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Journal of Chemical Engineering Research Progress, 3 (1) 2026, 37-43

Research Article

Recovery and Utilization of Waste Heat from Cooler Effluent for Preheating Applications

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Received: 12th December 2025; Revised: 17th December 2025; Accepted: 18th December 2025
Available online: 2nd January 2026; Published regularly: June 2026

Abstract

Maleic anhydride (MA) is an important intermediate for polymers, coatings, and fine chemicals, yet its production through n-butane oxidation remains energy-intensive due to the highly exothermic nature of the reaction. Inefficient heat management leads to excessive utility demand and reduced process performance. This study aims to improve energy efficiency by recovering and reusing waste heat from the cooler effluent for preheating applications. The process is simulated using Aspen HYSYS to compare the basic configuration with a modified design that integrates a recycle stream from the cooler outlet to the heater. The modified configuration demonstrates a significant reduction in external energy consumption, achieving a 43% energy saving compared to the basic process. Net energy decreases markedly, while overall energy efficiency increases to 86%. The recycle stream stabilizes temperature profiles, reduces utility demand, and enhances process reliability. These improvements confirm that waste heat recovery through heat integration provides a practical and effective approach to optimize maleic anhydride production. In conclusion, the modification advances the current state of process design by demonstrating that simple operational changes can deliver substantial energy savings and support sustainable chemical manufacturing. The findings highlight the potential application of waste heat recovery strategies in other exothermic oxidation systems and provide a foundation for future studies on coupling heat integration with advanced separation schemes.

Keywords: Maleic Anhydride; Waste Heat Recovery; Heat Integration; Energy Efficiency

How to Cite: Sulistiana, A. I., Adinda, A. P., Hakim, B. A., Izza, F. R., Dianingratri, X. F. (2026). Recovery and Utilization of Waste Heat from Cooler Effluent for Preheating Applications. *Journal of Chemical Engineering Research Progress*, 3 (1), 37-43 (doi: 10.9767/jcerp.20597)

Permalink/DOI: https://doi.org/10.9767/jcerp.20597

1. Introduction

Maleic anhydride (MA) remains an essential intermediate for producing unsaturated polyester resins, specialty polymers, coatings, and a wide array of fine chemicals. The steady rise in global consumption has been closely linked to expanding polymer and coating markets, which in turn has prompted renewed attention to the efficiency and environmental profile of existing production routes. While the traditional benzene-based route is well established, the n-butane oxidation pathway has increasingly drawn industrial interest due to its more favourable economics and lower emissions when operated under optimized conditions [1].

The challenge, however, lies in the delicate balance between conversion and selectivity during the selective oxidation of n-butane. The reaction is highly exothermic, and without careful management of local temperature gradients, MA can undergo further oxidation to CO and CO_2. Numerous studies on vanadium phosphorus-oxide (VPO) catalysts have underscored how sensitive the reaction is to heat removal, oxygen partial pressure, and catalyst morphology. In practice, small variations in reactor cooling configurations or tube-wall temperature can shift the distribution of products markedly. Earlier investigations have

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shown that mitigating hot-spot formation through strategies such as improved coolant circulation or optimized tube arrangements substantially reduces secondary combustion and helps preserve selectivity [2].

Downstream operations add another layer of complexity. Although MA can be absorbed efficiently using solvents like dibutyl phthalate (DBP) or via aqueous scrubbing, the compound's thermal sensitivity often complicates high-temperature purification. Poorly controlled evaporation or distillation can trigger side reactions such as polymerization or hydration to maleic acid, diminishing both yield and product quality. Process-level assessments have demonstrated that multi-stage separation schemes, particularly when paired with controlled heat integration and solvent recycling, can maintain purity targets while minimizing thermal degradation [1,3].

In recent years, research has begun to bridge catalyst science with broader process optimization. Yu *et al.* [4] compared several plant-scale configurations and reported that co-current cooling, paired with targeted heat recovery and water-based stripping, produced higher MA yields and better overall energy performance than classical designs. Meanwhile, advances in VPO catalyst synthesis have continued to push selectivity limits, although it is increasingly recognized that improvements in catalyst formulation alone cannot fully address the temperature-selectivity constraints inherent to the system [5].

Despite these contributions, a gap remains in understanding how optimized temperature control in the reactor interacts with high-temperature separation design to influence overall process performance. Much of the literature examines these components in isolation, leaving uncertainty around how they behave when integrated under industrial conditions [6]. This study therefore combines both aspects reaction temperature optimization through staged cooling and heat-integration schemes, together with an improved separation train featuring solvent screening and multi-stage distillation in a unified assessment. By employing rigorous process simulation and techno-economic analysis, the work quantifies trade-offs among yield, energy consumption, and carbon intensity, ultimately providing design guidance for more efficient and sustainable MA production [1].

