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Research Article

## Heat Integration Analysis of the Pre-Design Stage of an Ethyl Acetate Production Process using Pinch Technology

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### Abstract

Industrial heat exchanger networks often exhibit suboptimal energy utilization because of limited heat integration between process streams. This study aims to optimize a heat exchanger network (HEN) through the application of pinch analysis based on the initial process flowsheet. Hot and cold stream data, including inlet temperature, outlet temperature, and heat load, were first analyzed using Microsoft Excel and subsequently processed using the Heat Integration Network Tool (HINT). Pinch analysis was conducted by constructing composite curves to identify the pinch point, which represents the thermodynamic constraints of the system. Based on the analysis results, a redesigned heat exchanger network was developed in accordance with pinch principles, namely, the elimination of heat transfer across the pinch and the enhancement of internal heat recovery. The results demonstrate that the application of pinch analysis leads to a more efficient heat exchanger network configuration and reduces the reliance on external heating and cooling utilities compared with the initial system.

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### 1. Introduction

Ethyl acetate is an ester compound that is widely used in various industrial sectors, including as a solvent in the paint, ink, adhesive, and pharmaceutical industries, as well as an intermediate raw material in the chemical industry. The continuously increasing demand for ethyl acetate encourages the development of production processes that are not only oriented toward capacity but also toward energy efficiency and process sustainability. One commonly used route for ethyl acetate production is the esterification reaction between acetic acid and ethanol, which is operated under specific temperature and pressure conditions and involves various unit operations with significant energy requirements (Phasha et al., 2025).

In ethyl acetate production processes, heat transfer occurs intensively both among process streams and between process streams and utilities. Several unit operations, such as reactors, distillation columns, and heat exchangers, require a substantial supply of thermal energy, while other units generate heat that

has the potential to be recovered. Under existing conditions, heat utilization among process streams is often not optimal, resulting in high demands for heating and cooling utilities. Therefore, a systematic approach is required to improve energy efficiency through the maximization of internal heat recovery (Díaz and Willis, 2022; Šulgan et al., 2021).

Efforts to improve energy efficiency in process systems can be achieved by developing an integrated heat exchanger network (Abbate et al., 2023). To attain maximum energy recovery or minimum utility requirements, an analytical method capable of comprehensively evaluating the thermodynamic constraints of the system is required. One of the most widely used methods for this purpose is pinch analysis (Medina et al., 2024). Pinch analysis is an approach based on the first and second laws of thermodynamics that is used to determine heat exchanger network configurations with minimum energy consumption through the identification of the pinch point and heat transfer constraints among process streams (Muharja et al., 2023).

Pinch analysis enables the identification of hot and

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cold streams that have the potential to exchange energy, as well as the determination of the minimum allowable temperature difference ( $\Delta T_{min}$ ) in heat exchangers (Babaqi and Takriff, 2022). Through this approach, heat is only allowed to flow from higher to lower temperatures without violating the thermodynamic limits of the system. The concept of the pinch point serves as a critical boundary that governs the distribution of heating and cooling, thereby preventing heat transfer across the pinch (Kemp, 2007). The application of this principle can enhance process-to-process heat recovery and reduce dependence on external utilities (Febriana and Widodo, 2019).

With the advancement of computational technology, pinch analysis can be performed more rapidly and systematically using specialized software, one of which is the Heat Integration Network Tool (HINT). This software enables the construction of composite curves, determination of the pinch point, and redesign of heat exchanger networks based on heat integration principles. Consequently, pinch analysis can be effectively applied to complex process systems, including at the chemical plant pre-design stage (Isah et al., 2020; Tibasiima and Okullo, 2017).

Based on this background, this article aims to conduct pinch analysis on the heat exchanger network in the pre-design stage of an ethyl acetate plant produced from acetic acid and ethanol with a capacity of 25,000 tons per year (Pratama and Akbar, 2022). The analysis is carried out based on the initial process flowsheet to identify heat recovery potential and to redesign a more energy-efficient heat exchanger network. The results of this analysis are expected to serve as a basis for design decision-making related to heat integration and to support the development of a more energy-efficient and sustainable plant design (Muharja et al., 2023).

