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Journal of Chemical Engineering Research Progress, 3 (1) 2026, 107-111

Research Article

Improving Energy Efficiency with Reusage Outlet Stream of Heat Exchanger for Acrylic Acid Production from Propylene Oxidation

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Received: 12th December 2025; Revised: 19th December 2025; Accepted: 22th December 2025
Available online: 6th January 2026; Published regularly: June 2026

Abstract

Acrylic acid is a pivotal chemical intermediate extensively utilized in the manufacture of superabsorbent polymers, coatings, adhesives, and acrylate esters. Conventional production via propylene oxidation is markedly energy intensive and generates substantial by products, highlighting the imperative for process enhancement. The objective of this study is to advance energy efficiency in acrylic acid synthesis by reusing outlet stream heat from the heat exchanger during propylene oxidation. Aspen Plus simulations were employed to model propylene oxidation in a plug flow reactor under isothermal conditions with external cooling. The revised design incorporated heat integration strategies, most notably redirecting surplus heat from heater H-302 to fulfill the reboiler duty of distillation column T-304. Comparative evaluation demonstrated that this modification reduces external energy demand, augments conversion efficiency, and stabilizes thermal performance. In addition, the implementation of a heat transfer fluid recycle loop curtailed energy losses and enhanced operational consistency across both reactor and separation units. Mass and energy balance analyses confirmed that the modified configuration delivers superior efficiency while diminishing reliance on external utilities. Collectively, the findings underscore that process intensification coupled with heat integration provides a more sustainable and economically advantageous pathway for acrylic acid production.

Keywords: Acrylic acid; Propylene oxidation; Aspen Plus; Plug flow reactor; Heat integration; Energy efficiency

How to Cite: Deanti, N. A., Owen, A. N., Simarmata, C. E., Sidabukke, J. K., Almasyah, M. A. M., Silaen, S. A. (2026). Improving Energy Efficiency with Reusage Outlet Stream of Heat Exchanger for Acrylic Acid Production from Propylene Oxidation. *Journal of Chemical Engineering Research Progress*, 3 (1), 107-111 (doi: 10.9767/jcerp.20596)

Permalink/DOI: https://doi.org/10.9767/jcerp.20596

1. Introduction

Acrylic acid is an unsaturated carboxylic acid that has become indispensable in the chemical industry. It serves as a precursor for superabsorbent polymers, coatings, adhesives, and acrylate esters, with global consumption surpassing six million tons annually [1]. The conventional production route involves the oxidation of propylene to acrolein, followed by further oxidation to acrylic acid using Mo-V-based catalysts. Despite its industrial relevance, this process is energy-intensive and prone to by-product formation, while storage of acrylic acid carries risks of uncontrolled polymerization [6].

Efforts to improve process efficiency have increasingly relied on advanced simulation tools. Studies using Aspen Plus and Aspen HYSYS have shown that modifications in reactor configuration, particularly the elimination of recycle streams, can enhance propylene conversion beyond 96% while improving selectivity and thermal stability [4]. Reactor intensification approaches, such as glycerol conversion, further demonstrate the potential of process modeling to achieve safer and more energy-efficient operations [8].

Parallel to these developments, bio-based pathways for acrylic acid production are gaining attention as part of the global push toward sustainable chemical manufacturing. Lactic acid and 3-hydroxypropionate derived from lignocellulosic biomass can be dehydrated into acrylic acid using solid catalysts, offering a

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renewable alternative to fossil-based feedstocks [7]. Techno-economic studies indicate that integrating bio-acrylic acid production into biorefineries could reduce reliance on petrochemicals and align with sustainability targets [2].

Despite these advances, most studies have primarily focused on improving catalytic performance, reactor selectivity, or exploring bio-based alternatives. However, limited attention has been given to energy integration strategies within the conventional propylene oxidation route, particularly the reuse of thermal energy streams. Previous works treated heat management only as a utility aspect, without integrating it into the core process optimization framework. Therefore, this research introduces a novel approach by reusing the outlet stream heat from the heat exchanger to improve energy efficiency in acrylic acid production. This strategy not only reduces external energy demand but also enhances process sustainability and economic viability. By integrating energy recovery into the conventional process flowsheet, this study aims to bridge the gap between conversion efficiency, safety, and energy optimization an aspect not yet addressed in earlier works.

