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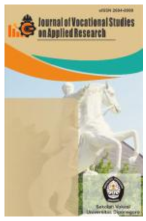

Research Article

Heat Integration Analysis for Enhancing Energy Efficiency in the Pre-Design Phase of a Sodium Hydroxide Factory Using Pinch Technology

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Abstract

Energy efficiency plays a crucial role in the initial design of chemical plants, as it directly influences operational costs and process sustainability. In sodium hydroxide plants, the substantial thermal energy demand, especially in heating and cooling units, necessitates effective energy optimization strategies. This study seeks to enhance energy efficiency in the preliminary design of a sodium hydroxide plant by incorporating heat exchangers (HE) through a Heat Exchanger Network (HEN) approach, utilizing the HINT application based on the Pinch Analysis method. Process stream data, including temperature, mass flow rate, and heat capacity flow rates of hot and cold streams, were analyzed to identify the pinch point, minimum heating and cooling utility requirements, and the optimal heat exchanger network configuration. The findings reveal that adding heat exchangers significantly boosts internal heat recovery and reduces the need for external utilities. Consequently, applying Pinch Analysis with the HINT application at the preliminary design stage of a sodium hydroxide plant effectively enhances energy efficiency, supporting a more economical and sustainable plant design.

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1. Introduction

Sodium hydroxide (NaOH) is a fundamental material in chemistry that plays a crucial role in various industrial sectors, including the pulp and paper industry, textiles, soap and detergent production, water treatment, as well as the oil and gas industry. The national demand for NaOH continues to rise, driving the need to design a NaOH factory that is not only technically and economically viable but also energy-efficient. In the preliminary design of a Sodium Hydroxide Factory with a capacity of 42,000 tons per year using the electrolysis cell diaphragm method, electrical and thermal energy requirements become dominant factors in the overall process operations (Hurairah, 2024).

The NaOH production process using the electrolysis cell diaphragm method involves several main stages, including brine purification, electrolysis, and product purification. This process operates at temperatures around 90 °C and atmospheric pressure, and it also produces by-products in the form of chlorine and hydrogen gas (Hurairah, 2024).

In the pre-design factory mentioned, several heat exchanger units have been employed to facilitate the transfer of heat between process flows. However, the optimal utilization of this heat has not yet been fully analyzed from a comprehensive energy integration perspective. This oversight results in the potential loss of energy that could otherwise be harnessed to reduce the need for external utilities, such as steam and cooling water. Therefore, it is systematically necessary to enhance internal heat recovery and decrease the factory's total energy consumption.

One of many methods implemented in optimization process energy is *Pinch Analysis*, which aims to determine minimum utility requirements hot and cold as well as designing network exchanger optimal heat (*Heat Exchanger Network/HEN*) (Linnhoff & Hindmarsh, 1983).

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The analysis of efficient energy is conducted on the process flow diagram by applying pinch technology and designing the addition of a heat exchanger to utilize the hot sensible heat from the hot flow for the cold flow. The inclusion of this heat exchanger is expected to reduce external utility consumption, enhance overall process energy efficiency, and support the design of more economical and sustainable factories.

The HINT application is a device software designed to assist with comprehensive pinch analysis through the analysis of hot and cold flow data, determination of the pinch point, and the design of efficient heat exchanger configurations. This application method is considered crucial at the pre-design stage of chemical plant development because it provides an initial overview of potential energy savings before the plant is constructed and operational.

Given the high energy demands of producing sodium hydroxide, especially in the electrolysis unit and evaporation circuit, a design strategy that thoroughly integrates energy needs and availability from the initial design phase is essential. The literature widely recommends the pinch analysis-based energy integration approach as an effective method for identifying potential internal heat recovery and establishing minimum target heating and cooling utility requirements based on the process system's thermodynamic constraints (Klemeš et al., 2020). Applying this method to energy-intensive chemical industries, such as the chlor-alkali industry, has been shown to significantly reduce thermal utility consumption without altering key operating conditions that are crucial for safety and product quality (Li et al., 2014).

Moreover, the advancement of energy analysis software facilitates a more systematic application of pinch analysis by enabling the visualization of composite curves and the design of heat exchanger networks. This, in turn, supports more precise design decision-making during the pre-design stage (Orosz et al., 2019; Atuonwu, 2025). Consequently, this study concentrates on applying pinch analysis to the pre-design of a sodium hydroxide plant, aiming to assess opportunities for enhancing energy efficiency through heat integration and the incorporation of heat exchangers, ultimately promoting a more efficient, economical, and sustainable plant design.

