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Article

Recent Advancement in Synthesis and Pinch Analysis of Heat Exchanger Networks

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Abstract: Crude oil distillation units in many global crude oil refineries contribute to the ultimate exergy disruption and massive thermal energy consumption compared to other components in such plants. Implementing pinch analysis, retrofitting , careful design, rearrangement, and optimization of heat exchanger networks (HENs) is considered influential and valuable for reducing the total annual cost and total energy consumption. Over the past few decades, numerous studies have employed conventional linear programming methods that are time-consuming, inefficient, and unable to accommodate nonlinearities, intricate system dynamics, various thermodynamic properties, and uncertainties that arise under actual operating conditions. Recent publications emphasize the shift from strictly mathematical approaches to hybrid simulation-optimization frameworks. Comprehensive research on HENs generally falls into two distinct categories: Heat Exchanger Network Synthesis (HENS) and integrating commercial process simulators (like Aspen Plus) with metaheuristic algorithms. The simulation and optimization of Heat Exchanger Networks (HENs) using Aspen HYSYS emphasize three primary methodologies: Pinch Analysis (via Aspen Energy Analyzer), rigorous steady-state and dynamic simulations, and stochastic algorithms integrated with HYSYS to minimize total annualized costs and energy use. The present review is conducted on the recent advancements, influential impacts, and advantageous benefits of active pinch analysis, synthesis, and retrofit procedures performed to manage crude oil refinery operations and refine existing low-efficiency heat exchanger networks.

Keywords: PRISMA, Aspen HYSYS, pinch analysis, heat exchanger networks (HENs), optimization

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1. Introduction

Typically, around half of the whole worldwide economy relies on the crude oil industry. Petroleum refinery facilities are considered one of the most imperative chemical industrial plants in the globe. Approximately, they operate in every land. Being this reason, it is very influential to conduct careful design, optimization, and evaluations that can provide significant enhancements of thermal energy flow, heat transfer efficiency, and heat recovery to minimize probable thermal losses that can obviously result in excessive fuel consumption and great thermal energy wastes dissipated into the environment. In this context, the ASPEN® software have developed to allow petroleum engineers, chemical engineering specialists, and mechanical engineering professionals to perform various practical simulation tasks to explore the thermal performance, heat transfer,

and operational efficiency of some major components in the petroleum refinery. ANSYS® HYSYS is picked for carrying out mathematical simulations of existing procedures in the petroleum refinery and analyzing them experimentally and theoretically.

Generally, ASPEN® has all necessary information feeds concerning mostly all the devices and equipment utilized in the distillation process, which majorly contain different types pipelines, cooling towers, distillation columns, reactors, separators, heat exchangers, and other more tools. These equipment and instruments can be designed and connected in the ANSYS® software to analyze different procedures in the petroleum refinery. Besides, this software has almost all kinds of crucial chemicals needed to be fed into various streams [1].

One submodule of the ASPEN® platform is the ASPEN® Energy Analyzer. This submodule is utilized mainly to examine and identify comprehensive solutions and strategic configurations of HENs that can supply many trade-offs in terms of cost, thermal performance, and environmental impact. Commonly, scholars utilize this software submodule to design, optimize, and carry out pinch analysis of many types of HENs in CDUs. These simulation and optimization processes can promote HENs' thermal performance and operational efficiency, and reduce their annual operation and maintenance costs, which can be reflected in less thermal wastes, less fuel bills, and significant heat recovery. These goals can be achieved through the pinch analysis. Advanced pinch analysis can be conducted utilizing this ASPEN® software submodule. The pinch means the point of minimal temperature difference between cold and hot streams flowing in various heat exchangers in the HENs [2].

More importantly, within the HEN, either isothermal mixing process or non-isothermal mixing would take place. However, isothermal fluid mixing is not similar to the non-isothermal stream mixing processes. Also, isothermal mixing process is less realistic since it does not correspond to changes in temperature, particularly when phase changes occur, like boiling or condensation. Distinct characteristics and critical properties of each type of mixing can be clarified in Table 1.

Table 1. Key variations between isothermal and non-isothermal fluid mixing [3] [4].

