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Research Article

Enhancing Energy Efficiency of Maleic Anhydride Production via Heat Integration and Feed Preheating

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Abstract

This study explores strategies to enhance energy efficiency in maleic anhydride production through heat integration and feed preheating modifications within an existing process configuration. The process, based on benzene oxidation in a plug flow reactor followed by absorption and distillation, was modeled under steady state conditions to evaluate energy utilization across key unit operations. In the baseline setup, the reactor feed depended entirely on external heating, while significant thermal energy in the reactor effluent was lost through cooling utilities. To address this inefficiency, a modified configuration was introduced in which part of the effluent heat was redirected to the feed preheater, enabling internal energy recovery and reducing reliance on external utilities. Simulation results demonstrated a marked improvement in energy efficiency, with energy savings rising from 1.219×108 kJ/h (93.93%) to 1.625×108 kJ/h (96.04%) after modification. The redistribution of thermal load across the heat exchanger network confirmed that internal heat was effectively harnessed without incurring additional utility costs or capital investment. Overall, these findings highlight heat integration as a practical and economically advantageous approach to improving energy efficiency in maleic anhydride production while preserving operability and separation performance.

Keywords: Maleic Anhydride; Heat Integration; Energy Efficiency; Benzene Oxidation; Feed Preheating

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1. Introduction

Maleic anhydride is an essential intermediate in the chemical industry, widely utilized as a key precursor in the production of unsaturated polyester resins, lubricant additives, and various copolymer materials. Industrially, it is primarily manufactured via the partial oxidation of hydrocarbon feedstocks most commonly n-butane using vanadium-based catalysts in fixed bed reactors. Given the highly exothermic nature of this reaction, stringent thermal management is crucial to maintain stable operating conditions, safeguard catalyst longevity, and achieve high product selectivity [1].

Effective energy management in chemical processes is vital, as energy consumption constitutes a significant driver of both operational costs and greenhouse gas emissions. In industrial settings, energy optimization strategies, particularly heat integration, offer considerable potential to reduce dependence on external heating and cooling utilities. Among these approaches, pinch analysis provides a systematic framework for identifying heat recovery opportunities and designing efficient heat exchanger networks. When implemented at the industrial scale, this method has consistently delivered substantial improvements in energy efficiency [2].

Moreover, processes involving highly exothermic reactions, such as maleic anhydride production, offer significant opportunities to

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harness reaction heat as an internal energy source. By effectively recovering and utilizing this inherent thermal energy, reliance on external utilities can be reduced, thereby improving the overall thermal efficiency of the system [3]. At the same time, stringent heat management within reactors remains essential to prevent temperature excursions that could accelerate catalyst deactivation or impair reactor performance, thereby safeguarding process stability and product selectivity [4].

The advancement of process simulation software has emerged as a crucial enabler of energy optimization in the chemical industry, facilitating comprehensive mass and energy balance analyses prior to full-scale implementation. These tools provide opportunities to design operating scenarios that maximize heat recovery, optimize heat exchanger networks, and enhance energy reuse. In doing so, they promote the development of processes that align with sustainability principles and modern industrial efficiency, while simultaneously reducing dependence on external utilities and mitigating environmental impact. [1].

Building on this background, a study centered on energy optimization in maleic anhydride production through detailed analysis of energy requirements and strategic utilization of reaction heat holds significant relevance. The outcomes are anticipated to yield valuable insights into potential energy savings and establish a foundation for designing processes that are not only more efficient, but also safer and more sustainable within the framework of modern industrial practice.

2. Methods

The process modeling was developed based on the integrated flowsheet presented in Figure 1, which depicts a conventional maleic anhydride production route enhanced with internal heat recovery pathways. The model encompasses benzene oxidation, gas cooling, absorption, solvent regeneration, and final product purification under steady-state conditions [5]. Steady-state operation was selected to enable direct closure of mass and energy balances and to facilitate meaningful comparison across different process configurations. This methodology is widely employed in contemporary energy-efficiency and process intensification studies for anhydride production systems [6]. The base case represents standard industrial operation prior to energy optimization, with all energy duties recorded from this configuration serving as the benchmark for subsequent comparisons [7].