2. Method

To improve the energy efficiency of the propylene oxidation process to acrylic acid, simulations were conducted using Aspen Plus. The process employs a plug flow reactor (PFR) operated under isothermal conditions, supported by an external cooling system to maintain a uniform temperature profile along the reactor [5]. Propylene is first compressed in C-301 to reach the operating pressure, then mixed with air in M-301 to provide the oxidant. The mixture is preheated in H-301 to the required reaction temperature before entering R-301. The oxidation reaction occurs in the reactor over a heterogeneous catalyst, producing acrylic acid along with by-products. Since the reaction is highly exothermic, heat removal is controlled to avoid hot spots and to preserve selectivity toward acrylic acid. The reactor effluent is cooled in H-302 before entering the separation system. Separation is carried out through a series of distillation columns (T-301, T-302, T-303, and T-304), assisted by mixers M-302 and M-303 for feed composition adjustment. This distillation train separates water, unreacted propylene, oxygen, and by-products such as acrolein and acetic acid, yielding an acrylic acid fraction of high purity. The energy efficiency of the base and modified processes can be compared using the net energy balance [8]:

$$NE = EP - EC \tag{1}$$

where *NE* is the net energy (kJ/h), *EP* is the energy produced from the exothermic reaction in R-301), and *EC* is the energy consumed heating in H-301 and distillation duties in T-301–T-304. This analysis demonstrates that the exothermic heat released in the reactor can be utilized to support downstream separation, thereby enhancing the overall energy efficiency of the process [9].

3. Results and Discussion

3.1 Comparison Between Basic and Modified Process

The process of acrylic acid production through oxidation of propylene are simulated in unmodified and modified process. The basic block diagram of unmodified process is shown on Figure 1, while process flow diagram (PFD) and Aspen Plus process simulation of unmodified process are

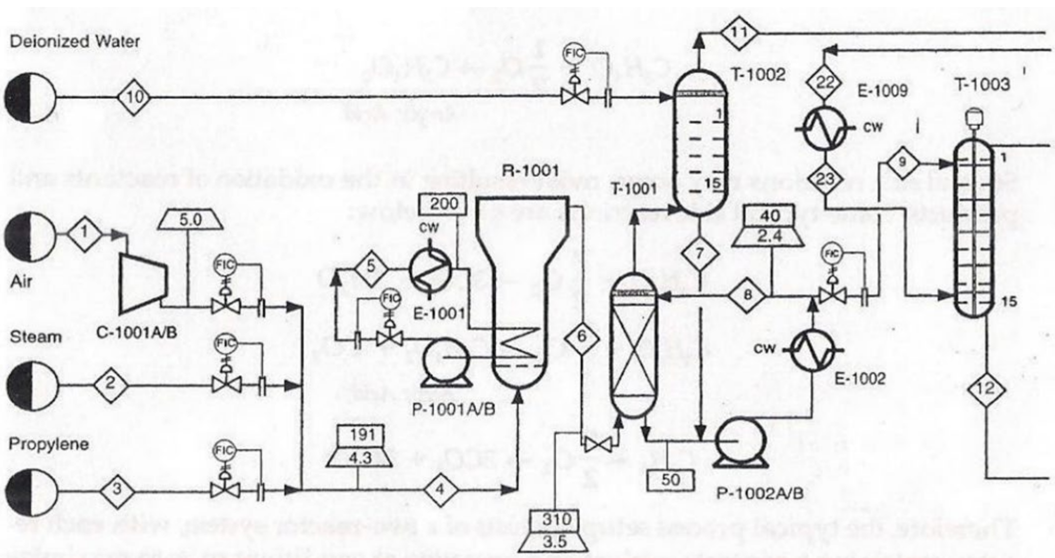

Figure 1. Process Flow Diagram (PFD) to produce acrylic acid from propylene [11].

shown in Figures 2 and 3. The difference of both process are on the energy who were used on the process which can be seen on the modified process that reused the energy that generated by heater B8, namely S11 to the distillation column T-304. The purpose of reusing the generated heat was to improve the energy efficiency of the overall process and conversion rate of the process. The improvement was based on the low conversion while the energy demand of the process was high. Strategic energy integration in similar petrochemical processes has also been reported in acrylic acid production, demonstrating the potential for energy savings through the utilization of waste heat [13].

3.2 Energy Balance and Mass Balance Results

The modified process as shown in Figures 4 and 5 in which in heater H-302 had a line that connected to distillation tower T-304. The S11 was representing the energy produced by heater H-302 and. Energy from S11 reused in T-304 with energy input 4456469 cal/s with temperature cooling from 310 ^{o}C to 40 ^{o}C.