2. Method

2.1 Effect of Operational Modifications on Waste Heat Recovery Efficiency

Recovery and utilization of waste heat from cooler effluent constitute a key strategy for improving energy efficiency in industrial process systems. As highlighted by Yu *et al.* [4], the hot effluent streams discharged from reactors and cooling units contain considerable thermal energy that can be reintegrated into the process through heat-recovery schemes. This recovered energy can be employed for feed preheating, steam generation, or other process-utility heating requirements, thereby reducing external heat demand and lowering environmental impact. The effectiveness of heat recovery is strongly influenced by operating conditions. Adjustments such as increasing the inlet temperature of the cooling medium and regulating flow rates have been shown to enhance the system's ability to extract heat from the effluent. These measures not only increase the driving force for heat transfer but also help mitigate thermal fouling, enabling more than a 15% increase in recoverable heat [7].

In addition, hot effluent from the reactor typically experiences a significant temperature drop as it passes through the heat-exchanger network. Process analysis indicates that variations in operating parameters such as molten-salt flow rate, air-feed distribution, and cooling-medium inlet temperature play critical roles in determining the amount of heat that can be recovered. Through heat integration, the thermal energy contained in the effluent can be transferred to various process units, including reboilers, preheaters, and steam generators, thereby improving overall thermal efficiency [8]. Further operational modifications involve optimizing effluent temperature and increasing the heat-transfer surface area. By minimizing heat losses throughout the exchanger network and enhancing the heat-transfer driving force, the available waste heat from the cooler can be maximized for preheating the n-butane (air fee). Yu *et al.* [4] report that optimized process configurations can achieve energy-efficiency levels exceeding 97%, underscoring the substantial potential for waste-heat utilization in such systems.

Overall, optimizing waste-heat recovery not only reduces external energy consumption but also lowers operating costs, decreases CO_2 emissions, and improves overall process performance. This approach aligns with modern process-design strategies that emphasize maximum energy recovery through heat integration and efficient utilization of internal thermal resources.

2.2. Role of Temperature Management in Optimizing Waste Heat Utilization

Temperature management is key factor in maximizing the effectiveness of waste heat recovery systems. The effectiveness of heat recovery depends strongly on the temperature driving force between the hot effluent and the process stream being preheated. A stable effluent temperature ensures a higher log mean temperature difference, which enhances the thermal performance of the heat exchanger and increases overall recovery efficiency [9].

In exothermic oxidation systems such as those evaluated by Yu *et al.* [4] temperature control in the reaction and cooling sections directly influences the thermal quality of the effluent. Yu *et al.* [4] reported that insufficient heat removal can lead to elevated hotspot temperatures and fluctuating outlet temperatures, which reduce the predictability and effectiveness of downstream heat recovery units. Maintaining a controlled thermal profile upstream is therefore essential to ensure that the waste heat stream remains suitable for preheating applications. Recent studies emphasize that temperature fluctuations negatively impact heat exchanger performance and energy integration. According to Cho *et al.* [10], unstable inlet temperatures reduce exchanger effectiveness and increase energy mismatches in heat recovery networks. Similarly, Yang *et al.* [11] demonstrated that stable temperature profiles significantly improve the thermal reliability of industrial waste heat recovery systems by maintaining consistent heat capacities and avoiding degradation of heat transfer coefficients.

In addition, temperature management helps prevent secondary thermal degradation mechanisms that may reduce the quality of the waste heat. For instance, in oxidation and combustion-related processes, excessive effluent temperatures may trigger unwanted downstream reactions or alter physical properties of the hot stream [12]. Effective cooling strategies, such as coolant flow regulation, optimized exchanger duty, and controlled reaction temperature ensure that the waste heat is maintained within an optimal range for preheating.

3. Results and Discussion

3.1. Comparison Between Basic and Modified Processes

The mass and energy balances of the modified process are presented in Table S1 (Supporting Information). The simulation results of the n-butane oxidation process for both the basic and modified configurations using Aspen HYSYS are shown in Figures 1 and 2. The basic process simulation, illustrated in Figure 1, includes only a limited number of equipment units such as the compressor, preheater, plug flow reactor, a single cooling section, and a simple separation step. In addition, the operating conditions such as temperature and pressure for each stream were not fully specified, resulting in a process representation that is less accurate and less reflective of actual industrial operations. A major drawback in the basic configuration is that the outlet stream from the first cooler is not recycled back to the heater, causing the remaining heat to be wasted. As a result, the heater requires additional energy input to reach the desired temperature, making the basic process more energy-intensive and less efficient.

