Journal of Vocational Studies on Applied Research, 7 (2), 2025, 52–58

Contents lists available at JVSAR website

Journal of Vocational Studies on Applied Research

Journal homepage: https://ejournal2.undip.ac.id/index.php/jvsar

Research Article

Energy Efficiency Analysis Using Pinch Technology in the Preliminary Design of a Nitromethane Plant from Nitric Acid and Methane

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Abstract

The production process of nitromethane through vapor phase nitration reaction between nitric acid and methane is a highly energy-intensive process requiring heating at high temperatures up to 653 K. The significant dependence on external utilities results in high operational costs and carbon emissions, necessitating energy system optimization to enhance efficiency and product competitiveness. This study aims to analyze energy efficiency in the preliminary design of a 25,000 tons per year nitromethane plant using pinch technology to determine minimum energy requirements and design an optimal Heat Exchanger Network. The pinch analysis method was applied by extracting process stream data including mass flow rate, heat capacity, inlet and outlet temperatures from four main heat exchanger units. The analysis was conducted using problem table, composite curve, and grid diagram with a ΔTmin value of 10 K. The analysis results show that the system requires a minimum hot utility of 798.418 kW and cold utility of 1,925.67 kW with a pinch temperature at 308 K. The optimal Heat Exchanger Network configuration successfully reduced the furnace load to 313.303 kW through internal heat integration, utilizing sensible heat from high-temperature reactor products for feed preheating. The implementation of pinch technology in this system has the potential to generate significant energy savings compared to conventional design, while contributing to CO_2 emission reduction and enhancing sustainability of chemical industrial processes.

Article history:
Received: 29th December 2025
Revised: 31st December 2025
Accepted: 31st December 2025
Available online: 31st December 2025
Published: 31st December 2025

Keywords:
Pinch Technology
Energy Efficiency
Nitromethane
Heat Exchanger Network
Heat Integration

Permalink/DOI: http://doi.org/10.14710/jvsar.v7i2.30763

1. Introduction

Nitromethane is a chemical derivative that plays a strategic role as a raw material in the manufacture of pesticides, industrial solvents, fibers, and fuel additives. With the increasing industrial demand in Indonesia, dependence on nitromethane imports needs to be minimized through the design of efficient domestic factories. Nitromethane is produced commercially by high-temperature vapor-phase nitration of alkanes using nitric acid as the nitrating agent, based on a free-radical reaction mechanism (Albright et al., 1996). However, the production process of nitromethane through vapor phase nitration between nitric acid and methane requires operating conditions at temperatures between 370-450 °C, which results in high heat energy consumption and significant cooling utility requirements.

In the context of a global energy crisis marked by fuel price fluctuations, energy efficiency has become a key component in reducing operational costs and ensuring that produced products remain highly competitive. The application of heat integration is urgently needed to improve energy efficiency and reduce operating costs in processes involving large thermal loads. One of the methodologies commonly used to analyze energy utilization in a chemical process is Pinch Technology. Developed in the late 1970s by Bodo Linnhoff and colleagues at the University of Leeds, this technology enables designers to determine minimum energy targets, maximize heat recovery, and design optimal heat exchanger networks through thermodynamically feasible energy targeting (Linnhoff & Ahmad, 1990). The fundamental principle

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of pinch analysis involves constructing composite curves for hot and cold streams, identifying the pinch point where these curves have the closest approach, and designing heat exchanger networks that respect the pinch point constraints.

Energy efficiency through heat integration can be achieved by optimizing the ΔTmin value, where the selection of this value will affect the balance between utility costs and the capital costs of heat exchanger equipment. The optimal minimum temperature difference (ΔTmin) represents a critical trade-off between energy costs and capital investment, as smaller temperature differences increase heat recovery but require larger heat exchanger areas, while larger temperature differences reduce capital costs but increase utility consumption (Bakar et al., 2016). Previous studies have demonstrated that systematic targeting procedures can identify the optimal ΔTmin value that minimizes total annual costs by balancing these competing factors.

Research on the preliminary design of nitromethane plants has been conducted, but most studies have focused on capacity selection, reactor optimization, and corporate management aspects (Rahmi & Siregar, 2023). Although the technical aspects of the process have been described, an in-depth evaluation of the heat exchanger network using the pinch technology approach in nitromethane production units has not been widely conducted. The application of pinch technology has proven highly effective in various chemical process industries for reducing energy consumption and improving process economics through optimized heat integration (Kemp, 2007). However, limited studies exist related to determining minimum energy targets and ΔTmin optimization specifically for the vapor phase nitromethane process stream.