2. Methods

2.1 Sodium Hydroxide Production with Method Electrolysis Cell Diaphragm

The production of NaOH begins with the preparation of a brine solution (Figure 1 and Figure 2). Solid NaCl salt from storage units is directed to the mixing tank, where it is dissolved in water to form a saturated salt solution. This solution then enters the reactor tank for purification, starting with the addition of Na_2CO_3 and NaOH, which precipitate impurities such as Ca^{2+} and Mg^{2+} in the form of $CaCO_3$ and $Mg(OH)_2$. The mixture is subsequently directed to the clarifier to separate the sediment from the brine solution. The clarified brine is then passed through an ion exchanger to remove any remaining impurity ions, resulting in a pure brine solution that meets the specifications for the electrolysis process.

The pure brine solution is then directed to the electrolyzer cell diaphragm. In this unit, with the aid of an electric current, electrolysis occurs at a temperature of approximately 90 °C and a pressure of 1 atm. In the anode chamber, Cl^- ions are oxidized to produce Cl_2 gas, while in the cathode chamber, water is reduced to produce H_2 gas and OH^- ions. The diaphragm functions to separate the anode and cathode chambers, preventing chlorine gas from mixing with the NaOH solution. The Na^+ ions that migrate to the cathode chamber react with OH^- to form an NaOH solution with an initial concentration of around 11–15%.

The NaOH solution from the electrolyzer is then directed to a multilevel evaporator circuit, consisting of evaporator effects I, II, and III, to gradually increase the NaOH concentration by evaporating the water. Subsequently, the concentrated solution enters the falling film evaporator to achieve a higher concentration of NaOH. If the target product is solid, the further concentrated solution is cooled in the crystallizer to form NaOH crystals, which are then separated using a centrifuge. The wet NaOH crystals are dried in a rotary dryer until a solid NaOH product is obtained according to specifications. Meanwhile, Cl_2 and H_2 gases produced during the electrolysis process are managed as by-products and can be utilized for other industrial needs.

2.2 Data Extraction

To enhance the efficiency of energy analysis, methodical data extraction involves collecting and processing operational data directly related to energy usage and flow within each process unit. The extracted data encompasses both primary and secondary information, such as mass and energy flow rates (kg/h, kJ/h), equipment inlet and outlet temperatures and pressures, electricity consumption, steam requirements, and the heating and cooling loads on heat exchangers. This data is sourced from the process flow diagram (PFD), mass and heat balance sheets, tool specifications, and operational design data. Subsequently, energy data is extracted by calculating the energy input (electricity, heat from steam, and combustion energy) and energy output (waste heat, products, and losses) for each operating unit. The results of this data extraction are then organized into an energy table to facilitate the identification of areas with high energy consumption (energy-intensive units).

The first step in conducting pinch analysis involves extracting thermal data from the process's mass and energy balances. This data includes inlet and outlet flow temperatures, mass flow rates, and heat capacity flow rates. Padullés et al. (2025) highlighted that the quality of pinch analysis results heavily relies on the accuracy of the energy balance data, especially during the initial design phase of a chemical plant.

2.3 *Pinch Analysis and HEN Arrangement*

Pinch analysis technology begins with the collection of thermal data from the entire process flow, including inlet and outlet temperatures, mass flow rates, heat capacity (Cp), and the heating and cooling requirements of each stream. This data is then adjusted using a specified ΔT_min value, based on technical and economic considerations. Subsequently, the arrangement of hot and cold streams is carried out to form composite hot and cold curves. The closest meeting point between these two curves is known as the pinch point, which marks the minimum energy utility requirements for heating and cooling. Based on the results of the pinch analysis, a minimum energy consumption target is established by applying the pinch rules: there must be no external heating below the pinch, no external cooling above the pinch, and no transfer of heat across the pinch.

The design of the heat exchanger addition was conducted by referring to the results of pinch and Heat Exchanger Network (HEN) analysis. The hot flow from the hot stream was utilized as much as possible to heat the cold stream, which has corresponding heating needs and is located in the same zone relative to the pinch point. The addition of a heat exchanger was designed with consideration of energy balance, minimum temperature difference, flow type (counter-current or co-current), and operational equipment limitations. The size and surface area of the heat exchanger were determined based on the heat transfer load and the overall heat transfer coefficient.