Physical and chemical properties were specified for benzene, maleic anhydride, oxygen, nitrogen, carbon dioxide, water, and dibutyl phthalate to ensure accurate prediction of phase behavior and enthalpy changes. Non-ideal vapor–liquid equilibrium effects were explicitly accounted for, given the presence of polar components and high-boiling solvents [8]. Emphasis was placed on thermodynamic consistency, as even minor temperature variations introduced through heat integration can significantly influence separation efficiency. Previous studies on anhydride absorption and solvent regeneration highlight the critical role of precise phase equilibrium modeling in energy-integrated systems [8]. Enthalpy calculations were directly employed to quantify heating and cooling duties across the flowsheet, thereby providing a robust framework for evaluating both the base and modified process configurations.

The modeled unit operations comprise a catalytic oxidation reactor, multiple heat exchangers, an absorber, and a solvent recovery distillation column. The oxidation reactor was configured to reflect the strongly exothermic conversion of benzene to maleic anhydride [9]. Heat exchangers were incorporated to capture sensible heat from reactor effluent streams,

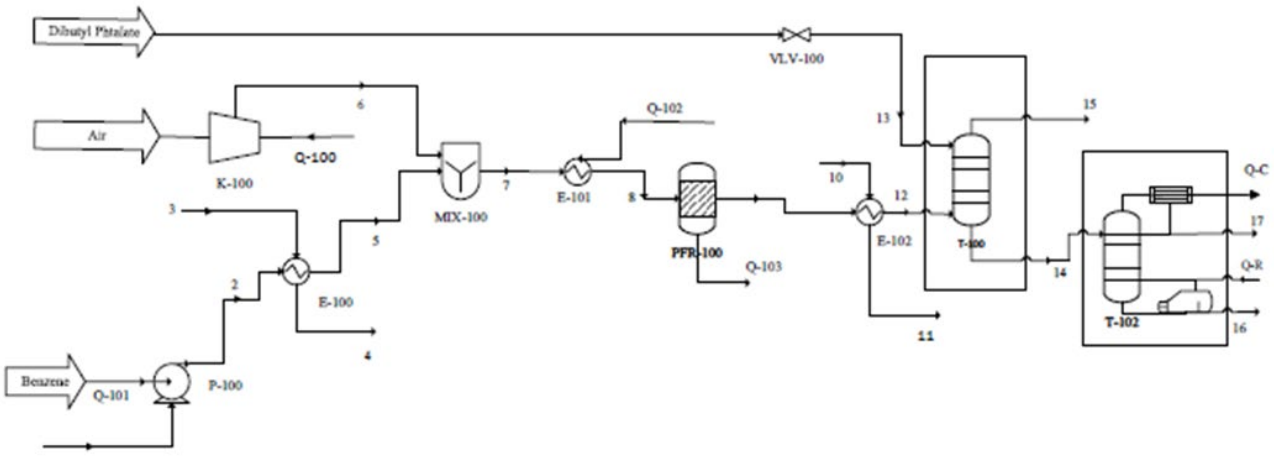

Figure 1. Process flow diagram (PFD) of maleic anhydride production before optimization.

facilitating energy recovery. The absorber utilizes dibutyl phthalate to selectively remove maleic anhydride from the gas phase while minimizing solvent losses. Subsequent distillation separates the product from the solvent, enabling efficient solvent to recycle. Overall, this process configuration aligns with industrial maleic anhydride production schemes documented in recent literature [10].

Heat integration was achieved by redirecting thermal energy from hot reactor effluent streams to preheat incoming feed streams, as illustrated in Figure 1. In the base case, excess heat was dissipated through external cooling utilities, leading to considerable energy loss. In the modified configuration, a portion of this heat was recovered internally, thereby reducing the demand for external heating [11]. Feed preheating was carefully regulated to prevent reactor overheating and ensure operational safety. Comparable integration strategies have been demonstrated to effectively lower utility consumption in anhydride-based chemical processes [12]. Collectively, these modifications exemplify a practical application of process intensification principles.