Therefore, this study focuses on pinch analysis in the preliminary design of a 25,000 tons/year nitromethane plant to identify potential energy savings. The objectives of this study are to determine the optimal ΔTmin value, calculate the minimum heating and cooling loads, and design a heat exchanger network that can minimize external utility energy consumption. By applying established pinch analysis methodologies to the specific context of nitromethane production, this research aims to contribute to the development of more energy-efficient chemical manufacturing processes in Indonesia.

2. Methods

2.1 *Nitromethane Production Process*

Nitromethane is produced through the vapor-phase nitration reaction of methane using nitric acid as the nitrating agent, based on free-radical reaction mechanisms where NO_2 and OH radicals react with alkanes at temperatures of 380-420 °C (Albright et al., 1996). This process takes place in the gas phase under specific temperature and pressure conditions to produce nitromethane as the main product along with other nitroparaffins such as nitroethane, 1-nitropropane, and 2-nitropropane as by-products. In this preliminary design, the production process is designed to be continuous with a capacity of 25,000 tons per year.

The process flow diagram illustrates the main stages, which include preheating and mixing the raw materials, the nitration reaction in the reactor, rapid cooling of the reaction product to prevent further decomposition, and the separation and purification stages of nitromethane to meet product specifications. The main raw materials used are high-purity methane (>99.5% purity) and concentrated nitric acid (60-70 wt%) as the nitrating agent. The selection of operating conditions and process configuration is based on literature data, thermodynamic considerations, reaction kinetics, and principles of inherent process safety to minimize hazards associated with handling reactive materials at elevated temperatures (Khan & Amyotte, 2019). The purification stage is designed to separate nitromethane from the remaining unreacted methane, residual nitric acid, water formed during the reaction, and by-product nitroparaffins through a series of condensation, liquid-liquid separation, and distillation units. Extractive distillation has become an important separation method in chemical engineering, particularly for separating close-boiling-point or azeotropic mixtures by introducing a high-boiling-point separating agent to increase relative volatility (Lei et al., 2003). The distillation sequence and column configurations are optimized to obtain a product with a purity of at least 95 wt%, which is suitable for industrial applications as a chemical intermediate, solvent, and fuel additive.

2.2 *Data Extraction*

Data extraction is performed to obtain the parameters required for heat integration analysis in process systems. The data collected includes mass flow rate, heat capacity of the flow (CP), inlet temperature (supply temperature), and outlet temperature (target temperature) of each process stream involved in the reaction, cooling, and separation stages. Data extraction is a crucial part of any pinch analysis as it translates flow-sheet information into relevant thermal and cost parameters that are essential for accurate energy targeting (Kemp, 2007).

Process streams are classified into two groups, namely hot streams and cold streams. Hot streams are streams that require cooling to reach the target temperature and release heat to the surroundings, while cold streams are streams that require heating to reach the desired operating temperature and absorb heat from external sources or other process streams.

This stream data is used as the basis for calculating energy requirements, constructing composite curves, and preparing pinch analysis. The extraction of accurate stream data, including the consideration of phase changes and variable heat capacities, is essential for determining realistic minimum energy requirements and optimal heat exchanger network configurations (Furman & Sahinidis, 2002).

2.3 *Pinch Analysis and Heat Exchanger Network Design*

Heat integration analysis was performed using the pinch technology method to determine the minimum energy requirements and design an optimal heat exchanger network (HEN). Pinch technology provides a systematic methodology for achieving maximum energy recovery from process-to-process heat exchange before resorting to external utilities (Linnhoff & Hindmarsh, 1983). Several tools used in this analysis included the problem table algorithm for energy targeting, composite curves to visualize hot and cold stream profiles, grand composite curves for multiple utility placement, and grid diagrams for HEN design representation.

The basic principles of pinch analysis were applied rigorously, including three fundamental design rules: (1) not transferring heat across the pinch point, as this would increase both heating and cooling utility requirements; (2) not using cooling utilities above the pinch, where the process has a heat deficit; and (3) not using heating utilities below the pinch, where the process has a heat surplus (Linnhoff & Ahmad, 1990). These golden rules ensure that the designed network achieves the minimum utility consumption targets established during the targeting phase.