3.3 Heat Transfer Fluid Recycle

The methanol-to-formaldehyde process operates at 590–720 °C, conditions that resemble industrial fixed-bed systems. The reaction is highly exothermic, requiring careful heat management to avoid temperature spikes. Studies using tubular fixed-bed reactors demonstrate that at such high temperatures, formaldehyde can easily dissociate, forming CO and CO_2. These characteristics highlight the need for effective heat-transfer control, including rapid cooling or heat exchangers, to maintain stability and product selectivity [3].

The unmodified process loses considerable energy because no heat is recycled, causing the heat removed during cooling to be wasted and requiring extra external heating. Processes without proper heat recovery experience high utility demand and inefficient energy use. In contrast, the modified process reflects the journal's concept of internal heat integration, where recovered thermal streams are reused. By utilizing the cold fluid from E-100 for heat exchangers like E-103 and E-105, the system forms a continuous heat-reuse cycle that improves energy efficiency and reduces overall energy consumption [10]. The concept of process intensification through heat recovery in exothermic oxidation reactions has been proven to enhance thermal stability and energy efficiency [14].

3.4 Improving Energy Efficiency by Reducing Net Energy

Based on the simulation results, the total energy demand of the system can be determined through the heat flow data. This information illustrates the extent to which energy can be conserved when compared to the unmodified process [12]. Using these values, the amount of energy saved in the modified process can be calculated mathematically.

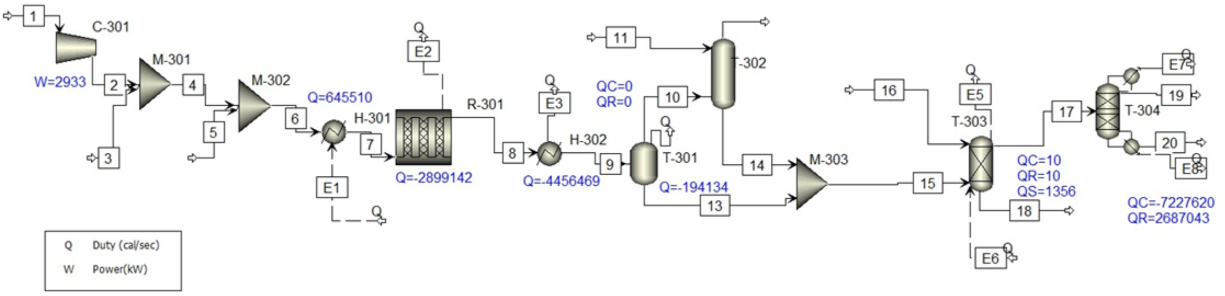

Figure 2. Unmodified process simulation using Aspen Plus.

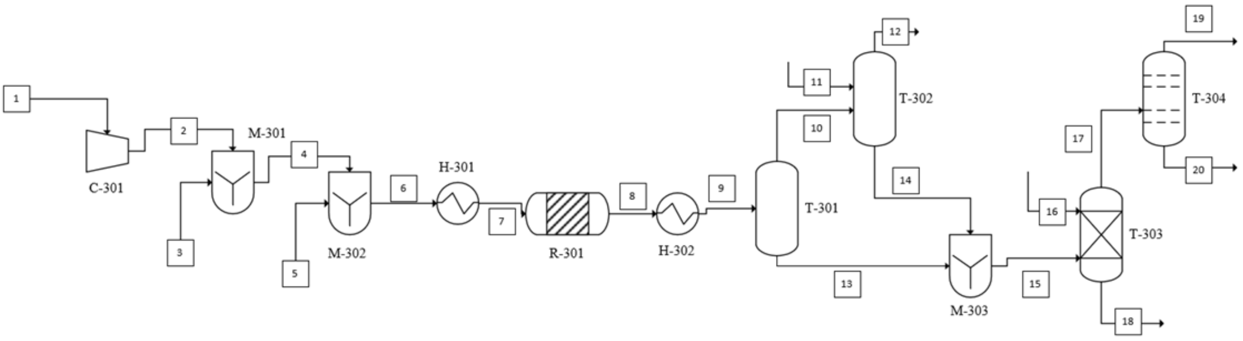

Figure 3. Process flow diagram (PFD) of unmodified process.

The energy performance of the process was evaluated by comparing the unmodified and modified configurations in terms of net energy consumption. The unmodified process required a net energy of 1.88×10^7 kJ.h^{-1}, whereas the modified process reduced the net energy demand to 4.12×10^6 kJ.h^{-1}. As a result, an overall energy reduction of 1.47×10^7 kJ.h^{-1} was achieved after process modification. The strategy of reusing thermal streams to enhance efficiency aligns with the findings who demonstrated that optimizing heat exchanger networks can substantially reduce a plant's overall energy loss. Their exergy-based approach provides a theoretical foundation for the 78.1% energy reduction achieved in this study through the integration of the H-302 outlet stream [15].

