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Studying the Decrease in CO_2 Emission and Energy Consumption of the Process of Light Naphtha Hydrotreating

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1. ABSTRACT

Simultaneously reducing energy consumption and environmental pollutants in refining industries has become a major challenge and priority. This study aimed to perform a techno-economic and environmental optimization of a Light Naphtha Hydrotreating (LNH) unit by employing Pinch Analysis. Pinch Technology is a systematic method for designing and optimizing energy consumption of industrial plant to specify the process optimum condition for achieving this purpose. This study aims to optimize the economic and environmental performance of a Light Naphtha Hydrotreating unit of a petroleum refinery using the Pinch Dnalysis Method (PDM). For this purpose, three modifications were made based on different minimum approach temperatures of 8, 12, and 16 °C. These modifications were evaluated from the perspectives of energy consumption, carbon dioxide emissions, and economic costs. The modification based on a minimum approach temperature of 12 °C was selected as the optimum option. This retrofitting resulted in 40% reductions in energy consumption, 41% in carbon dioxide emissions, and 41% increase in operating costs with a payback time of approximately three and a half years, confirming the project's economic viability. This study ultimately demonstrates the effectiveness of Pinch Analysis in achieving sustainability goals within the refining industry and introduces an optimal retrofit scheme for practical implementation.

Keywords: CO_2 Emission, Heat Exchanger Network, Total Costs, Energy Consumption, Pinch Analysis.

2. Introduction

The Light Naphtha Hydrotreating (LNH) unit is a critical process in refineries, designed to remove sulfur and nitrogen compounds to produce cleaner gasoline. However, due to its intensive use of furnaces and distillation columns, it is also one of the most energy-consuming and polluting units, making its optimization essential for both economic and environmental reasons. Pinch Analysis has been widely recognized as a powerful methodology for Heat Exchanger Network (HEN) optimization in refineries, significantly reducing energy consumption and CO_2 emissions by recovering waste heat [1]. Previous studies, such as those by Ghazizahedi and Hayati-Ashtiani [2] on isomerization units and Mohammadzadeh and Hayati-Ashtiani [3] on the LNH unit, demonstrated substantial improvements by optimizing the minimum temperature approach ($\Delta T_{min.}$). Recent advancements have integrated economic and environmental considerations, including carbon taxes [5]. For instance, Liu et al. [4] combined Pinch Analysis with AI-based optimization in a methanol plant, achieving 20% energy savings and 14% CO_2 emission reduction, though high implementation costs remained a challenge. However, the application of a comprehensive techno-economic-

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environmental analysis to optimize the $\Delta T_{min.}$ for a light naphtha hydrotreating unit remains underexplored, presenting a clear research gap. This study aims to bridge this gap by performing a detailed optimization of an LNH unit using Pinch Analysis. Three distinct retrofit scenarios were developed based on ΔT_{min}. values of 8, 12, and 16 °C. These scenarios were rigorously evaluated and compared using key energy, environmental, and economic indicators to identify the most balanced and viable option for practical implementation. The results demonstrate the profound effectiveness of Pinch Analysis in achieving sustainability goals within the refining industry.

3. MATERIALS AND METHODS

A systematic process integration approach was employed in this study to optimize the LNH unit. The methodology consisted of some key steps. In the base case simulation and data extraction step, the existing hydrotreating process was rigorously simulated using Aspen HYSYS V11 and Aspen Energy Analyzer V11 to establish a reliable base case. Critical process data were extracted from the Process Flow Diagrams (PFDs), including temperatures, pressures, and flow rates of all hot and cold streams. In the second step, Pinch Analysis and HEN design, the extracted stream data were imported into Aspen Energy Analyzer V11 to perform a detailed Pinch Analysis. This analysis identified the minimum energy requirements (MER) of the process. Three distinct modified HEN designs were proposed and optimized based on different minimum temperature approach values, that is, $\Delta T_{min.}$ = 8, 12, and 16 °C. Then, the CO_2 emission calculation was applied. The rate of CO_2 emissions for each scenario was calculated based on the fuel consumption of the furnaces. The CO_2 emission rate (kg/sec) was then determined by equation 1:

$$(CO_2)_{Emission} = \left(\frac{Q_{Process}}{NHV}\right) \times \left(\frac{C\%}{100}\right) \times \alpha \times \left(\frac{T_{TFT}-T_0}{T_{TFT}-T_{Stack}}\right) \quad (1)$$