The design of the heat exchanger network was carried out by considering both technical and economic constraints simultaneously. Technical constraints were determined by energy balance equations, the laws of thermodynamics (particularly the second law regarding temperature driving forces), and heat transfer feasibility criteria. Economic constraints were related to the heat exchanger area requirements, capital costs of equipment, piping costs, and system operating costs. The trade-off between energy costs and capital investment represents a fundamental challenge in HEN synthesis, as reducing utility consumption through increased heat recovery requires larger heat transfer areas and thus higher capital investment (Pavão et al., 2017).

The heat exchanger surface area was calculated based on the heat load (Q), overall heat transfer coefficient (U), and logarithmic mean temperature difference (LMTD) using the fundamental heat transfer equation Q = U × A × LMTD. The capital cost of heat exchangers was estimated as a function of the heat exchanger surface area using cost correlations from literature, typically in the form C = a + b × An, where 'a' and 'b' are cost coefficients and 'n' is an exponent typically ranging from 0.6 to 0.8 depending on the heat exchanger type. The utility cost was determined based on heating and cooling requirements multiplied by the respective unit costs of hot and cold utilities. Total annual cost (TAC) was calculated as the sum of annualized capital costs and annual operating costs.

Variations in the minimum temperature difference (ΔTmin) were systematically evaluated to determine its effect on energy requirements, heat recovery potential, and total system cost. A smaller ΔTmin results in greater process-to-process heat recovery and lower utility consumption but requires larger heat exchanger areas and consequently higher capital investment. Conversely, a larger ΔTmin reduces capital costs but increases utility consumption and operating costs. The optimal ΔTmin is identified at the point where the total annual cost reaches its minimum value, representing the best economic balance between capital expenditure and operating expenses (Yee & Grossmann, 1990).

3. Results and Discussions

3.1 *Mass Balance Analysis and Process Configuration*

Based on the mass balance data in Table 1, the nitromethane process system involves four main heat exchangers with different thermal characteristics. The vaporizer operates at a mass flow rate of 14.749.48 kg/h and an average heat capacity of 1,182.93 kW/K, heating the feed from 309 K to 442 K. The first heat exchanger handles a flow with a mass flow of 11,761.533 kg/h and a mean Cp of 629.56768 kW/K in the temperature range of 442 K to 653 K, indicating a significant need for high-level heating. The furnace is the unit with the highest thermal load, processing 5,523.9537 kg/h with a mean Cp of 1,514.86 kW/K from 303 K to 653 K, indicating an intensive endothermic process. Meanwhile, the second Heat Exchanger functions as a heat source by cooling the

Table 1. Mass balance calculation results.

Flow	Flow Number	Flow Type	Mass Flow (kg/hr)	Cp mean (kW/K)	T in (K)	T out (K)
Vaporizer	2	Cold	14749.48	1.182.93	309	442
Heat Exchanger	5	Cold	11761.533	629.5676868	442	653
Furnace	7	Cold	5523.9537	1514.862981	303	653
Heat Exchanger	13	Hot	11342.631	385.1341049	370	308

heat flow from 370 K to 308 K with a capacity of 385.13 kW/K. This configuration is in line with Kemp's (2007) research, which states that accurate identification of heat and cold flow characteristics is a fundamental step in pinch analysis.

The process flow diagram presented shows a significant transformation between the configurations before and after energy analysis (Figure 1). In the initial configuration, the system relied entirely on external utilities to meet the heating and cooling needs of each operating unit separately, which is a conventional but energy-inefficient practice. After the implementation of pinch analysis, the flow diagram shows the integration of a Heat Exchanger Network (HEN) that enables direct heat transfer between process streams, reducing dependence on external utilities (Figure 2). This change is consistent with the basic principles of pinch technology, which emphasizes maximizing internal heat recovery before using external utilities (Smith, 2016). Research by Klemeš et al. (2010) shows that this type of process integration can reduce energy consumption by 30-50% in the chemical industry.