Utilizing the extracted thermal data, an analysis of hot and cold stream integration was performed to assess the compatibility of process streams concerning temperature levels, heat capacity flow rates, and exchangeable heat loads, all while adhering to pinch constraints. This step is designed to optimize the use of sensible heat through effective stream matching, thereby enhancing the efficiency of internal heat recovery (Mrayed et al., 2021). Following this, a pinch-based targeting approach was employed to ascertain the minimum heating and cooling utility requirements via composite curve analysis, which establishes a quantitative energy target before the detailed design of the heat exchanger network. Setting this energy target is crucial for identifying the maximum achievable internal heat recovery while ensuring the thermodynamic feasibility of the process system (Pavão et al., 2022).

3. Results and Discussion

According to the data stream (Table 1), the hot flow 24 & 25 (hot stream) experienced a temperature decrease from 386.15 K to 323.15 K (ΔT = 63 K) with an average Cp value of 7.38 kW/K. In contrast, the cold flow 10 & 11 (cold stream) saw a temperature increase from 303.15 K to 363.15 K (ΔT = 60 K) with an average Cp of 28.76 kW/K. Following the integration of the HE-01 heat exchanger into the flow diagram, a portion of the heat from the hot stream was directly utilized to

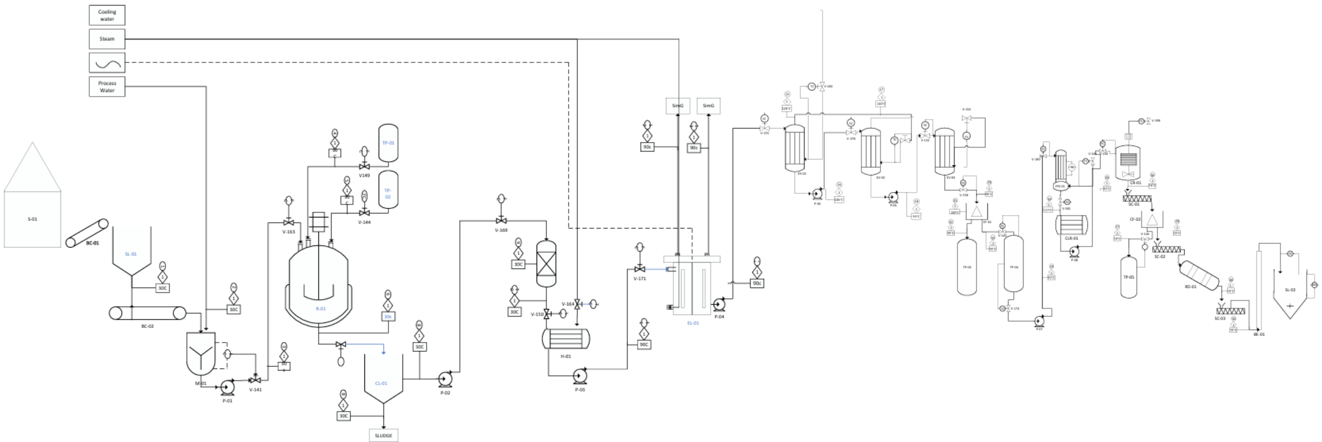

Figure 1. Flowchart Before Energy Analysis.

Table 1. Calculation Mass Balance.

Stream	Stream Type	Mass Flow (Kg/h)	Cp Mean (kW/K)	Tin (K)	Tout (K)	ΔT (K)
24 & 25	Hot	6078.89	7.38	386.15	323.15	63
10 & 11	Cold	25912.76	28.76	303.15	363.15	60

warm the cold stream before it entered the steam-based heating unit. Consequently, the heat requirements of the cold stream can be met through internal process heat integration.

In essence, this indicates that the consumption of utilities for heating (steam) decreases significantly due to the successful heat recovery by HE-01. This is evident in the flowchart, where the reduced load on the downstream heater/evaporator is observed because the inlet temperature of the cold stream has already increased significantly before further warming. Additionally, the heat that was previously discarded into the cooling water by the hot stream is now utilized, thereby reducing the burden on coolant utilities as well. In other words, the integration of HE-01 enhances the energy system's efficiency by utilizing the hot sensible inter-process flow, minimizing heat losses, and reducing reliance on external utilities.