4. Conclusion

The simulation of acrylic acid production via propylene oxidation using Aspen Plus demonstrates that the implementation of heat-recovery modifications significantly improves the overall energy efficiency of the process. In the unmodified configuration, a large portion of the reaction heat is wasted, resulting in high external energy demand for both reactors preheating and the distillation sequence. By integrating a heat-recovery loop, particularly through reuse of the heat stream from H-302 to support the reboiler duty of T-304, the modified process reduces net energy consumption and minimizes thermal losses across the system. The mass and energy balance results confirm that the modified design not only enhances thermal integration but also improves process performance by increasing conversion efficiency and reducing the reliance on external utilities. The recycled heat-transfer fluid loop further contributes to stabilizing temperature control within the reactor and separation units, supporting safer and more consistent operation. Overall, the modified process provides a more energy-efficient, economically favorable, and thermodynamically optimized route for acrylic acid production compared to the conventional configuration. This demonstrates the importance of process intensification strategies and heat-integration approaches in improving industrial chemical manufacturing systems.

CRedit Author Statement

Author Contributions: A. N. Owen: Conceptualization, Methodology, Validation, Data Curation, Writing, Review and editing, C. E. Simarmata: Conceptualization, Methodology, Validation, Data Curation, Writing, Resources, J. K. Sidabuke: Conceptualization, Software, Methodology, Validation, Data Curation, Resources, M. A. M. Almasyah: Conceptualization, Methodology, Validation, Data Curation, Writing, Resources, N. A. Deanti:

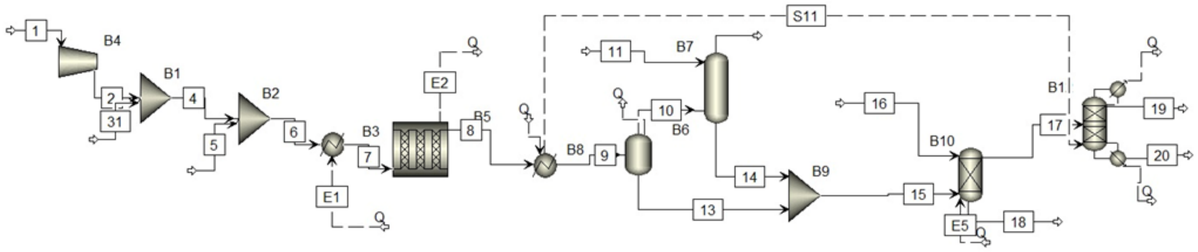

Figure 4. Process simulation of the modified process using Aspen Plus.

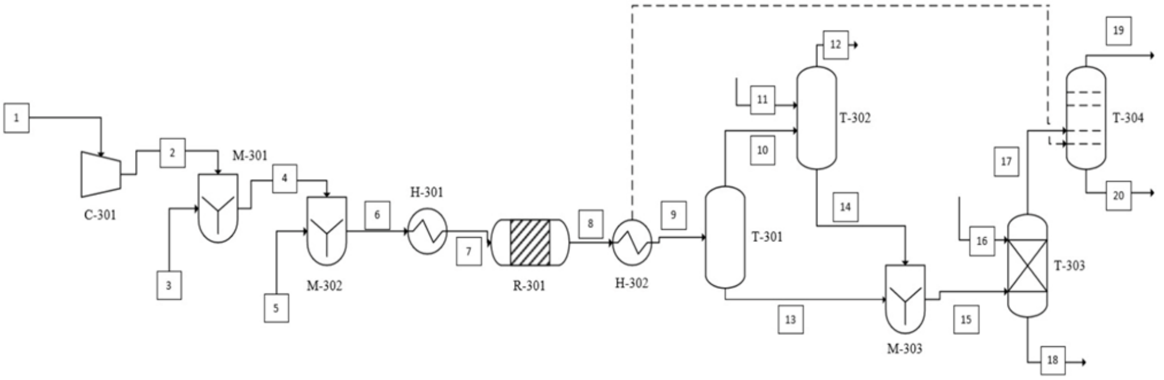

Figure 5. Process Flow Diagram (PFD) of the modified process.

Conceptualization, Software, Methodology, Validation, Data Curation, Writing, Review and editing, Resources, S. A. Silaen: Conceptualization, Methodology, Validation, Data Curation, Writing, Resources. All authors have read and agreed to the published version of the manuscript.

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