3.2 *Energy Analysis and Minimum Energy Requirement*

The pinch analysis results show that the system requires a minimum hot utility of 798.418 kW and a cold utility of 1,925.67 kW, with a pinch temperature occurring at 308 K. The highly disproportionate ratio between heating and cooling requirements (approximately 414:1) indicates that the nitromethane production process is highly endothermic, consistent with the characteristics of the nitration reaction, which

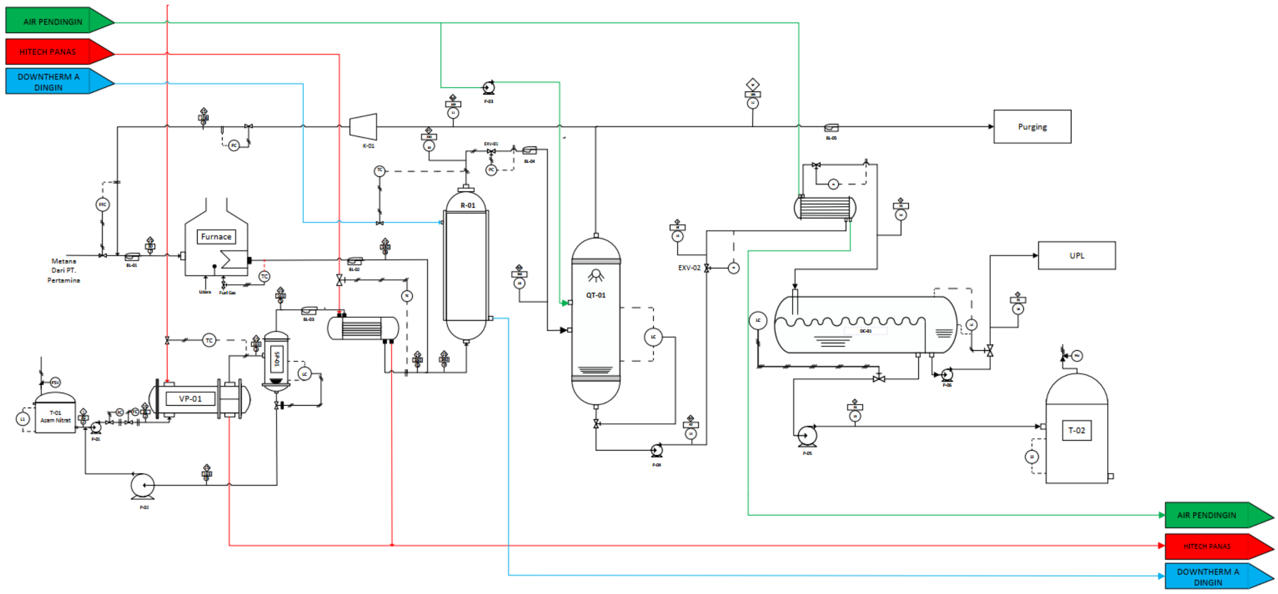

Figure 1. Flow diagram of the nitromethane process before energy analysis.