The overall analysis of the results, as depicted in the flow diagram, indicates that the implementation of pinch technology through the addition of HE-01 has successfully achieved effective heat integration. This has led to a reduction in the need for primary energy and an enhancement in process energy performance without altering the operating conditions of the main unit. This confirms that the design of HE-01 aligns with the principles of pinch technology, which aim to maximize heat recovery and minimize the consumption of hot and cold utilities.

The composite curves in Figure 3 illustrate the relationship between temperature (T) and cumulative hot load (H), which is used to analyze the energy requirements for heating in the process. The red curve represents the hot composite curve, depicting the combination of all hot overflows in the system that release heat, with a temperature decrease from approximately 380 K to 320 K as heat release increases. This indicates that the process has internal heat sources that can be utilized, although the amount is relatively limited. In contrast, the blue curve represents the cold composite curve, showing the combination of all cold overflows that require heating, with a temperature increase from around 300 K to 360 K. The demand for external heat is greater compared to the available heat from the hot flow.

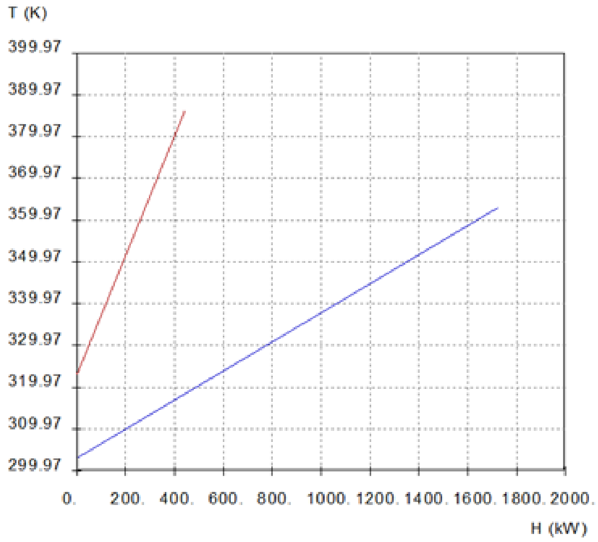

Figure 3. Composite Curves.

The horizontal distance between the heat curve and the cold curve indicates the need for external utilities, specifically the addition of heat from heating to meet the requirements of the heating process, as well as cooler utilities to dissipate excess heat. Since the two curves do not intersect, it can be concluded that the available heat from the process is insufficient to fully meet the heating needs. The closest point between the two curves represents the pinch point, which is the most critical operational condition and sets the limit for maximum heat recovery.

It is important to ensure that heat is provided in the cold stream, as it cannot be supplemented with a hot stream later. The available utility heat (H2) is insufficient, being less than 1284.6 kW. The absence of heat displacement across the pinch line indicates that the heat exchanger network is designed in accordance with the pinch principle, which aims to maximize internal heat recovery and minimize the use of external utilities. Consequently, this diagram illustrates that the integration of hot streams has been effectively implemented, directly contributing to the enhancement of process energy efficiency (Figure 4).

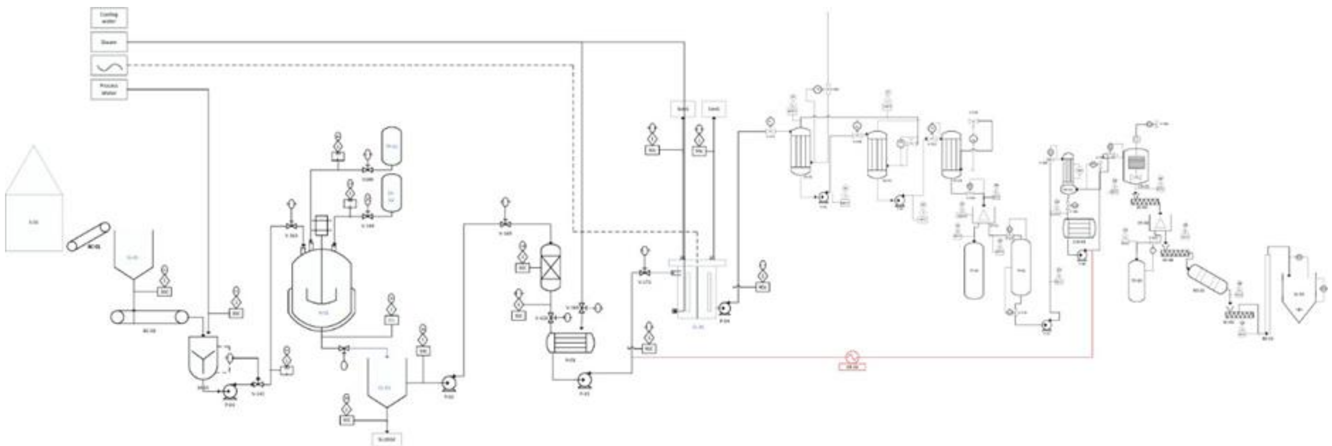

Figure 2. Flowchart After Energy Analysis.

