



RETROFIT DESIGN OF HEAT EXCHANGER NETWORKS FOR KADUNA REFINERY'S VACUUM DISTILLATION UNIT

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ABSTRACT

Effective Heat Exchanger Network (HEN) design is pivotal for improving energy efficiency and realizing substantial cost savings in chemical and petrochemical sectors. While contemporary refineries reap the benefits of economical HEN designs, there is an urgent need to enhance the utility and cost-saving features of aging refineries. These older facilities often suffer from suboptimal designs, characterized by high energy requirements and limited cost savings. To address this issue, a thorough analysis of HEN design and retrofit options is essential. The pinch design approach stands out as a preferred tool for retrofitting HENs due to its physical insight and ease of application. In this study, based on pinch technology (PT), various retrofit design scenarios (re-sequencing, addition of heat exchangers, and area addition) were explored for improving the HENs of the refinery section's vacuum distillation unit (VDU). The study revealed that the base case design achieved a Total Annual Cost (TAC) of $\$1.738 \times 10^6$. Significant cost savings were attained through re-sequencing, addition of area, and addition of a new heat exchanger, amounting to $\$439.5/\text{year}$, $\$746.6/\text{year}$, and $\$33,810$ respectively. These retrofit strategies are exceptional in reducing utility demand and improving operating cost savings. However, they required a substantial capital expenditure of $\$1,733$, $\$3,191$, and $\$167,100$ respectively, with payback periods of 3.9, 4.3, and 4.9 years respectively. Therefore, it is critical to explore additional retrofit possibilities to further optimize cost savings.

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1.0 Introduction

Petroleum refining is a complex process that demands advanced and innovative solutions to minimize costs and maximize energy efficiency, as it consumes a significant amount of energy (Han et al. 2020). VDU is a vital component of a typical refinery process, facilitating the additional recovery of the atmospheric residue obtained from an atmospheric distillation unit (H'ng et al., 2024). Alongside the Crude Distillation Unit (CDU), these units collectively contribute to a substantial portion of the overall energy consumption in the refinery (Yang et al., 2020). Consequently, these units incur the highest operating expenses within a refinery (H'ng et al., 2021).

As a result, there has been significant research interest in retrofitting and optimizing these units to enhance efficiency and cost saving (Klemeš et al., 2020). Retrofitting an existing HEN is crucial for achieving significant energy savings, eliminating excess loads in heat exchangers, and optimizing energy usage during refining processes (Alhajri et al., 2021). The retrofit design is often necessary to attain a cost-effective design and meet product requirements (Chin et al., 2020). Modifying the existing network is typically feasible (Khorshidi et al., 2016), making it more prevalent and economical to revamp most projects in process industries through retrofitting, as designing a new HEN may not always be feasible (Ulyev et al., 2018), due to substantial capital cost involved (Wang et al., 2020). Although HEN retrofit scenarios are often more complex than grassroots designs, given the need to consider existing infrastructure (Gundersen, 2023). However, it enhances energy

recovery, reduces heating and cooling requirements (Osman et al. 2019), and consequently lowers fuel consumption (Wang et al., 2020).

HEN retrofitting can be accomplished through the pinch method, numerical programming approaches, and hybrid approaches (Alhajri et al., 2021). In retrofit and new designs, the Pinch approach is considered efficient and feasible (Alhajri et al., 2021; Al-Riyami et al., 2001). For example, implementing HEN design through pinch analysis can optimize processes and increase distillation efficiency, resulting in cost savings and reduced fuel consumption (Fumuassuca et al., 2020). Klemeš and Varbanov (2018) offers an extensive review of research in this field.

The term Pinch was coined by Linnhoff in 1979 to establish a new set of thermodynamic principles for determining the minimum energy levels in HEN design (Linnhoff et al. 1982). The robustness of the pinch method in achieving energy savings for optimal design can be found in the works of Mrayed et al. (2021), Yang et al. (2020), Li et al. (2019), Bandyopadhyay et al. (2019), Ndunagu et al. (2021), Bello and Zangeri (2021), Mehdizadeh et al. (2017), Ulyev et al. (2018), Ghaderi et al. (2023). Improving energy efficiency can provide substantial economic benefits (Mrayed et al., 2021). Additionally, studies have shown the advantages of the pinch approach in the power sector (Lopez et al., 2021) and the waste water treatment and food processing industry (Lima et al., 2021) for achieving energy savings, utility cost savings, and emission reduction. However, achieving an appropriate HEN is quite challenging due to the complexity of process streams in most process industries (Khorshidi et al., 2016).

