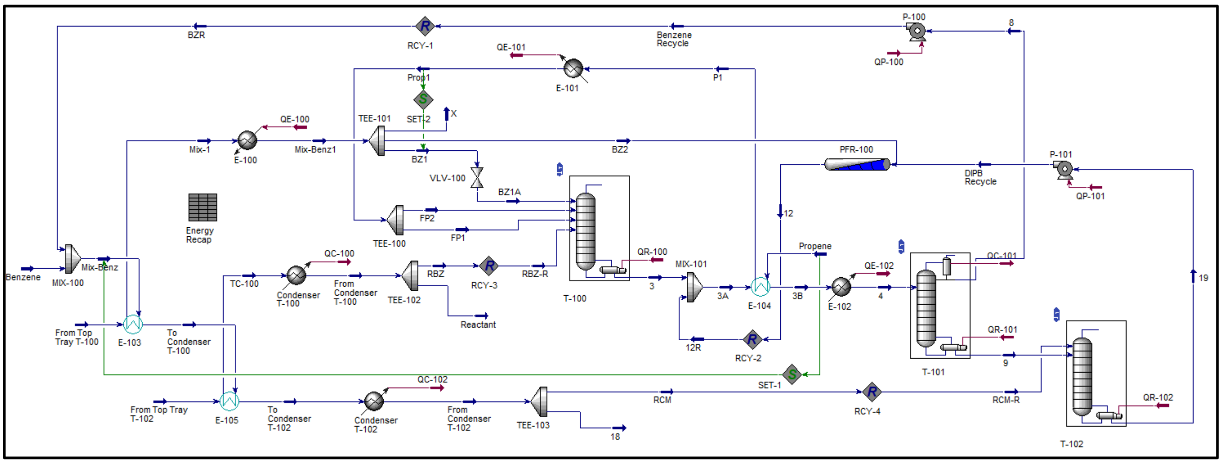

Figure 4. Cumene HYSYS Process With Heat Integration

A significant enhancement in heat integration is the incorporation of E-100 and E-101, which utilize heat from the product stream exiting the T-100 distillation column to preheat the incoming propylene and benzene streams before they enter the reactor. This approach improves energy efficiency by reducing the amount of external energy required to heat the reactants. Additionally, E-102 captures heat from the cumene stream exiting the T-101 distillation column, repurposing it to preheat the reactants entering the T-100 column, thereby further lowering energy consumption.

The T-100 distillation column remains the core component of the process, where the alkylation reaction occurs simultaneously with product separation. With the addition of the E-103 heat exchanger, heat generated at the top of the T-100 column is utilized to preheat the feed entering the bottom of the column. This practice stabilizes temperature conditions and significantly reduces the energy demand for the reboiler, as much of the required heat is already provided by the existing process. Consequently, the heat integration process substantially decreases the reboiler energy requirements for the T-100 column, leading to improved overall energy efficiency.

Heat integration is also implemented in other distillation columns, such as T-101 and T-102, where the addition of heat exchangers E-104 and E-105 captures heat from the top streams of these columns to preheat the incoming feed for the subsequent columns. This ensures that the entire distillation system operates efficiently by minimizing heat losses and reducing total energy consumption. Overall, the application of heat integration in this reactive distillation process enables an energy reduction of up to 11 MW compared to the process without heat integration.

When compared to a system without heat integration, the energy efficiency improvements are significant. In the non-integrated process, the total energy demand for the reboilers and condensers across the main distillation columns (T-100, T-101, and T-102) reaches 48,023 kW, as shown in Table 1. Conversely, with heat integration, the total energy requirement is reduced to 37,956 kW, achieving an energy saving of 11 MW, as presented in Table 2. The integration of heat exchangers at various stages of the process effectively reclaims heat that would otherwise be lost, thereby minimizing the reliance on external energy sources. This results in a more sustainable and cost-efficient cumene production process.