Because heat integration elevates the reactor inlet temperature, operational adjustments were necessary to sustain stable reaction conditions [13]. The air-to-benzene ratio was modified to regulate the reactor temperature profile and mitigate the risk of excessive hotspot formation. Reactor stability was continuously monitored throughout the simulation to ensure that conversion and selectivity remained within acceptable limits. Such adjustments are routinely implemented in energy-integrated reaction systems to balance efficiency with safety [6]. The modified configuration successfully maintained stable operation without introducing additional control complexity.

Energy consumption was quantified by extracting heater and cooler duties from the simulation results for each unit operation. The total external energy demand was then calculated for both the base case and the heat-integrated configuration [14]. Energy savings were determined by comparing the differences in heating and cooling requirements between the two scenarios. This evaluation approach is consistent with recent methodologies employed to quantify energy efficiency improvements in process industries [7]. Overall, the analysis establishes a clear numerical basis for assessing the effectiveness of heat integration.

A comparative analysis was performed between the base case and the modified configuration to assess the overall impact of heat integration. Key performance indicators included total energy consumption, recovered heat, and the stability of separation processes [14]. Emphasis was placed on the absorber and distillation units, given their sensitivity to temperature fluctuations. Previous studies have shown that poorly designed heat integration can adversely affect solvent-based separations [7]. In contrast, the present comparison confirms that the proposed integration strategy improves energy efficiency while preserving process performance.

3. Results and Discussions

Figure 2 presents the process flowsheet for maleic anhydride production prior to modification. In this configuration, the benzene and air feed streams are first pumped and compressed, then heated by an external heater (E-101) before entering the reactor (PFR-100). All the heat required to reach the reaction temperature is supplied externally, with no recovery of thermal energy from the reactor effluent or downstream units. Following the oxidation reaction, the hot reactor effluent is directly cooled in heat exchanger E-102 before being directed to the separation units T-100 and T-102. Aspen HYSYS simulation results reveal that the heat duty of heater E-101 is substantial, owing to the large temperature difference between the feed and the reactor operating

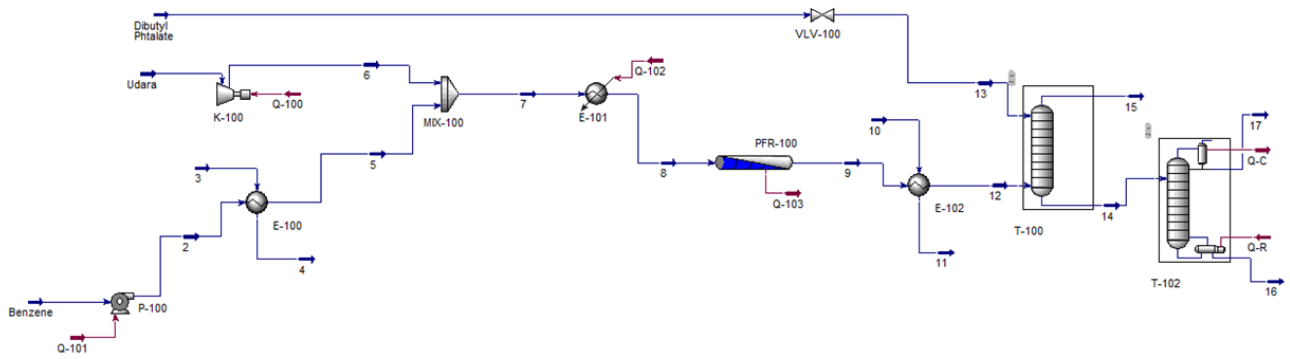

Figure 2. Aspen HYSYS simulation of maleic anhydride production without heat integration.

conditions. Most of the thermal energy contained in the reactor effluent is discharged through the cooling system, indicating that internal process heat is not effectively utilized. Consequently, utility energy consumption remains high despite the presence of high-temperature streams within the system.