Lai et al. (2020) found that retrofitting HEN with process modifications resulted in an additional 18.4% reduction in heating utility demand compared to retrofitting alone. Modifying the process temperature led to energy savings of 230.8% and annual cost savings of \$1.6M. Mrayed et al. (2021) proposed two retrofit solutions using Pinch analysis to enhance the thermal effectiveness of an existing HEN. The first involved adding a new heat exchanger, which achieved utility savings of 9.3 MW with a 3-year payback period. The second solution involved reconfiguring the feed line to the condenser, incurring lower capital expenses.

Gadalla (2015) introduced a new graphical method for analyzing heat recovery systems in HENs. This graph can identify opportunities for modifications to improve energy performance and reduce fuel and water requirements. The method can be used to analyze existing networks, compare them to energy targets, and modify designs or networks for better energy integration and lower fuel demands. Al-Mutairi and Babaqi, (2014) demonstrated that the retrofitting costs were offset by the energy savings, resulting in an overall cost saving of \$32,800 per year and a relatively short payback period of less than a year. Modifying HEN via pinch approach reduced the utilities requirement, thereby saving cost (Zhang and Liu, 2016; Alhajri et al., 2021 and Al-Mayyahi et al., 2019). Retrofitting HEN design of CDU achieved optimum design (Mehdizadeh Fard et al., 2017, Hussain et al., 2022, Farooq and Al-Qahtani, 2024, Xu et al., 2023).

Effective HEN design plays a crucial role in enhancing energy efficiency and achieving significant cost savings across chemical and petrochemical sectors (Jiang et al., 2020). While modern refineries benefit from efficient HEN designs, older facilities often operate with suboptimal configurations, resulting in high energy consumption and limited cost-effectiveness. This disparity underscores the urgent need to enhance the utility and cost-saving capabilities of aging refineries through rigorous analysis and strategic retrofitting of HENs.

In particular, the VDU at Kaduna Refinery and Petrochemical Company (KRPC) presents a pertinent case study. The VDU is pivotal in recovering valuable products from atmospheric residue (H'ng et al., 2024), yet its HEN retrofitting strategies have not been comprehensively explored in existing literature. Previous studies primarily focus on CDUs, leaving a research gap in understanding and optimizing HEN designs specifically tailored for VDUs.

To address this gap, this research undertook a detailed retrofit design of HEN for the VDU at KRPC. The study investigated various retrofit options such as re-sequencing, area addition, and adding heat exchangers, leveraging the pinch technology approach known for its effectiveness in optimizing HENs. By evaluating these design strategies, the research sought to identify the efficiency of retrofit designs in enhancing energy efficiency, reducing operational costs, and ensuring sustainable refinery operations at KRPC. This study was not only timely but essential in contributing to the broader knowledge base of refining operations, particularly in optimizing HENs for enhanced efficiency and cost savings in aging refinery infrastructures like KRPC's VDU.

2. Materials and Methods

These include; VDU process flow diagram (PFD), Aspen HYSYS, Aspen Energy Analyzer (AEA), and MatLap. To conduct the retrofit design of the HENs for the unit using the pinch design approach, the procedure was outlined in four stages, including data extraction, targeting for optimum ΔT_{min} , HEN design, and retrofitting HENs.

2.1 Data Extraction and Targeting

Data extraction is essential for targeting and predicting the optimum trade-off, which was obtained at 25°C, as shown in Figure 1. This driving force corresponds to the minimum TAC that could result in cost-effect HEN design. The data were extracted from the PFD of the unit obtained from the refinery, presented in Table 1. However, detailed analysis of the data extraction and targeting has been presented in our previous work (Bello and Zangeri, 2021). The benchmark presented in this research is HEN design and retrofits analysis. The trade-off value obtained falls within the standard range of ΔT_{min} for VDU as provided by Linnhoff et al. (1982).