Table 1. Energy Process Consumption

Parameter	Withour Heat Integration	With Heat Integration
Energy Consumption	48,023	37,956
Energy of Reboiler T-100 (kW)	1,793	1,794
Energy of Reboiler T-101 (kW)	14,577	14,579
Energy of Reboiler T-102 (kW)	3,902	3,901
Cumene Production (kg/h)	7,055	7,055

In addition to reducing energy consumption, heat integration also helps improve process stability and product separation efficiency. With better temperature stability and lower energy requirements, the quality of the produced cumene remains high, with a production rate of 7,055 kg/h, similar to the process without heat integration. The improved temperature control ensures that the reaction conditions are optimal, leading to consistent product quality and yield. This stability is crucial for maintaining the reliability and predictability of the production process, which is essential for large-scale industrial operations.

Moreover, the significant energy savings achieved through heat integration translate directly into reduced operational costs. The annual cost savings are estimated to be $377,309, which is a substantial reduction in the overall production expenses. These savings can be reinvested into further process improvements, research and development, or other strategic initiatives, thereby enhancing the competitiveness and profitability of the production facility. The economic benefits, combined with the environmental advantages of reduced energy consumption, make heat integration an attractive option for the long-term sustainability of the cumene production process.

In conclusion, the implementation of heat integration in the cumene production process offers multiple benefits, including enhanced energy efficiency, improved process stability, and significant cost savings. By reclaiming and reusing heat within the system, the process becomes more sustainable and economical. This approach not only reduces the reliance on external energy sources but also minimizes the environmental impact of the production process. As a result, reactive distillation with heat integration emerges as a viable and advantageous solution for the chemical industry, particularly in the production of cumene.

Table 2. Comparison of Total Energy Consumption

Parameter	Without Heat Integration (kW)	With Heat Integration (kW)	Energy Savings (kW)	Cost Savings ($/year)
Total Energy	48,023	37,956	10,067	377,309

Based on Table 2, the comparison between cumene production processes without and with heat integration is based on the total energy required. Without heat integration, total energy consumption reaches 48,023 kW. This high energy demand reflects the inefficiencies inherent in the traditional production process, where significant amounts of energy are lost due to the lack of integrated heat recovery systems. The absence of heat integration not only leads to higher energy consumption but also contributes to increased operational costs and a larger environmental footprint.

After the implementation of heat integration, energy consumption drops significantly to 37,956 kW. This reduction of 10,067 kW in energy usage highlights the effectiveness of heat integration in optimizing the production process. By recovering and reusing heat within the system, the process becomes more energy-efficient, reducing the need for external energy inputs. This improvement in energy efficiency not only lowers the operational costs but also enhances the sustainability of the production process by minimizing energy waste and reducing greenhouse gas emissions.

The energy savings achieved through heat integration have a substantial impact on reducing annual operational costs. With estimated savings of $377,309 per year, the implementation of heat integration proves to be a financially beneficial strategy. These cost savings can be reinvested into further process improvements or other areas of the business, enhancing overall profitability. In conclusion, the adoption of heat integration in the cumene production process is a more economical and sustainable choice, offering significant benefits in terms of energy efficiency, cost reduction, and environmental impact.

Conclusions

This study successfully optimized the cumene production process through the application of reactive distillation with heat integration. Simulations showed that the implementation of heat integration could reduce the total energy requirement from 48,023 kW to 37,956 kW, providing an energy saving of 10,067 kW. Additionally, this energy saving also resulted in annual operational cost savings of $377,309. Although the amount of cumene produced remains the same at 7,055 kg/h, heat integration has proven effective in enhancing energy efficiency and reducing operational costs. With these results, reactive distillation with heat integration can be adopted as a more economical and sustainable solution for the chemical industry, particularly in cumene production.

Acknowledgments

We would like to express our sincere gratitude to the LPDP (Indonesia Endowment Fund for Education) for sponsoring us throughout our studies. This research would not have been possible without the financial assistance provided by LPDP.

References

Dimian, A. C., & Bildea, C. S. (2008). *Chemical Process Design: Computer-Aided Case Studies*. Wiley-VCH Verlag Gmbh & Co.

Furman, K. J., & Simmons, M. J. (2015). *Energy Integration In Reactive Distillation*. Journal Of Chemical Engineering, 102(4), 341-355.