The modified flowsheet is presented in Figure 3. The principal change involves redirecting the hot effluent from heat exchanger E-102 to heat exchanger E-100, where it is utilized to preheat the benzene feed prior to mixing and subsequent heating. In this configuration, a portion of the sensible heat from the process stream is recovered and reused for feed preheating. While the overall sequence of unit operations remains unchanged, internal heat integration between process streams is introduced. Consequently, the initial heating step no longer depends entirely on heater E-101, as the reactor feed enters the heater at an elevated temperature, thereby reducing the demand for external heat.

Aspen HYSYS simulation results indicate that, following process modification, the heat duty of the process heat exchangers increased relative to the original configuration. This rise does not signify greater external energy demand; rather, it reflects a shift in the heat source from external utilities to internal process energy. In the pre-modification setup, reactor feed heating relied exclusively on the external heater, while the thermal energy contained in the reactor effluent was discarded through cooling units without recovery. With the integration of heat exchangers, the sensible heat from the high-temperature reactor effluent is captured and reused to preheat the feed prior to entering the PFR reactor. Consequently, exchangers such as E-100 and E-102 assume an active role in internal heat transfer, resulting in higher recorded heat duties for these units. This increase represents successful heat recovery rather than additional external energy consumption. By harnessing internal heat, the heating load is redistributed across the network of process exchangers instead of being concentrated on the external heater. Although the total exchanger heat duty rises, external utility demand remains unchanged, as evidenced by the relatively stable annual utility cost in both configurations. This outcome demonstrates that heat previously wasted is now effectively recovered and reused within the system. The redistribution of thermal load is a defining characteristic of successful heat integration, with the higher exchanger duties serving as a clear indicator of improved efficiency in utilizing internal process energy, where reaction heat is harnessed to preheat the reactor feed rather than rejected through cooling.

Table 1 presents a comparison of energy performance before and after process modification. Simulation results indicate that, prior to modification, energy savings amounted to 1.219×10^8 kJ/h (93.93%). Following heat exchanger integration, the savings increased to 1.625×10^8 kJ/h (96.04%). This improvement demonstrates that the modification effectively enhances the recovery and utilization of internal process heat. Although the equipment configuration was slightly adjusted, the required capital investment remained largely unchanged. Thus, the observed gains in energy efficiency are primarily attributable to the optimization of heat

Table 1. Comparison of process performance before and after heat integration.

Parameter	Before Modification	After Modification
Heater E-101 Duty (kJ/h)	3.053×10^7	4.501×10^7
Energy Saving (kJ/h)	1.219×10^8	1.625×10^8
Energy Saving (%)	93.93	96.04
Utility Cost (USD/year)	2,107,520	2,107,520
Capital Cost (USD)	16,023,000	16,015,600

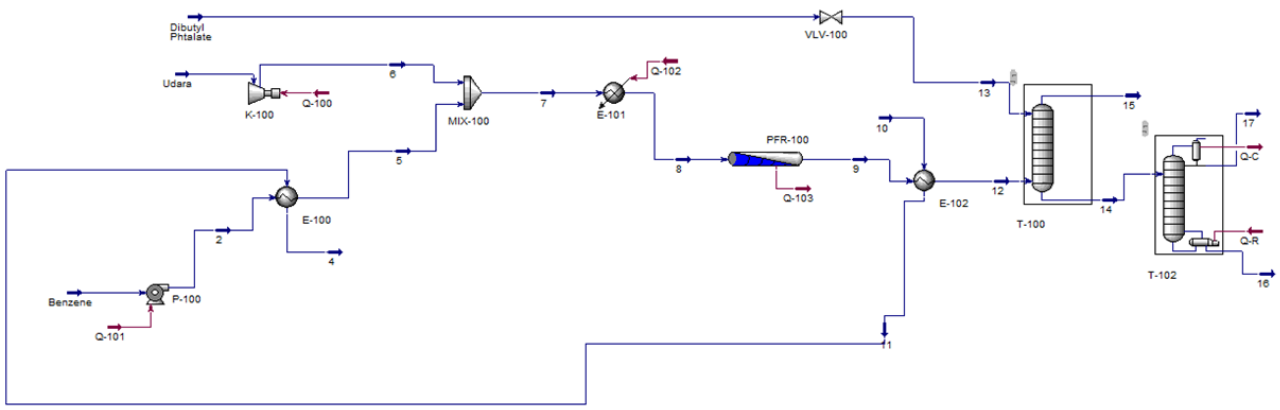

Figure 3. Aspen HYSYS simulation of maleic anhydride production with heat integration.

flows rather than the introduction of complex new unit operations. The final configuration resulting from these optimization measures is depicted in Figure 4.

