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Research Article

# Heat Efficiency Improvement of Ethanolamine Plant from Ethylene Oxide and Ammonia Through Heat Integration Analysis Using Pinch Technology

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**Abstract**

This study evaluates the impact of pinch analysis on energy efficiency in the preliminary design of an ethanolamine production plant using ethylene oxide and ammonia. The objective is to quantify reductions in external energy demand and to assess the feasibility of heat integration at the early design stage. Pinch analysis was conducted using process stream data derived from mass and energy balances, followed by composite curve construction, pinch point identification, and Heat Exchanger Network (HEN) synthesis using HINT software. The results show a significant reduction in both hot and cold utility requirements after heat integration, with internal heat recovery dominated by the reactor effluent and hot streams prior to distillation. The identified pinch temperature divides the process into distinct regions, enforcing strict utility placement and eliminating cross-pinch heat transfer. Maximum Energy Recovery (MER) analysis indicates substantial potential for internal heat utilization, directly translating into lower specific energy consumption and reduced utility costs. The synthesized HEN meets minimum energy targets while remaining thermodynamically feasible for preliminary plant design. Overall, the application of pinch technology demonstrates a strong and quantifiable impact on improving energy efficiency and provides a robust basis for energy-conscious decision-making in ethanolamine plant pre-design.

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## 1. Introduction

Ethanolamine is an important compound in the gas processing, petrochemical, and surfactant industries due to its role as an acid gas absorbent and as an intermediate in chemical processes (Liu et al., 2020). The production of ethanolamine from ethylene oxide and ammonia involves exothermic reactions and multistage separation, which lead to high energy consumption, particularly in the reaction and distillation units (Wang et al., 2024; Liu et al., 2020).

The high energy intensity of this process requires early evaluation of energy performance and the implementation of heat-efficiency strategies at the pre-design stage to reduce utility demand and operating costs (Radhi et al., 2025). Without heat integration, heat recovery between process streams is not fully utilized, so dependence on external utilities remains high (Özkan & Dinçer, 2001; Kusuma et al., 2025; Safitri et al., 2025).

Pinch technology is a thermodynamics-based heat-integration method used to determine the minimum heating and cooling utility requirements by identifying the pinch point and constructing composite curves (Linnhoff et al., 1982). Further developments in pinch methods, including the problem table approach, floating pinch, and computerized optimization, enable more accurate and cost-effective energy targeting for complex process systems (Linnhoff et al., 1982; Tan et al., 2014).

The integration of pinch technology with Heat Exchanger Network (HEN) design allows simultaneous optimization of energy efficiency and heat exchanger investment costs, thereby minimizing the total annual cost (Kravanja & Glavič, 1997; Liu et al., 2020; Wang et al., 2024). Although this method has

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been widely applied in various energy-intensive and ethylene oxide–based industrial processes, studies on heat integration at the pre-design stage of ethanolamine plants remain limited. Therefore, this study focuses on identifying heat recovery potential, determining the optimal $\Delta T_{min}$, and designing an energy- and cost-efficient HEN.

## 2. Methods

### 2.1 *Description of the Ethanolamine Production Process*

The Process Flow Diagram (PFD) shown in Figure 1 represents the ethanolamine production process from ethylene oxide and ammonia, which includes feed heating, reaction, product cooling, and multistage separation using distillation columns, in accordance with industrial ethanolamine process configurations (Seider et al., 2017; Jones et al., 2004; Ernst et al., 2022; Wang et al., 2024). Hot and cold streams were identified directly from temperature changes in the heater and cooler units shown in the PFD (Figure 1). Streams experiencing temperature increases were classified as cold streams, while streams undergoing temperature decreases were classified as hot streams, following the definitions used in pinch analysis (Linnhoff et al., 1982; Xu et al., 2022; Zhi et al., 2024).

### 2.2 *Data Extraction*

Data for heat integration analysis was extracted from the PFD shown in Figure 1. The parameters considered include mass flow rate, heat capacity flow rate ($Cp$), inlet temperature ($T_{in}$), and outlet temperature ($T_{out}$) for each stream experiencing temperature changes in Heater-1 (Stream 3), Heater-2 (Stream 7), and the Cooler (Stream 18), as indicated in the PFD and summarized in Table 1, consistent with systematic data preparation procedures in pinch-based process studies (Xu et al., 2022; Zhi et al., 2024).