Table I: Extracted Data from the PFD

Streams ID	Supply Temperature (°C)	Target Temperature (°C)	Heat Capacity	Heat Duty
			C_p (10^6 KJ/h°C)	ΔH (10^6 KJ/h)
Cold A	287.6	289	32.84	45.97
Cold B	151	293	0.323	45.97
Cold C	289	306	0.261	4.44
Cold D	293	309	0.278	4.44
Hot A	309	175	0.258	34.62
Hot B	309	210	0.350	34.62
Hot C	354	306	0.087	4.19
Hot D	354	309	0.093	4.19

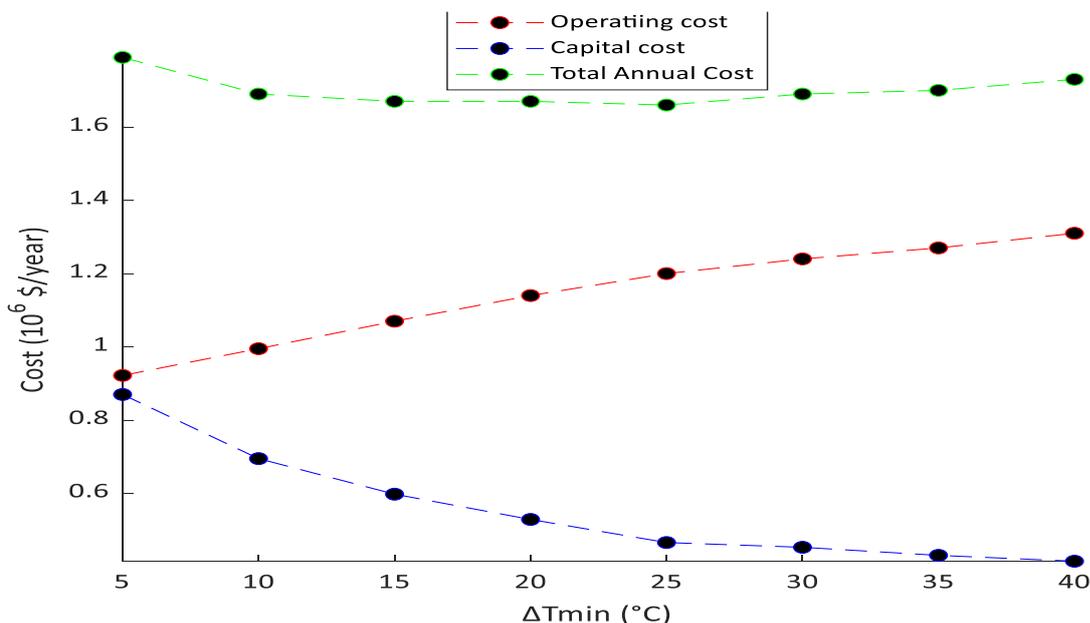


Figure 1: Evaluation of ΔT_{min}

2.2 Total Annual Cost (TAC)

TAC is the summation of the energy or operating cost (OC) and the annualized capital cost (CC.Af) as expressed in equation 1. The capital cost, defined is by the expected plant life in equation 2, contrasts with the recurring annual expense of the operating cost in equation 3. To ensure compatibility, both costs are standardized to the same annual unit. The capital cost is annualized by multiplying it with an annual factor (Af) as detailed in equation 4. The ratio of the capital cost to the operating cost gives the payback period as shown in equation 5

$$TAC = OC + CC.A_f \quad 1$$

$$CC(\$)_{HEN} = [N_{min}\{a + b(A_{min}/N_{min})^c\}]_{AP} + [N_{min}\{a + b(A_{min}/N_{min})^c\}]_{BP} \quad 2$$

Where CC is the capital cost, a, b, and, c, are cost in exchanger cost law, N_{min} is minimum number of unit, AP and BP are above pinch and below pinch areas

$$OC = \sum_{u=1}^u Q_u * C_u \quad 3$$

Q_u = Duty of utility U, KW

C_u = cost of utility, \$KW/ yr.