In contrast, the modified process shown in Figure 2 incorporates several key improvements that enhance both operational realism and energy efficiency. Additional equipment units are integrated into the flowsheet, including multiple coolers (E-102, E-103, and E-104), a complete absorber–stripper system, a two-phase separator

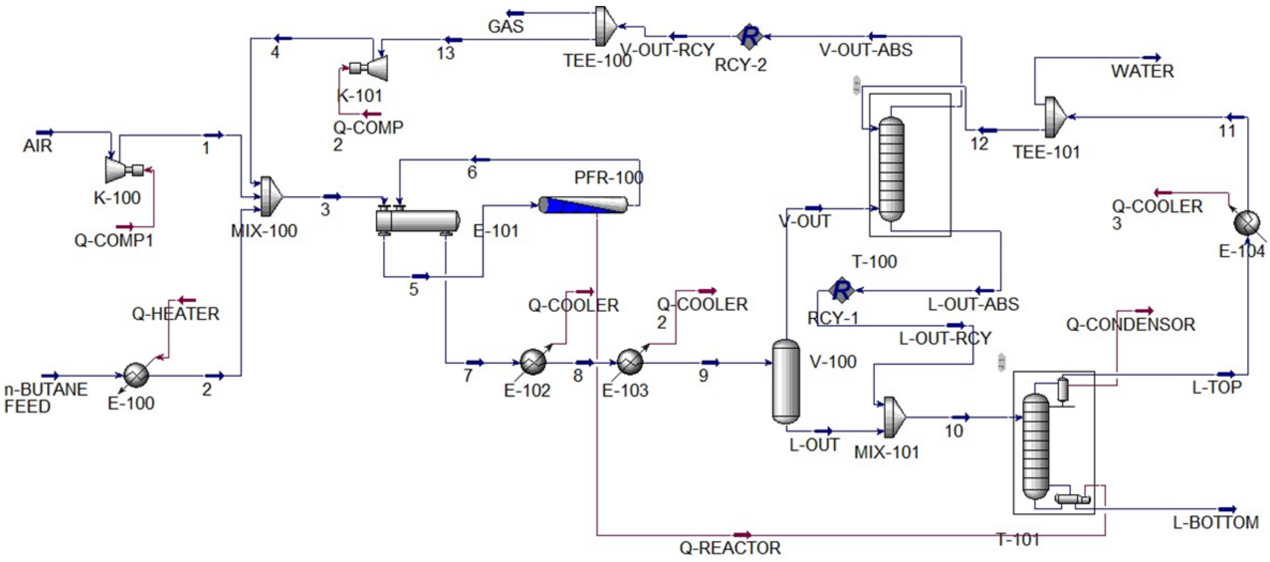

Figure 1. Process simulation of unmodified process using Aspen HYSYS.

(V-100), and recycle loops (RCY-1 and RCY-2). One of the most significant enhancements is the inclusion of a recycle stream from the first cooler back to the heater. This modification enables heat recovery and reuse, thereby reducing the heating duty required and improving the overall thermal efficiency of the system. The multi-stage cooling and the continuous separation through the absorber and stripper also contribute to better removal of undesired components and improved product purity. Overall, the modified process provides a more energy-efficient, stable, and realistic simulation compared to the basic configuration.

3.2. Thermodynamics Review

The selective oxidation of n-butane to maleic anhydride (MA) is an exothermic gas-phase reaction whose thermodynamic characteristics strongly influence both reactor behavior and separation requirements. The main reaction involved in MA formation is:

$$C_4H_{10} + 3.5O_2 \rightarrow C_4H_2O_3 + 4H_2O \quad (1)$$

Using these values, the standard heat of reaction at 298 K is determined from:

$$\Delta H^\circ_{298} = \Sigma\Delta H^\circ_{f,\text{products}} - \Sigma\Delta H^\circ_{f,\text{reactants}} = -1407.9\ \text{kJ/m}$$

The reaction is therefore highly exothermic, consistent with the observed hot-spot temperatures in the Aspen HYSYS simulations. In the *unmodified* process, the model predicts a reactor inlet temperature of ~449 °C and a hot-spot peak around 485–500 °C, indicating rapid heat release at the catalyst bed entrance. Meanwhile, the *modified* configuration using additional heat exchange and optimized temperature control reduces the hot-spot to ~395–410 °C, lowering the risk of deep oxidation into CO and CO_2.