Hot and cold stream classification was performed by tracing the function of heating and cooling units in the PFD based on pinch analysis principles, without modifying the existing process configuration (Linnhoff et al., 1982; Fu et al., 2021).

### 2.3 *Pinch Analysis Method*

Pinch analysis was conducted using the stream data presented in Table 1, which were developed from mass and energy balance calculations and directly linked to the PFD in Figure 1 as a representation of the process system (Linnhoff et al., 1982; Towler & Sinnott, 2021; Fu et al., 2021). The minimum temperature difference ($\Delta T_{min}$) was used as a key parameter to represent the trade-off between internal heat recovery potential and heat exchanger investment cost (Fu et al., 2021; Padullés et al., 2025).

The Problem Table was constructed using stream temperature and $Cp$ data to determine temperature intervals, net heat balance, and minimum utility targets for the system (Linnhoff et al., 1982; Ghorbani et al., 2020). Composite Curves and the Grand Composite Curve were developed from the same dataset to represent the cumulative profiles of hot and cold streams and to determine heating and cooling utility requirements at different temperature levels, following the pinch technology methodology (Linnhoff et al., 1982; Tan et al., 2014; Radhi et al., 2025; Zhi et al., 2024).

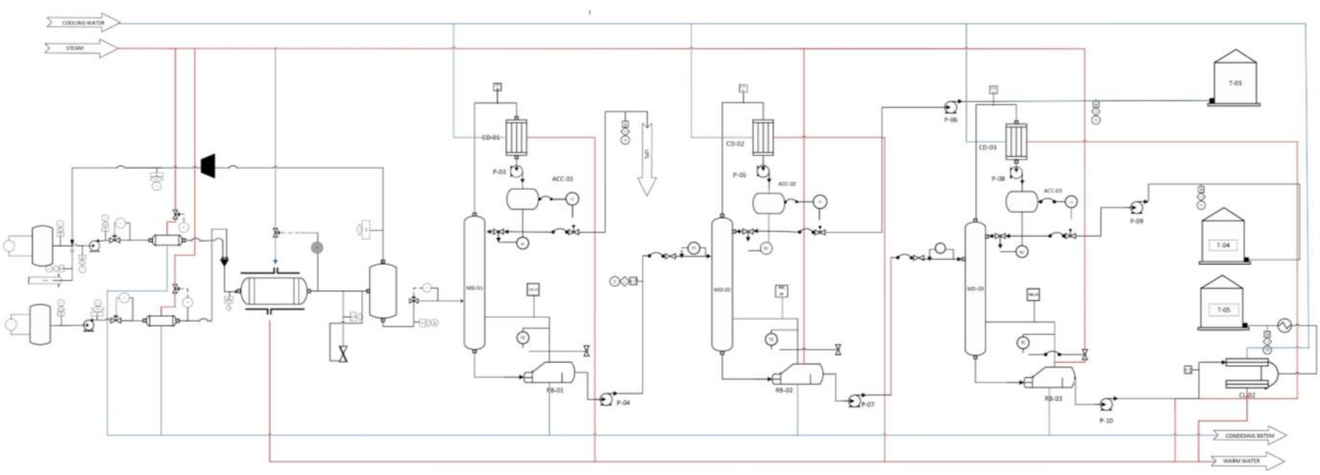

Figure 1. Process flow diagram ethanolamine production plant.

Table 1. Stream data for heat integration analysis.

| Stream | Stream Type | Mass Flow (kg/h) | $Cp$ mean (kW/K) | $T_{in}$ (°C) | $T_{out}$ (°C) | $\Delta T$ (°C) |
|---|---|---|---|---|---|---|
| 3 | Cold | 11,340.98 | 26,791.60 | 30 | 50 | +20 |
| 7 | Cold | 2,847.76 | 2,316.93 | 30 | 50 | +20 |
| 18 | Hot | 1,897.24 | 1,495.46 | 318.84 | 30 | −288.84 |

### 2.4 Heat Exchanger Network (HEN) Design

The HEN configuration was developed conceptually based on the arrangement of unit operations in the PFD (Figure 1) and the hot and cold stream data listed in Table 1, with the objective of maximizing internal heat recovery without altering the existing process structure (Towler & Sinnott, 2021; Zhi et al., 2024). Heat duties for each stream pair and heat exchanger area estimations were calculated using $T_{in}$, $T_{out}$, and $Cp$ data. The number of heat exchangers was determined by meeting minimum energy targets while complying with pinch constraints and the resulting network configuration (Seider et al., 2017; Kravanja & Glavič, 1997; Zhi et al., 2024).