According to the analysis results, the pre-pinch analysis condition reveals that the system had not yet implemented heat integration between process streams. Consequently, the entire heating demand of the cold streams, totaling 1725.6 kW, had to be met by the heating utility, while an equivalent amount of heat (1725.6 kW) from the hot streams was entirely rejected to the cooling utility. In this scenario, no heat recovery occurred (recovered energy = 0 kW), highlighting the system's inefficiency in process heat utilization. Such conditions are typically observed in systems not designed with energy integration principles in mind.

Following the implementation of pinch analysis and the installation of a heat exchanger (HE–02/H2), the process's energy efficiency saw a significant boost (Table 2). Heat from the hot streams was effectively recovered and used to warm the cold streams by 1284.6 kW, leading to a notable decrease in the external heating utility requirement to 441 kW. The recovered energy of 1284.6 kW illustrates that a substantial portion of the internal process heat, which was previously wasted, can now be efficiently reused. These findings confirm that pinch analysis is a powerful method for determining minimum utility targets and maximizing heat recovery within the process.

Meanwhile, the cooling load remained steady at 1725.6 kW, as the excess heat above the pinch temperature still needed to be rejected to the cooling utility, in line with the fundamental principles of pinch analysis, which prohibit heat transfer across the pinch (Kim et al., 2022). Although the cooling load remained unchanged, the substantial reduction in the heating load offers direct benefits, such as energy savings, lower operating costs, and potential reductions in greenhouse gas emissions. These findings align with established theory and previous studies, which suggest that applying pinch analysis is a systematic and effective method for enhancing energy efficiency in industrial processes (Zhao et al., 2022).

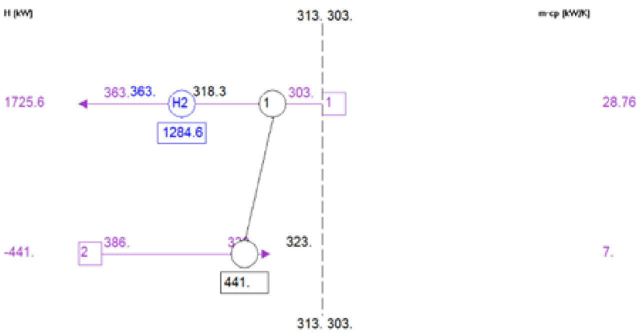

Figure 4. Heat Exchanger Network.

Table 2. Energy Loads Before and After Pinch Analysis

Energy Parameter	Before Pinch Analysis	After Pinch Analysis
Heating Load (kW)	1725.6	441
Cooling Load (kW)	1725.6	1725.6
Recovered Energy (kW)	0	1284.6

The diagram illustrates that the cold stream (1), with a heat capacity of approximately 28.76 kW/K, starts at a temperature of around 303 K and needs to be warmed to a range of 318–363 K. To achieve this, the cold stream is heated through a heat exchanger using heat from the hot stream (2), which has a heat capacity of about 7 kW/K and experiences a temperature drop from approximately 386 K to 323 K. The energy flow of about 441 kW indicates the heat transferred from the hot stream to the cold stream, signifying an internal heat recovery process.

4. Conclusion

Based on the analysis of composite curves and the application of pinch analysis in the pre-design phase of a Sodium Hydroxide Factory with a capacity of 42,000 tons per year, it can be concluded that the energy required for the heating process is still greater than the available internal heat from the hot flow. This is indicated by the absence of an intersection between the hot composite curve and the cold composite curve, which signifies the need for external utilities in the form of heaters and coolers. However, the integration of heat through the addition of a heat exchanger (HE-01) allows for the utilization of part of the heat from the hot stream to warm the cold stream, thereby reducing steam requirements and cooling loads. The presence of a pinch point serves as a limit for maximum heat recovery and is an important reference in designing an efficient heat exchanger network. Overall, the implementation of pinch technology at the pre-design stage has proven to increase energy process efficiency, reduce external utility consumption, and support the design of a more economical and sustainable NaOH factory.

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