## 2. Materials and Methods

Process stream data and the flowsheet required for pinch analysis were obtained from the design and simulation results of the heat exchanger system prior to energy integration optimization (Gao et al., 2022). The initial flowsheet represents the existing condition of the heat exchanger network, in which heat utilization among process streams has not been optimized and external heating and cooling utilities are still required. This system was subsequently analyzed

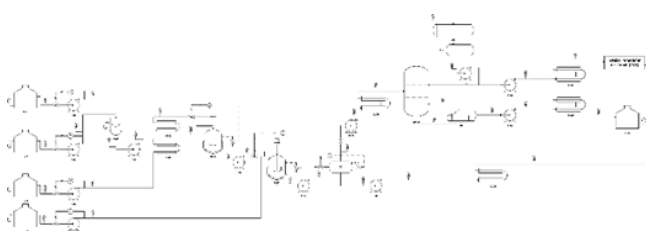


Figure 1. Process flow diagram before pinch analysis.

using the pinch method to identify internal heat recovery potential and to determine a more thermodynamically efficient heat exchanger network configuration (Wu et al., 2021).

Pinch analysis was conducted based on hot and cold stream data obtained from the system energy balance (Zhao et al., 2022). The data used included inlet temperature ( $T_s$ ), outlet temperature ( $T_i$ ), and heat duty of each process stream (Oliveira and Borges, 2024). All of these data were extracted from the initial flowsheet and used as the basis for calculations and heat integration analysis.

To perform pinch analysis on the heat exchanger network system, the following steps were carried out:

1. A process flow diagram was developed to illustrate the relationships among heat exchanger units and the energy flow within the system prior to optimization (Figure 1).
2. Process stream data, including inlet temperature ( $T_s$ ), outlet temperature ( $T_i$ ), and heat duty of each stream, were determined based on the results of energy balance calculations.
3. The heat requirement or heat transfer potential ( $Q$ ) of each hot and cold stream was calculated based on the corresponding temperature changes.
4. The calculated data were subsequently analyzed using the Heat Integration Network Tool (HINT) software to construct composite curves, determine the pinch point, and redesign the heat exchanger network according to pinch principles:
  - a. The required heat duty is calculated using equation (1).

$$Q = m \times C_{p_{mean}} \times \Delta T \quad (1)$$

Where  $m$  is the molar flow rate (mol/s),  $C_{p_{mean}}$  is the average heat capacity of the stream (kW/mol.K), and  $\Delta T$  is the temperature difference (K).

- b. The heat exchanger area is calculated using equation (2).

$$A = \frac{Q}{U \times \Delta T_{LMTD}} \quad (2)$$

Where  $A$  is the heat exchanger area ( $m^2$ ),  $Q$  is the heat duty (kW),  $U$  is the overall heat transfer coefficient (kW/ $m^2 \cdot K$ ), and  $\Delta T_{LMTD}$  is the log mean temperature difference (K).

- c. The installed heat exchanger cost is calculated using equation (3).

$$total\ cost = a + bA^c \quad (3)$$

Where total cost represents the cost required for the installed heat exchangers;  $a$ ,  $b$ , and  $c$  are conversion constants whose values depend on the type of heat exchanger used. In this case, a shell-and-tube heat exchanger is employed, with  $a = 4600$ ,  $b = 920$ , and  $c = 0.7$ , while  $A$  represents

the heat exchanger surface area ( $m^2$ ).

d. Techno-economic analysis

Pinch analysis involves a systematic approach to identify the potential Maximum Energy Recovery from counter-current heat transfer within a process. In addition, pinch analysis can assist in identifying utility requirements during the detailed design of the Heat Exchanger Network. With these practical objectives, pinch analysis can be further developed for HEN design with the aim of minimizing the total cost.

Through this analysis, an optimized heat exchanger network was obtained that satisfies pinch thermodynamic constraints, namely the absence of heat transfer across the pinch point and enhanced heat utilization among process streams.