## 3. Results and Discussion

### 3.1 Impact of Pinch Analysis on Process Energy Requirements

Based on Table 2 and Figure 2, pinch analysis substantially reduces external utility requirements in the ethanolamine plant. The heating load decreases from 540,452 kW to 123,347 kW (−77.2%), indicating that most cold-stream heating is satisfied through internal heat recovery. Concurrently, the cooling load is reduced from 525,502 kW to 14,950 kW (−97.2%), leaving only the thermodynamically unavoidable minimum below the pinch point. Composite curve and problem table results show that these reductions are achieved by cascading sensible heat from high-temperature hot streams, including reactor effluent, enabling a recovered energy of 510,552 kW. The heat cascade identifies a net heat deficit of 387,205 kW at high temperature levels (589–330 K), followed by downward redistribution of excess process heat to the pinch point at approximately 310 K, below which residual heat must be rejected as cold utility. These results confirm that the process is heat-rich and that the obtained utility targets represent the thermodynamic minimum for the selected $\Delta T_{min}$, demonstrating the effectiveness of pinch-based heat integration for energy optimization of the ethanolamine process (Fu et al., 2021; Ghorbani et al., 2020).

### 3.2 Pinch Point Analysis and Energy Load Distribution

Figure 3 shows the composite curves for the ethanolamine process. The composite curves represent the cumulative heat availability of the hot streams (red curve) and the cumulative heat demand of the cold streams (blue curve) as functions of temperature. The hot composite curve exhibits a steep slope over a wide temperature range, indicating a large release of thermal energy primarily originating from the ethanolamine reactor and hot process streams prior to distillation. In contrast, the cold composite curve shows a relatively shallow slope, reflecting a comparatively lower heating demand dominated by reactor feed preheating and distillation inlet streams. The substantial horizontal overlap between the two curves confirms a strong potential for internal heat recovery, demonstrating that the ethanolamine process is intrinsically heat-rich and well suited for pinch-based heat integration.

The minimum vertical temperature separation between the curves corresponds to the selected $\Delta T_{min}$ and defines a pinch point located at approximately 305–315 K, which divides the system into regions above and below the pinch. Above the pinch, the process is constrained by a net heat deficit, resulting in a minimum hot utility requirement of approximately 123,347 kW, while below the pinch the process exhibits excess heat that must be rejected through cold utilities amounting to about 14,950 kW. The Grand Composite

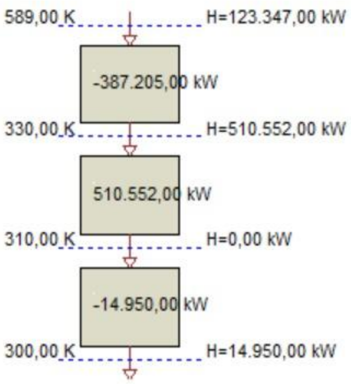


Figure 2. Heat cascade diagram of the ethanolamine process.

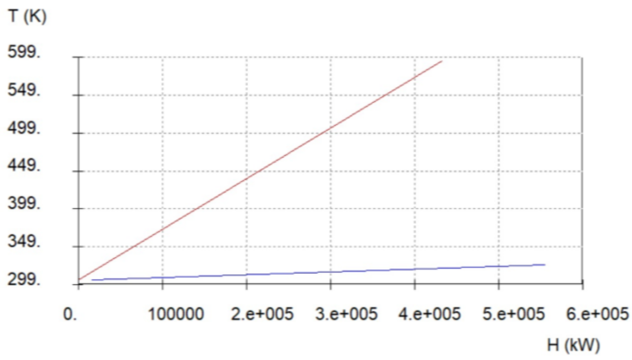


Figure 3. Composite curves for the ethanolamine process.