U = Total number of utilities utilized.

$$A_f = \frac{i(1+i)^n}{(1+i)^n - 1} \quad 4$$

$$Payback\ period\ (year) = \frac{Capital\ cost\ (\$)}{Operating\ cost\ (\$/year)} \quad 5$$

2.3 HENs Design

HEN design is a pivotal research domain aimed at minimizing total annual cost. It has been effectively implemented in various process industries as a reliable heat integration technology (Alhajri et al., 2021). Essentially, HEN design seek to identify the optimal network configuration of heat exchangers for efficient heat transfer between cold and hot streams (Al-Mayyahi Mohammad et al., 2019), thereby significantly reducing the reliance on utility energy sources. HEN design in this research was achieved using pinch approach in Aspen Energy analyzer according to the optimum ΔT_{min} of 25°C, as depicted in Figure 2. This tradeoff is essential in HEN design as it enhanced the heat transfer process of the unit, leading to minimum energy consumption and lower operating costs (Wang et al., 2020). The HEN design shows the exchange of heat between process to process heat exchanger (hot and cold stream), indicated by ash, hot stream and cold utility indicated by blue, cold stream and hot utility shown in red. The hot and cold utilities were added to supplement the heat surplus and deficit respectively to reduce the energy requirement. Furthermore, HEN design depends on various parameters, including area, number of units, number of shells, capital cost, and operating costs, which collectively contribute to predicting the TAC, an economic tool that determine the cost effective design (KariMi et al., 2020).

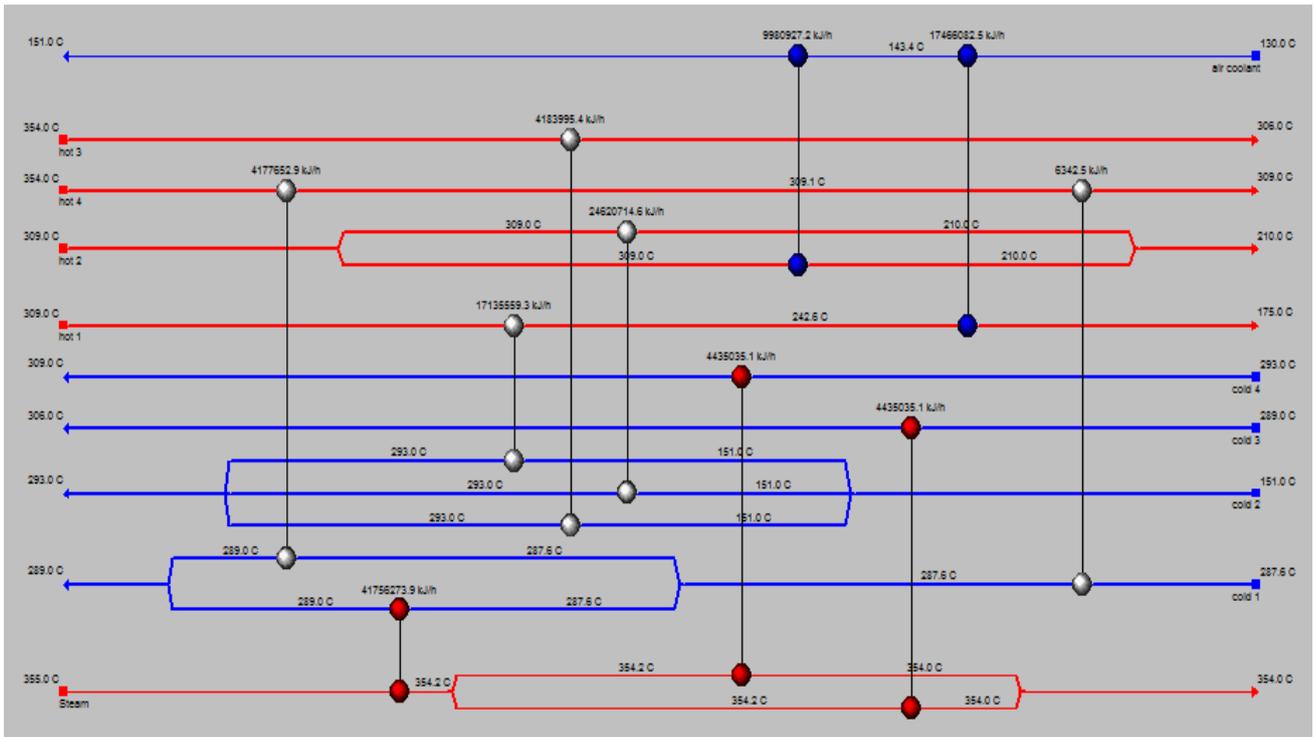


Figure 2: Base case HEN Design

2.4 Retrofits Design of HEN

HEN retrofitting is done to improve energy recovery, optimize existing HENs to accommodate increased throughput of the overall processes (Sieniutycz & Jeżowski, 2018). In this research, three retrofits design were considered, including re-sequencing, addition of heat exchangers, and area addition.