### 3. Results and Discussion

At the initial stage of the analysis, a process flow diagram was developed to illustrate the configuration of unit operations and the position of heat exchangers

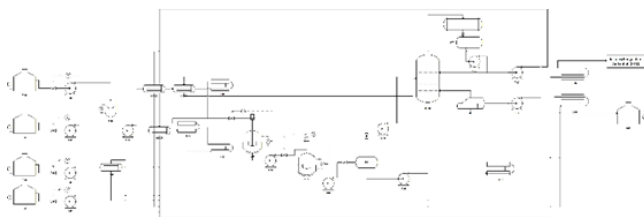


Figure 2. Process flow diagram after pinch analysis.

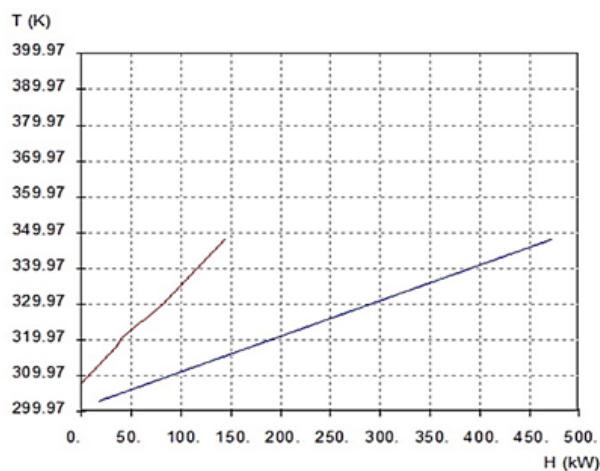


Figure 3. Composite curves of the ethyl acetate production system ( $\Delta T_{min} = 10$  K).

after the application of pinch analysis with a  $\Delta T_{min}$  of 10 K. This flow diagram shows the relationships among process units, hot and cold streams, and heat integration between process streams without excessive involvement of external utilities.

This flow diagram serves as the basis for stream numbering, extraction of thermal data, and interpretation of the resulting heat exchanger network. Based on the process flow diagram shown in Figure 2, four hot streams and three cold streams were identified as contributing to heat transfer within the system. Supply temperature ( $T_s$ ), target temperature ( $T_t$ ), heat capacity flow rate ( $m \cdot Cp$ ), and heat duty of each stream were extracted from the HINT simulation results. Notably, the cold stream requirements were split to accurately reflect the heating demand, resulting in a significantly higher total cold duty compared to the initial analysis.

The hot and cold composite curves were constructed using the data presented in Table 1. with a  $\Delta T_{min}$  of 10 K. These curves illustrate the relationship between temperature and cumulative heat load within the system.

The analysis results indicate that the pinch point occurs at a temperature of 313 K, which represents the thermodynamic boundary for heat integration. At this point, the minimum distance between the hot and cold curves is equal to the specified  $\Delta T_{min}$  and therefore heat transfer across the pinch is not permitted.

The presence of a single pinch point indicates that the system has a clearly defined heat integration constraint, and the design of the heat exchanger network must comply with pinch rules (Wang et al., 2024).

Based on the composite curves shown in Figure 3 and Table 2, a Maximum Energy Recovery (MER) value of 126.96 kW was obtained. This energy is utilized to meet a portion of the heating requirements of the cold streams. However, due to the total cold stream demand significantly exceeding the available hot stream load, the system is thermodynamically limited and cannot completely eliminate external heating. Consequently, an external heating load of 327.57 kW is still required. Meanwhile, the external cooling load was successfully minimized to 16.94 kW.

The heat exchanger network was designed based on pinch rules, ensuring no heat transfer across the pinch point. The resulting heat exchanger network

Table 1. Hot and cold stream data for pinch analysis ( $\Delta T_{min} = 10$  K).

No	Stream Type	$T_s$ (K)	$T_t$ (K)	$\Delta T$ (K)	$m \cdot Cp$ (kW/K)	Heat Load, $Q$ (kW)
1	Hot	348	320.5	27.5	1.7847	-49.08
2	Hot	348	308	40	1.6435	-65.74
3	Hot	317.9	308	9.9	0.7588	-7.51
4	Hot	329.9	308	21.9	0.9850	-21.57
5	Cold	303	348	45	1.6478	74.15
6	Cold	303	348	45	1.6905	76.07
7	Cold	303	348	45	6.7623	304.30

configuration consists of 10 heat exchanger units, including process-to-process heat exchangers, external heaters, and one external cooler (Table 3).