Gmehling, J., & Kolbe, B. (2001). *Distillation: Fundamentals And Principles*. Elsevier.

Bouderbala, I. Y., Rebhi, S., & Bouras, I.-E. (2025). Green Catalysts: Driving Sustainable Reactions For A Cleaner Future. In *Breaking Boundaries: Pioneering Sustainable Solutions Through Materials And Technology* (Pp. 163–190). Springer.

Chen, W., Huang, Z., & Chua, K. J. (2022). Sustainable Energy Recovery From Thermal Processes: A Review. *Energy, Sustainability And Society*, *12*(1), 46.

Hazmi, H. A. (2022). Process Simulation & Sensitvity Analysis Of Cumene Production From An Integrated Alkylation And Transalkylation Reaction. *Journal Of Chemical Process Engineering*, *7*(2), 64–78.

Jamshidi, M., Mallahzadeh, A., Khalili-Garakani, A., & Kasiri, N. (2025). Reaction/Distillation Matrix Algorithm Development To Cover Sequences Containing Reactive Dividing Wall Column: Validation In Process Of Cumene Production. *Chemical Engineering And Processing-Process Intensification*, 110289.

Kurniawan, R., Daud, M., & Hasibuan, A. (2023). Study Of Power Flow And Harmonics When Integrating Photovoltaic Into Microgrid. *MOTIVECTION: Journal Of Mechanical, Electrical And Industrial Engineering*, *5*(1), 33–46.

Samad, A., Saghir, H., Ahmad, I., Ahmad, F., & Caliskan, H. (2023). Thermodynamic Analysis Of Cumene Production Plant For Identification Of Energy Recovery Potentials. *Energy*, *270*, 126840.

Saxena, V., Manna, S., Rajput, S. K., Diwania, S., & Gupta, V. (2024). Sustainable Energy Solutions: Integrating Hybrid CCHP Systems With Renewable Technologies For Efficient Urban Development. *Journal Of The Brazilian Society Of Mechanical Sciences And Engineering*, *46*(11), 668.

Shen, S.-J., Tseng, A.-H., Shi, C.-C., & Yu, B.-Y. (2023). Development Of The Cumene Oxidation Process: Rigorous Design, Optimization, And Control. *Chemical Engineering Research And Design*, *200*, 602–614.

Tayefeh, A., Aslani, A., Zahedi, R., & Yousefi, H. (2024). Reducing Energy Consumption In A Factory And Providing An Upgraded Energy System To Improve Energy Performance. *Cleaner Energy Systems*, *8*, 100124.

Yadav, A., Labhasetwar, P. K., & Shahi, V. K. (2022). Membrane Distillation Crystallization Technology For Zero Liquid Discharge And Resource Recovery: Opportunities, Challenges And Futuristic Perspectives. *Science Of The Total Environment*, *806*, 150692.

Helfferich, F. G. (2004). *Kinetics And Catalysis In Chemical Processes*. Springer.

Jiménez, A., & Costa-López, N. (2017). *Energy Efficiency In Chemical Process Design Using Heat Exchangers*. Chemical Engineering Transactions, 61, 535-540.

Kondamudi, K., & Upadhyayula, S. (2015). *Transalkylation Of Diisopropylbenzene With Benzene Over SAPO-5 Catalyst: A Kinetic Study*. Journal Of Chemical Technology & Biotechnology, 83(5), 699-706.

Liu, Y., & Grossmann, I. E. (2007). *Optimization Models For Heat Exchanger Networks*. Computers & Chemical Engineering, 31(1), 630-646.

Qiu, L., Murashov, V., & White, M. A. (2020). *Zeolite 4A: Heat Capacity And Thermodynamic Properties*. Solid State Sciences, 2(8), 841-846.

Seider, W. D., Seader, J. D., & Lewin, D. R. (2009). *Product And Process Design Principles: Synthesis, Analysis, And Evaluation.* John Wiley & Sons.

Smith, R. (2016). *Chemical Process Design And Integration*. John Wiley & Sons.

Vassiliadis, C. G., & Pantelides, C. C. (2002). *Computational Approaches For Heat Integration In Process Design*. Aiche Journal, 48(10), 2435-2450.