2.4.1 Re-sequencing

Re-sequencing of a HEN involves rearranging the order in which heat exchangers are connected within the network (Farooq and Al-Qahtani, 2024). This optimization method is aimed at improving the overall efficiency and effectiveness of the HEN. During the re-sequencing process, we analyze the current configuration of HEN to identify areas for modification. Figure 3 shows that by strategically adjusting the heat exchanger that was at the extreme right in the base case design toward the middle, indicated by green spot, result in structural alteration of the design and minimize energy wastage, lower utility usage, and improve the efficiency of heat recovery. Additionally, as a result of this modification area of heat transfer increased, reducing the operating cost which has effect on TAC. However, it should be noted that the initial investment required for this modification may be higher. Nonetheless, the long-term benefits of improved energy efficiency and cost savings can outweigh the initial investment costs.

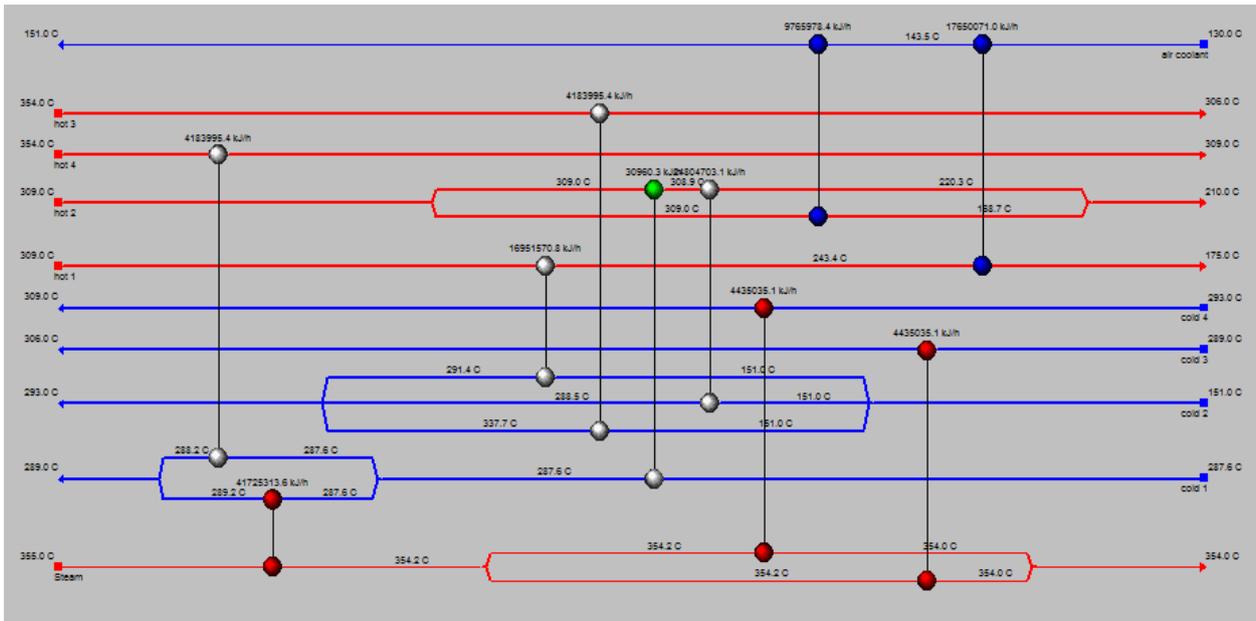


Figure 3: Re-sequenced HEN Design

2.4.2 Addition of a New Heat Exchanger

In this retrofit scenario, a new heat exchanger was incorporated to the original design to exchanger heat between hot and cold streams, as indicated by green spot in Figure 4. This modification can increase the heat recovery potential of the system, leading to reduced energy consumption and lower operating costs as a result of the increment in area of heat transfer area. However, this may require additional space and capital costs, the benefits of improved energy efficiency can result in significant cost savings in the long run.