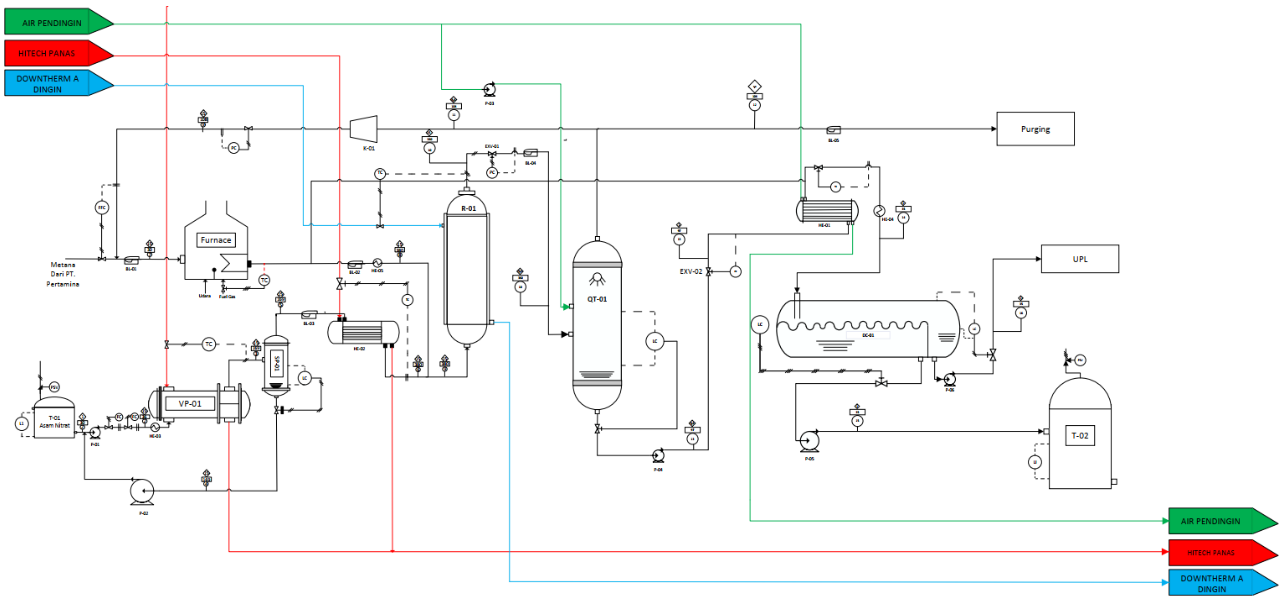

Figure 2. Flow diagram of the nitromethane process after energy analysis.

requires substantial energy input to achieve optimal conversion. The pinch temperature at 308 K is a critical point in system design, where, according to the pinch analysis principle, there should be no heat transfer across the pinch point to achieve minimum energy consumption (Linnhoff, 1993). The selected ΔTmin value of 10K is a trade-off between operational energy savings and heat exchanger investment costs, where a smaller ΔTmin results in greater energy savings but requires a larger heat exchanger area and higher capital costs (Furman & Sahinidis, 2002).

The pinch analysis results show a reduction in heating load from 1,521 kW to 798.4 kW and a decrease in cooling load from 3,652 kW to 1,925.7 kW, accompanied by an increase in energy recovery from 17.6 kW to 63.5535 kW. This indicates an improvement in energy efficiency and a reduced dependence on external utilities.

Identification of the Minimum Energy Requirement (MER) provides a theoretical target that must be achieved in the design of a Heat Exchanger Network. With a total heat energy of 798.418 kW, there is significant potential for savings compared to conventional designs without integration, which would likely require much greater hot utility. A study by Čuček et al. (2012) on the petrochemical industry shows that the implementation of pinch analysis can reduce fuel consumption by up to 40% and CO_2 emissions in proportion to these energy savings. Recent research by Rahaghi & Hayati-Ashtiani (2025) demonstrates that pinch technology applied to a naphtha hydrotreating unit achieved a 40.4% reduction in energy consumption of hot utilities and 41.3% decrease in CO_2 emissions through HEN modification. Moreover, Aziz et al. (2017) developed a systematic integrated framework using multiple Pinch Analysis tools including Heat Pinch Analysis, Total Site Heat Integration, and Carbon Emissions Pinch Analysis to enable industrial site planners to achieve low-CO_2 processes. In the context of nitromethane plants, these savings not only have an impact on reducing operational costs but also contribute to reducing the carbon footprint of the chemical industry, in line with the sustainable development agenda.

3.3 Grid Diagram Heat Exchanger Network (HEN)

The developed HEN grid diagram shows the optimal configuration for heat integration between process streams, taking into account temperature constraints and thermodynamic feasibility (Figure 3). Three main heat flows (H1, H2, H3) are identified with different characteristics: H1 operates in the low temperature range (370K-309K) with a heat capacity of 157.330 kW/K, H2 in the medium temperature range (653-442 K) with CP 132.839 kW/ K, and H3 at the