The standard Gibbs free energy of reaction is calculated as:

$$\Delta G^\circ_{298K} = \Sigma\Delta G^\circ_{f,\text{products}} - \Sigma\Delta G^\circ_{f,\text{reactants}} = -1416.9\ \text{kJ/mol}$$
$$\Delta G^\circ_{673K} = -1605.3\ \text{kJ/mol}$$

The large negative value indicates a highly spontaneous reaction, which is consistent with industrial operation where the oxidation proceeds irreversibly once initiated. This agrees with established literature showing that MA formation from n-butane is kinetically limited rather than thermodynamically reversible at typical operating temperatures (400–450 °C).

The equilibrium constant at 298 K is obtained from:

$$K_{298} = \exp\left(-\frac{\Delta G^\circ}{RT}\right) \quad (2)$$

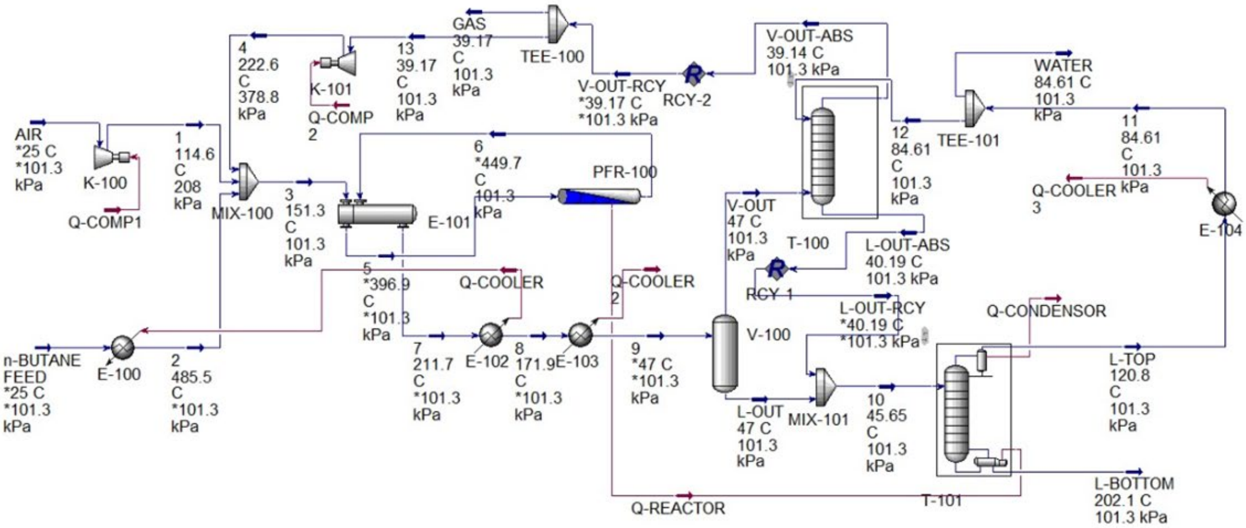

Figure 2. Process simulation of modified process using Aspen HYSYS.

Table 1. The value of ΔH_f° and ΔG_f° of compounds

Compound	Formula	ΔH_f° (kJ/mol)	ΔG_f° (kJ/mol)
n-Butane	C_4H_{10}	–125.6	–15.9
Oxygen	O_2	0	0
Maleic anhydride	$C_4H_2O_3$	–454.9	–390.5
Water (g)	H_2O	–241.8	–228.6

K_{298}=4.1 × 10^{248}

This extremely large equilibrium constant indicates that reaction (1) is thermodynamically irreversible, consistent with both industrial practice and simulation outputs. To evaluate equilibrium at reactor conditions (~673 K), the van 't Hoff relation is applied:

$$\text{In}\left(-\frac{K_T}{K_{298}}\right) = -\frac{\Delta \mathrm{H}^{\circ}}{\mathrm{R}}\left(\frac{1}{T}-\frac{1}{298}\right) \tag{3}$$

Substituting:

$$\text{In}\left(-\frac{K_{673}}{4.1\times10^{248}}\right) = -\frac{-1.4079\times10^{6}}{8.314}\left(\frac{1}{673}-\frac{1}{298}\right)$$

$$K_{673} = 1.7\times10^{212}$$

Overall, the thermodynamic evaluation confirms that improvements in reaction temperature control and high-temperature separation design significantly enhance process performance. The modified HYSYS simulation better conforms to the exothermic and irreversible nature of the oxidation reaction, maintaining reactor temperature inside the optimal selectivity window and ensuring a thermodynamically favorable environment for MA recovery. The combined thermodynamic and process modifications therefore provide a strong basis for the observed improvements in yield, purity, and energy efficiency in the optimized flowsheet.