4. Conclusions

In this study, the maleic anhydride production process was modified by integrating a heat exchanger upstream of the PFR reactor to harness internal process heat. Under the initial configuration, the reactor's entire heat requirement was supplied by an external heater, while the thermal energy from the reactor outlet was dissipated through the cooling system. This arrangement led to high energy consumption and inefficient heat utilization. Aspen HYSYS simulation results demonstrate that the addition of a heat exchanger substantially reduces the heater's load and enhances the overall energy efficiency of the process. Energy savings increased from 93.93% in the pre-modification case to 96.04% after modification, without any notable rise in annual utility costs or capital investment. These findings confirm that the recovery and reuse of internal heat provide a simple yet effective strategy for improving process energy performance. More broadly, the results establish that upstream heat integration of the reactor can serve as a viable process intensification approach in maleic anhydride production, reducing energy demand while simultaneously supporting operational stability and long-term sustainability.

CRedit Author Statement

Author Contributions: V.D. Nafisah: Conceptualization, Resources, Investigation, Methodology, Software (Aspen HYSYS simulation), Formal analysis, Writing, Review & Editing; S. Lieliani: Resources, Investigation, Methodology, Software (Aspen HYSYS simulation), Formal Analysis, Writing, Review, Validation Data Curation & Editing; K. Huwaida: Resources, Investigation, Methodology, Software (Aspen HYSYS simulation), Formal Analysis, Writing, Review, Validation Data Curation & Editing; M. Khairunnisa: Resources, Conceptualization, Investigation, Methodology, Writing, Review & Editing; B.C. Najma: Resources, Conceptualization, Investigation, Methodology, Writing, Review & Editing. All authors have read and agreed to the published version of the manuscript.

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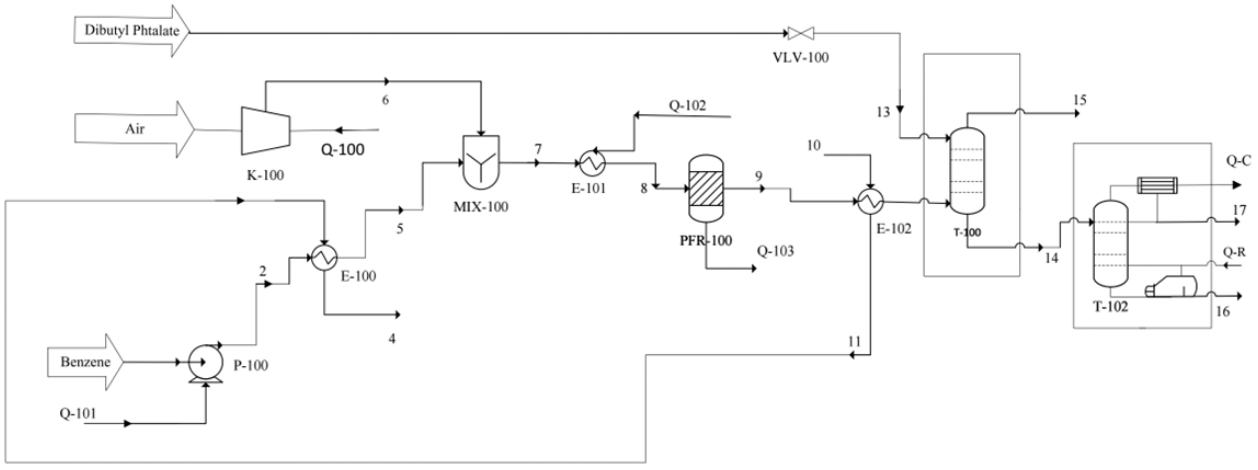

Figure 4. Process flow diagram (PFD) of maleic anhydride production after optimization.

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