Category	**Type of Mixing**	
	Isothermal Mixing	**Non-isothermal Mixing**
Temperature Consideration	It considers fluid mix at a single, fixed temperature.	It enables for mixing across a broad range of temperature amounts.
Existence in Reality	It is less realistic since it does not correspond to changes in temperature, particularly when phase changes occur, like boiling or condensation.	It is more realistic since it can precisely model fluids that have phase change situations or streams that do not mix at single temperature values.
Model/ Design Complexity	It is simple to design and model.	It is more complex to optimize, model, and analyze, necessitating special, advanced software tools or breakthrough mathematical strategies.
Efficiency and Cost	This mixing process can result in overestimation of the surface area of heat exchangers and TAC, limiting active trade-offs between various HEN arrangements.	This type of mixing can provide an optimized and economically feasible HEN design. It enables for highly efficient thermal energy recovery. In turn, less external

		heat utilities are needed.
Common Applications	This mixing type is mostly utilized as an early estimation or a simplification of fluids with no phase change.	It is favorable for precise, cost viable configuration, certainly for fluids that have complex interactions or phase changes.

It can be realized from Table 1 that the major variation is that isothermal mixing of streams considers a fluid mix at a fixed temperature value, contributing to a simple design. Nonetheless, this would potentially result in an overestimation of expenses. It would also result in limitations in the optimum varying temperature rates. These observations can be realized in streams that undergo phase changes. Comparatively, the non-isothermal mixing of fluids can contribute to remarkably cost viable design and enhanced thermal energy recovery. In this respect, breakthrough analytical optimization tools and mathematical computer simulation approaches are necessitated to save corresponding investigation costs, laborious, complex, and time-consuming estimation processes when enhancements and comprehensive upgrading solutions are needed to refine and renovate outdated HENs that operate in many crude oil refinery plants, certainly in CDUs.

In this review, the major research goals are summarized the resent advancement related to ASPEN® Energy Analyzer implementation to provide estimations, innovative rearrangements, viable optimizations, and holistic solutions to retrofit and upgrade old, low energy efficiency HENs operating currently in many crude oil plants.

2. Methodology

2. Systematic reviews and Meta-Analyses

Systematic reviews differ from conventional surveys by their novelty, quality, depth discussion, and breadth to bridge the knowledge gap, avoiding citing repeatedly many unnecessary and nonrelated subject ideas. They provide sufficient justification for each claim reported in the study. Therefore, their outcomes have greater validation rates compared to other types of studies, shown in Figure 1.

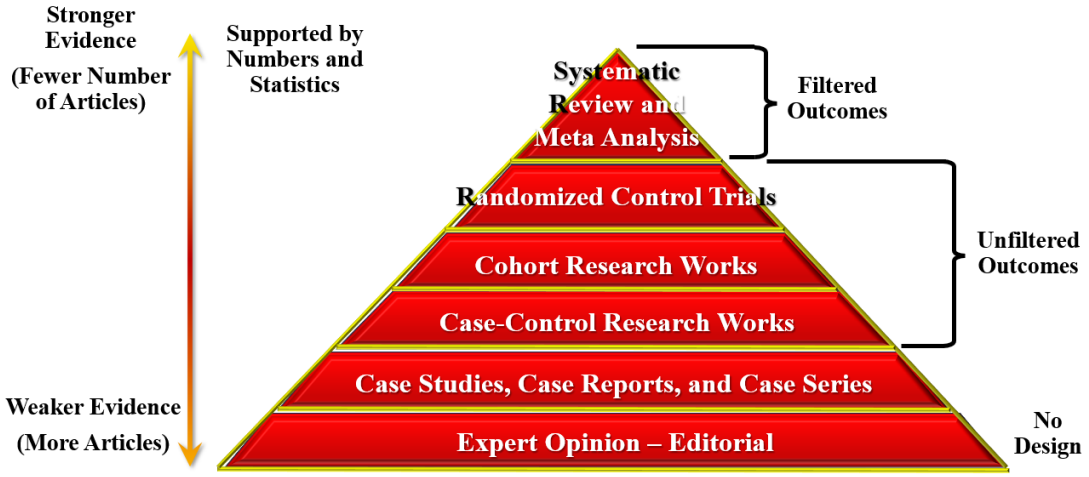


Figure 1. Critical characteristics of the systematic review.

Systematic review data collection approach is recognized with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) as well. The PRISMA strategy is viable in strengthening the efficiency, quality, and reliability of the study outcomes in comparison to other kinds of overviews. This strategy supplies a framework to report meta-analyses and systematic reviews holistically and transparently. It contains a number of guidelines to ensure the provision of

reproducibility, clarity, and completeness in research works. The main phases that are typically adopted in the PRISMA approach can be shown in Figure 2.