Where $Q_{Process}$ heat load used in the process or thermal equipment (kW), T_{TFT} theoretical flame temperature (°C), T_{Stack} temperature of the exhaust gas from the furnace stack (°C), T_o temperature of the surrounding environment (°C), NHV (Net Heat Value) of the fuel used in the furnace (kJ/kg), C% percentage of carbon in the fuel used and α(=3.67) is the molar mass ratio for CO_2 to C which is a constant coefficient.

The Total Annual Cost was calculated for each design, including operational savings (from reduced fuel consumption) and the annualized capital cost of new heat exchangers. The Payback Period for the capital investment was calculated using equation 2:

$$\text{Payback Time} = \frac{\text{Capital Cost}_{\text{Modified Design}} - \text{Capital Cost}_{\text{Base Case}}}{\text{Operating Cost}_{\text{Base Case}} - \text{Operating Cost}_{\text{Modified Design}}} \quad (2)$$

4. RESULTS AND DISCUSSION

Comparing the three modified designs with the base case showed significant improvements in energy efficiency and environmental performance. The base case design exhibited significant energy inefficiency, with a high hot utility consumption of 10.49 MW and substantial CO_2 emissions of 2906 kg/h, as the heat recovery from furnaces was low. This underscored the critical need for HEN optimization. All suggested modifications successfully reduced energy consumption and CO_2 emissions. The design with ΔT_{min}. = 8 °C achieved the highest reduction in hot utility to 5.909 MW and CO_2 emissions to 1613 kg/h (a 44.7% and 44.5% decrease in energy and CO_2 emission from the base case, respectively). However, this design required the highest capital investment due to the largest heat transfer area (23,420 m²), resulting in the longest payback period (4.9 years). Conversely, the design with $\Delta T_{min.}$ = 16 °C, while requiring a lower capital cost, offered less significant reductions in energy consumption (6.581 MW) and emissions (1796 kg/h), leading to higher annual operating costs compared to other modifications.

The design based on $\Delta T_{min.}$ = 12 °C was identified as the optimum scenario, striking the best balance between economic and environmental objectives. It achieved a substantial 40.4% reduction in energy consumption (to 6.245 MW) and a 41.3% reduction in CO_2 emissions (to 1704 kg/h). Crucially, it featured the lowest total annual cost ($2,443,409/yr) and a financially attractive payback period of 3.59 years, demonstrating good economic viability alongside its environmental benefits. The key to this success was the strategic elimination of the H-1802 furnace and intelligent stream splitting to maximize internal heat recovery. A summary of the discussion and results is given in Table 1.

Table 1. Energy, environmental and economic evaluation of three improvement designs and the base case of the unit

Design	Q_H (MW)	HE Total Surface Area (m^2)	Capital Cost (USD)	Operating Cost (USD/yr)	Total Cost (USD/yr)	CO_2 Emission (kg/h)	Payback Time (yr)
Base-Case	10.49	8032	1,302,000	2,145,709	2,489,136	2906	-
ΔT_{min} = 8 °C (No. 1)	5.909	23420	5,951,000	1,197,107	2,766,969	1613	4.0
ΔT_{min} = 12 °C (No. 2)	6.245	17620	4,468,000	1,264,594	2,443,409	1704	3.59
ΔT_{min} = 16 °C (No. 3)	6.581	15340	3,895,000	1,592,883	2,620,326	1796	4.69

4. CONCLUSION

This study conclusively demonstrates that applying Pinch Analysis to the LNH unit is both economically and environmentally beneficial. The optimum design based on ΔT_{min} = 12 °C successfully reduces energy consumption and CO_2 emissions by over 40% compared to the base case. The payback period of 3.59 years provides a strong incentive for refineries to implement this modification, achieving significant operational savings and environmental benefits.

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