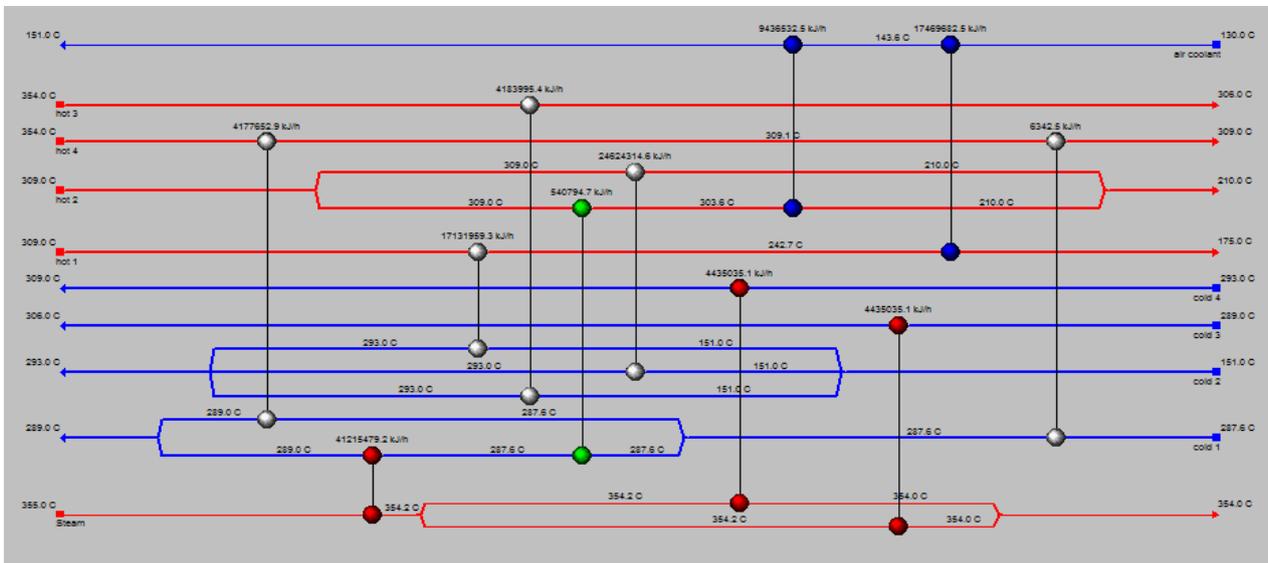


Figure 4: Modified HEN Design Via HX Addition

2.4.3 Addition of Area

In this case, the goal is to reduce the operating cost of the original design by expanding the areas of heat transfer. This was achieved by shifting the heat exchanger that was at the extreme right towards the extreme left of the original design shown by green spot in Figure 5. By doing so, less energy will be required for the heat transfer and the operating cost will be reduced. Increasing the heat transfer area result in a reduction of utilities requirement, energy, and achieved cost savings. This modification option can be an effective way to improve the energy efficiency and cost-effectiveness of the process. However, the investment costs and payback period must be carefully considered before deciding to proceed with this modification.