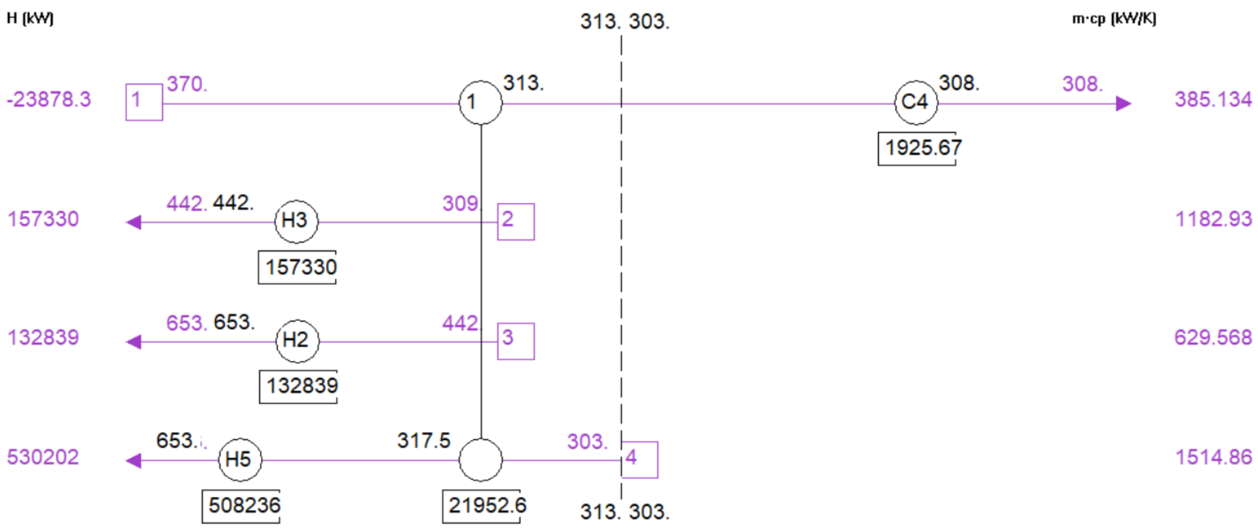

Figure 3. Heat exchanger network at ΔTmin 10 K.

Table 2. Comparison of Energy Requirements Before and After Pinch Analysis.

Analysis Parameters		Amount
Before pinch analysis	Heating Duty (Q_h)	1.521 kW
	Cooling Duty (Q_c)	3.652 kW
After pinch analysis	Heating Duty (Q_h)	798.418 kW
	Cooling Duty (Q_c)	1925.67 kW
Maximum energy recovery (MER)		63.5535 kW
Number of Installed Heat Exchangers		5
Total Cost of Installed Heat Exchangers ($/yr)		1,541,000

highest temperature range (653-303 K) with the largest heat capacity of 630.202 kW/K. The matching between heat and cold flows is done by considering the ΔTmin constraint to ensure sufficient driving force for heat transfer. The H3 flow, which has the widest temperature range and the highest thermal capacity, is the main source for heat recovery, heating the feed to the heat exchanger and furnace, thereby substantially reducing the external heating load.

The optimized HEN configuration shows that the furnace load as a hot utility can be reduced to 313.303 kW, which is much lower than the total heating requirement of the system (Table 2). This reduction is achieved through the utilization of sensible heat from high-temperature reactor products (653 K) for reactor feed preheating, in accordance with the heat cascade concept in pinch analysis. Research by Morar & Agachi (2010) demonstrates that an optimal HEN design not only minimizes utility consumption but must also consider controllability and flexibility aspects to accommodate variations in operating conditions. Escobar et al. (2013) further emphasize that simultaneous consideration of flexibility and controllability during HEN synthesis is essential to ensure economic performance can be achieved in practical operating environments. Additionally, Leitold et al. (2019) highlight that the structural properties of HENs significantly affect their operability, noting that while more interconnected networks require fewer actuators and sensors for controllability, they also result in increased complexity in operation. In this case, the grid diagram shows a relatively simple structure with a reasonable number of heat exchangers, avoiding excessive complexity that can cause operational and maintenance problems.

4. Conclusions

The application of pinch analysis technology in the preliminary design of a 25,000 tons per year nitromethane plant successfully identified significant potential for energy efficiency optimization. Analysis with ΔTmin of 10K resulted in Minimum Energy Requirement targets with hot utility of 798.418 kW and cold utility of 1,925.67 kW, with pinch temperature at 308K serving as the critical point of system design. The developed Heat Exchanger Network design successfully reduced the furnace load to 313.303 kW through the integration of three main hot streams (H1, H2, H3) with process cold streams. This reduction was achieved by utilizing sensible heat from stream H3 exiting the reactor at 653K for feed preheating, effectively implementing the heat cascade concept. The high heating-to-cooling requirement ratio (414:1) reflects the endothermic characteristics of the nitration process, yet the designed integration strategy maximized internal heat recovery with a relatively simple and feasible structure.

The implementation of pinch technology provides dual benefits: operational cost reduction through fuel consumption savings and environmental contribution through CO_2 emission reduction proportional to energy savings. For practical implementation, further analysis is required including detailed economic evaluation, payback period analysis, and operability and flexibility studies to ensure thermally, economically, and operationally optimal design. Further development can be directed toward additional integration alternatives such as split stream operation, multi-stage heat exchange, waste heat recovery from furnace flue gas, and thermal storage system implementation to enhance operational flexibility and long-term energy efficiency.

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