Table 2. Comparison of energy requirements before and after pinch analysis.

| Energy Parameter | Before Pinch Analysis (kW) | After Pinch Analysis (kW) | Change |
|---|---|---|---|
| Heating load (Hot utility) | 540,452 | 123,347 | ↓ 417,105 (−77.2%) |
| Cooling load (Cold utility) | 525,502 | 14,950 | ↓ 510,552 (−97.2%) |
| Recovered energy (MER) | 0 | 510,552 | ↑ 510,552 |

Curve confirms that no heat transfer across the pinch is required in the target design, indicating full compliance with pinch rules and thermodynamic optimality. This distribution directly correlates the dominant heat release from the reactor section with the reduced external utility demand and confirms that further reductions in hot or cold utilities are thermodynamically infeasible without decreasing $\Delta T_{min}$ or altering process operating temperatures.

### 3.3 *Maximum Energy Recovery (MER) and Process Significance*

The Maximum Energy Recovery (MER) achieved is ≈510,552 kW, representing the amount of heat internally exchanged between hot and cold streams. The dominant contributor to MER is the reactor outlet stream (hot stream, ≈432,055 kW), while the main beneficiaries are the large cold streams upstream of reaction and separation, particularly the primary feed stream with a heating demand of ≈535,832 kW. The magnitude of MER relative to total process heat duties confirms that the ethanolamine process is highly suitable for heat integration (Riyanto et al., 2019).

### 3.4 *Evaluation of the Heat Exchanger Network (HEN)*

Figure 4 shows the heat exchanger network (HEN) grid diagram for ethanolamine plant after pinch analysis at $\Delta T_{min}$ of 10 K. The Heat Exchanger Network synthesized using HINT meets the minimum energy targets predicted by pinch analysis. Internal heat exchange significantly reduces reliance on external heaters, limiting hot utility use to the pinch-constrained minimum. Similarly, the number and duty of coolers are minimized, with cooling demand concentrated below the pinch. The resulting HEN respects thermodynamic constraints, avoids cross-pinch heat transfer, and operates within feasible temperature approaches, consistent with current HEN synthesis practices (Riyanto et al., 2019; Zhi et al., 2024).

### 3.5 *Technical and Economic Implications for Ethanolamine Plant Pre-Design*

From a technical perspective, heat integration reduces the specific energy consumption of the

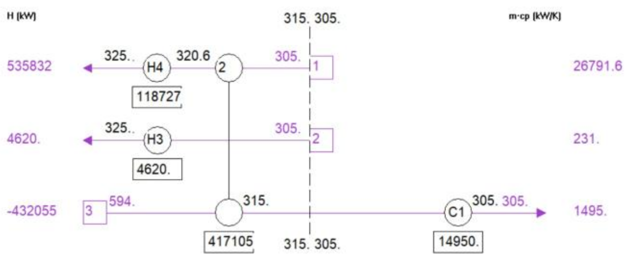


Figure 4. Heat Exchanger Network (HEN) grid diagram for ethanolamine plant after pinch analysis ($\Delta T_{min}$ = 10 K).

ethanolamine plant by reallocating more than 500 MW of process heat internally (Padullés et al., 2025). Economically, the reduction of hot and cold utility duties directly translates into lower operating costs for steam and cooling utilities. At the pre-design stage, these results demonstrate that pinch technology provides a robust quantitative basis for early design decisions, particularly in selecting utility systems, defining energy targets, and justifying the inclusion of integrated heat recovery in the ethanolamine production process (Radhi et al., 2025).

## 4. Conclusions

Pinch analysis effectively reduced hot and cold utility demands in the ethanolamine plant by maximizing internal heat recovery from reactor and separation streams. The identified pinch point governed a thermodynamically consistent energy distribution, while the achieved MER confirmed significant potential for internal heat utilization. The resulting HEN satisfies minimum energy targets and operational constraints, demonstrating that heat integration substantially improves energy efficiency at the pre-design stage. Further work should extend the analysis to include detailed economic optimization of $\Delta T_{min}$ and exchanger sizing, as well as dynamic and controllability considerations for the integrated network. Incorporating utility system integration and evaluating alternative separation configurations may yield additional energy savings.

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