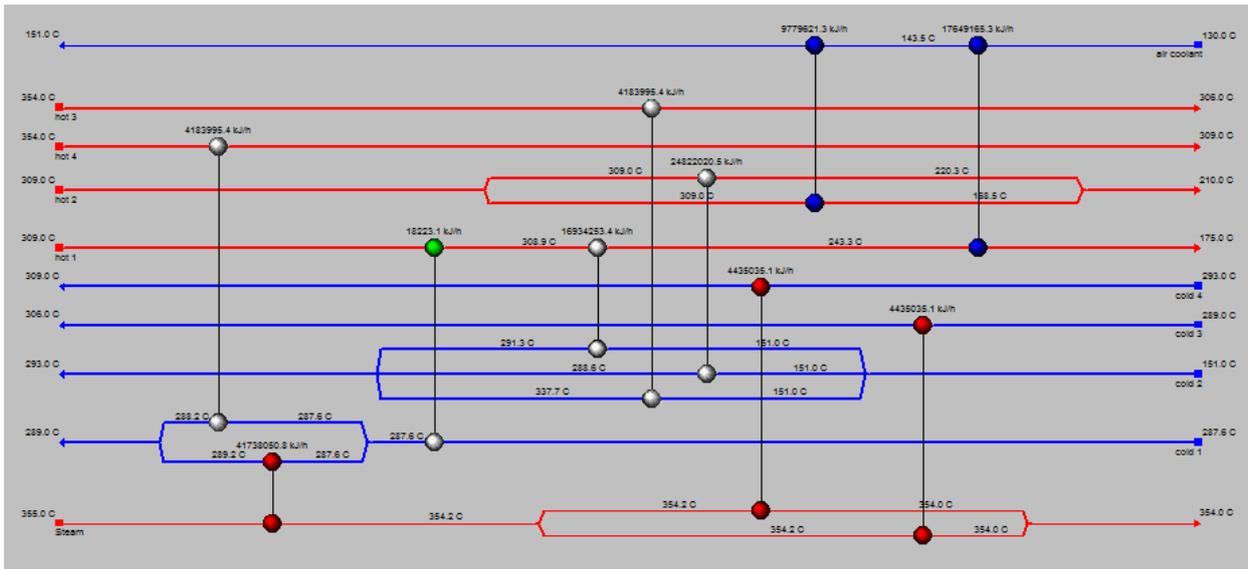


Figure 5: Modified HEN Design (Area Addition)

3. Results and Discussion

The designed HEN has proven effective to some extent in reducing utility requirements, yet it achieved a TAC of 104.5% (1.738 MM\$/year). To enhance both cost and energy savings, three retrofit scenarios were implemented: re-sequencing, addition of a heat exchanger, and area addition, with their outcomes detailed in Table I.

The area addition scenario increased the heat transfer area by 4.9 m², resulting in annual operating cost savings of \$439.5. However, this enhancement required an initial investment of \$1,733, with a payback period of 4.3 years. Conversely, the re-sequencing scenario expanded the area by 9.8 m², leading to improved energy savings of \$746.6 annually. The capital outlay for this scenario was also \$1,733, recouped over 3.9 years. Meanwhile, the addition of a new heat exchanger significantly increased the heat transfer area, resulting in substantial utility savings and annual energy cost reductions of \$33,810. However, the upfront investment required was substantial at \$167,100, with a payback period of 4.9 years. These findings aligned with recent research by Ndunagu et al. (2021) demonstrating energy savings of 8% through retrofits such as re-sequencing and the addition of new heat exchangers, albeit with higher initial costs recouped over 2 years. Similarly, Mengying et al. (2021) highlighted significant energy cost reductions and rapid payback periods for retrofit strategies in similar systems. Furthermore, Alhajri et al. (2021) reported that retrofitting scenarios achieved substantial energy savings of approximately 10.4 MW compared to existing designs, translating to annual energy cost savings of about MM\$2 and a payback period of less than one year.

Therefore, the retrofit strategies studied showed promise in reducing utility demand and improving operating cost savings. However, they require a significant capital investment with a payback period that exceeds one year.

Table I: Evaluation of HENs Design

HENs Design	New Area (m ²)	Area (m ²)	Heating (10 ⁷ KJ/h)	Cooling (10 ⁷ KJ/h)	Installation cost (\$)	Payback period (year)	Operating savings (\$/year)
Addition of area	4.9	5654	5.061	2.743	1,733	3.9	439.5
Re-sequencing	9.8	5657	5.060	2.742	3,191	4.3	746.6
Addition of HX	541	6098	4.922	2.605	167,100	4.9	33,810

4. Conclusion

This research demonstrated that retrofit scenarios such as re-sequencing, adding heat exchangers, and increasing area stand-out for improving energy efficiency and reducing operational costs. Despite their effectiveness in lowering energy requirements and achieving operating cost savings, they require substantial investment and entail payback periods exceeding one year. Therefore, it is crucial to explore additional retrofit possibilities to further enhance cost savings.

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