3.3. Recovery of Waste Heat from Maleic Anhydride to Improving Energy Efficiency

The production of maleic anhydride (MA) through n-butane oxidation is an exothermic reaction that generates a significant amount of waste heat. Without heat integration, this energy is released to the environment, which increases external utility demand and reduces process efficiency. Waste heat recovery therefore represents an essential strategy to improve energy efficiency and sustainability in chemical processes [4,13]. Based on comparison stated in Table 2, in the basic configuration, the outlet stream from the first cooler is not recycled to the heater, and the residual heat is lost. As a result, the heater requires additional duty to reach the desired operating temperature, which makes the process energy intensive. This condition corresponds with the findings of Jouhara *et al.* [7], who report that systems without heat recovery lose 15–30% of potential energy.

The modified configuration introduces a recycle stream from the cooler outlet to the heater. Aspen HYSYS simulation shows that this modification reduces energy consumption by 43% compared to the basic process. The recycle stream decreases external utility demand and stabilizes the temperature profile, which improves process reliability. From a thermodynamic perspective, heat integration through recycle increases the log mean temperature difference (LMTD) in the heat exchanger, enhances the driving force for heat transfer, and reduces external energy requirements. This result is consistent with Yu *et al.* [4], who demonstrate that co-current cooling with heat recovery achieves an energy efficiency of 97.52%. Furthermore, the 43% energy saving obtained in this study exceeds the average industrial efficiency improvement of 15–30% [7], which highlights the effectiveness of the modification. This finding also aligns with Iftinan *et al.* [13], who report that reusing the outlet stream of a heat exchanger in formaldehyde production decreases net energy from 18.8 million kJ/h to 4.1 million kJ/h, resulting in a 78.12% increase in energy efficiency. Although the study of Asyfianto *et al.* [1] focuses on improving maleic anhydride purity through multi-stage distillation, the writing style and process modification approach using Aspen HYSYS provide a useful reference for presenting simulation-based improvements. The modification of recycling steam to the heater therefore improves energy efficiency by 43% and contributes significantly to the sustainability of maleic anhydride production. The results confirm that waste heat recovery through heat integration is an effective approach to reduce external energy consumption and support environmentally friendly process design.

Table 2. Comparison of energy consumption, net energy, and energy efficiency before and after process modification unmodified and modified processes based on process simulation using Aspen HYSYS

Parameter	Basic Process	Modified Process
Energy Consumption (E_c)	1.00 (basis)	0.57 (decrease 43%)
Energy Produced (E_P)	1.00 (basis)	1.00 (basis)
Net Energy ($N_E = E_P - E_C$)	1.00 (basis)	0.14 (significant decrease)
Energy Efficiency (%)	0%	86%

4. Conclusion

This research achieves the objective of improving energy efficiency in maleic anhydride production by recovering and reusing waste heat from the cooler effluent. The modification of recycling the cooler outlet stream to the heater reduces external energy consumption by 43% and increases overall efficiency to 86%, which advances the current understanding of process-level heat integration in exothermic oxidation systems. The results provide strong scientific justification for adopting waste heat recovery strategies, as they not only decrease utility demand but also stabilize reactor operation and reduce carbon intensity. This contribution highlights the potential application of heat integration in other chemical processes where energy losses remain critical. Future studies should extend this work by coupling waste heat recovery with advanced separation schemes, evaluating long-term operability under variable feed conditions, and exploring alternative recovery technologies such as organic Rankine cycles or phase change materials to further enhance sustainability in maleic anhydride production.

CRedit Author Statement

Author Contributions: A. P. Adinda contributed to the conceptualization and design of the study, methodology development, investigation, software analysis, data curation, formal analysis, project administration, supervision, and manuscript writing, reviewing, and editing. B. A. Hakim was involved in conceptualization, methodology, investigation, software processing, manuscript preparation, reviewing and editing, as well as supervision. X. F. Dianingratri contributed to the investigation process, data validation, resource provision, data curation, and manuscript writing, reviewing, and editing. F. R. Izza participated in the investigation, data validation, resource provision, data curation, and manuscript writing, reviewing, and editing. A. I. Sulistiana contributed to software development, data visualization, resource provision, and manuscript writing, reviewing, and editing. All authors have read and agreed to the published version of the manuscript.

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