The HEN diagram shows that most of the heating demand of the cold streams is supplied by waste heat from the hot process streams, leading to a significant improvement in system energy efficiency.

Based on the HEN configuration shown in Figure 4, the total heat exchanger area was calculated to be 10.20 m<sup>2</sup>, with a total investment cost of USD 228,100. This cost reflects the installation of the necessary heat exchangers to achieve the targeted energy recovery.

A comparison of the conditions before and after the application of pinch analysis demonstrates that heat integration significantly improves the system's energy profile (Table 4). While the external heating load could not be completely eliminated due to the high thermal demand of the cold streams, it was successfully reduced from 454.53 kW to 327.57 kW. Conversely, the external cooling load was substantially minimized, dropping from 143.90 kW to 16.94 kW, which indicates a high degree of effective heat recovery.

#### 4. Conclusion

The application of pinch analysis at the pre-design stage of ethyl acetate production from acetic acid and ethanol has proven to be effective in improving the overall energy efficiency of the system. Based on composite curve analysis with a  $\Delta T_{min}$  of 10 K, a single

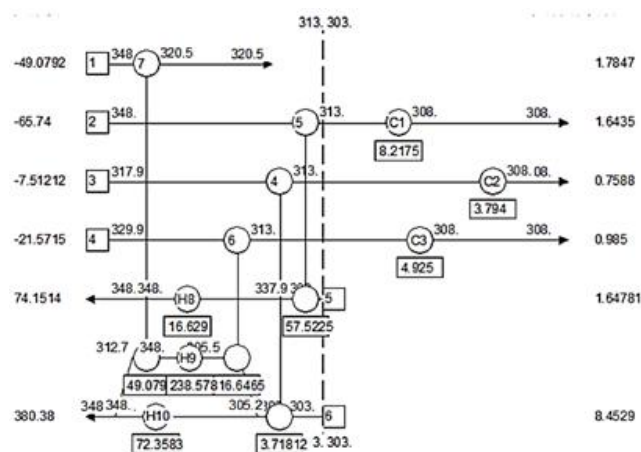


Figure 4. Heat exchanger network of the ethyl acetate production process at  $\Delta T_{min}$  of 10 K.

Table 2. Summary of system energy evaluation at  $\Delta T_{min}$  of 10 K.

Parameter	Value
$\Delta T_{min}$ (K)	10
Pinch Point (K)	313
Total hot stream load (kW)	143.90
Total cold stream heat demand (kW)	454.53
Maximum Energy Recovery (MER) (kW)	126.96
External heating load (kW)	327.56
External cooling load (kW)	16.94

pinch point was identified as the thermodynamic boundary for heat integration, with a Maximum Energy Recovery (MER) potential of 126.96 kW. Although the total elimination of external heating was not thermodynamically feasible due to the significant heat deficit of the cold streams, the design successfully reduced the heating utility requirement to 327.57 kW. Furthermore, the heat integration strategy resulted in a substantial minimization of the cooling load to 16.94 kW. The redesign of the heat exchanger network, consisting of 10 units with a total investment cost of USD 228,100, satisfies thermodynamic constraints and significantly enhances internal heat utilization. These results confirm that heat integration using pinch technology is a feasible and valuable approach for optimizing energy consumption and supporting sustainable process design in the early stages of plant development.

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Table 3. Evaluation of the heat exchanger network at  $\Delta T_{min}$  of 10 K.

Parameter	Value
Number of heat exchanger	10 unit
Heat Exchanger type	Shell and Tube
Total heat exchanger area (m <sup>2</sup> )	10.2
Overall heat transfer coefficient (kW/m <sup>2</sup> ·K)	1
Total installed heat exchanger cost (\$)	228,100
Process-to-process heat transfer (kW)	126.96
Utility heating load (kW)	327.56
Utility cooling load (kW)	16.94

Table 4. Comparison of energy performance before and after pinch analysis.

Parameter	Before Heat Integration	After Pinch Analysis
Heating load (kW)	454.53	327.57
Cooling load (kW)	143.90	16.94
Maximum energy recovery (kW)	-	126.96
Number of HE	-	10
HE investment cost (\$)	-	228,100

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