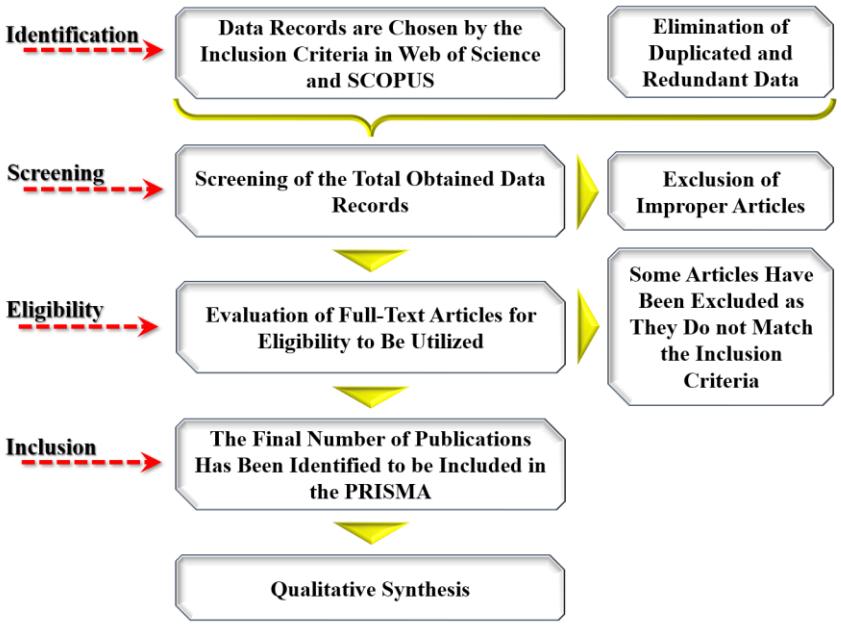


Figure 2. Pivotal stages related to the PRISMA strategy.

Simultaneously, the corresponding PRISMA GRADE system harnessed to distinguish the effectiveness of the research outcomes can be displayed in Table 2. This table was designed to enable scientists and reviewers to examine the robustness, performance, efficacy, strength, and viability of the total outcomes obtained from a specific research, especially systematic reviews. The table provides the capability to mark the quality of statistics, risk of bias, confidence of the evidence, the effectiveness of the novelty, and whether if the current investigated research has successfully answered the critical RQs efficiently and sufficiently.

Table 2, The PRISMA GRADE framework to identify the potential of its contributions.

No.	General Evaluation Category	Specific Domain Estimation	**Quality Grading (✓)** Excellent	Very Good	Intermediate	Poor	Very Weak
			Existence of Bias and Flaws Very Low	Low	Intermediate	High	Very High
1	Confidence and Robustness of the Evidence	Risk of bias					
2		Inconsistency					
3		Indirectness					
4		Imprecision					
5		Publication bias					
1	Statistical Importance,	Risk of bias					
2		Inconsistency					

3	Efficiency, and Noteworthiness of the Meta Analysis	Indirectness
4		Imprecision
5		Publication bias
1	Contribution/ Novelty to the Current Literature and Scientific Community	Risk of bias
2		Inconsistency
3		Indirectness
4		Imprecision
5		Publication bias
1	Results' Coherence, Scope, and Reliability of the RQ Answers	Risk of bias
2		Inconsistency
3		Indirectness
4		Imprecision
5		Publication bias

- The GRADE specific and general classification sorts are imperative to distinguish whether the overall systematic review outcomes are coherent, homogenous, consistent, feasible, and confident. The GRADE framework is pivotal to recognize if the total results are free from errors, bias, irrelevant and heterogeneous data.

To conduct the PRISMA data collection process and answer the RQs efficiently, a number of research stages has been implemented through the research methodology, which is illustrated in Figure 3. Firstly, the problem definition or the main subject of the study has been identified, which revolves around bridging the previously-cited knowledge void; highlighting innovative and breakthrough research outcomes related to practical pinch analysis, feasible refinement, and cost effective configuration of HENs in CDUs, aiming at lessening adverse ecological effects due to excessive consumption of fossil fuel due to the outdated configuration and low efficiency devices integrated in the old HENs in crude oil refinery plants. These objectives have been identified in the second research phase. Through the third stage, the approach of data collection process has been chosen. It expresses the provision of secondary data from various articles existing in the available literature. Then, the secondary data collection strategy was specifically identified, including systematic review applied by the PRISMA tactic.

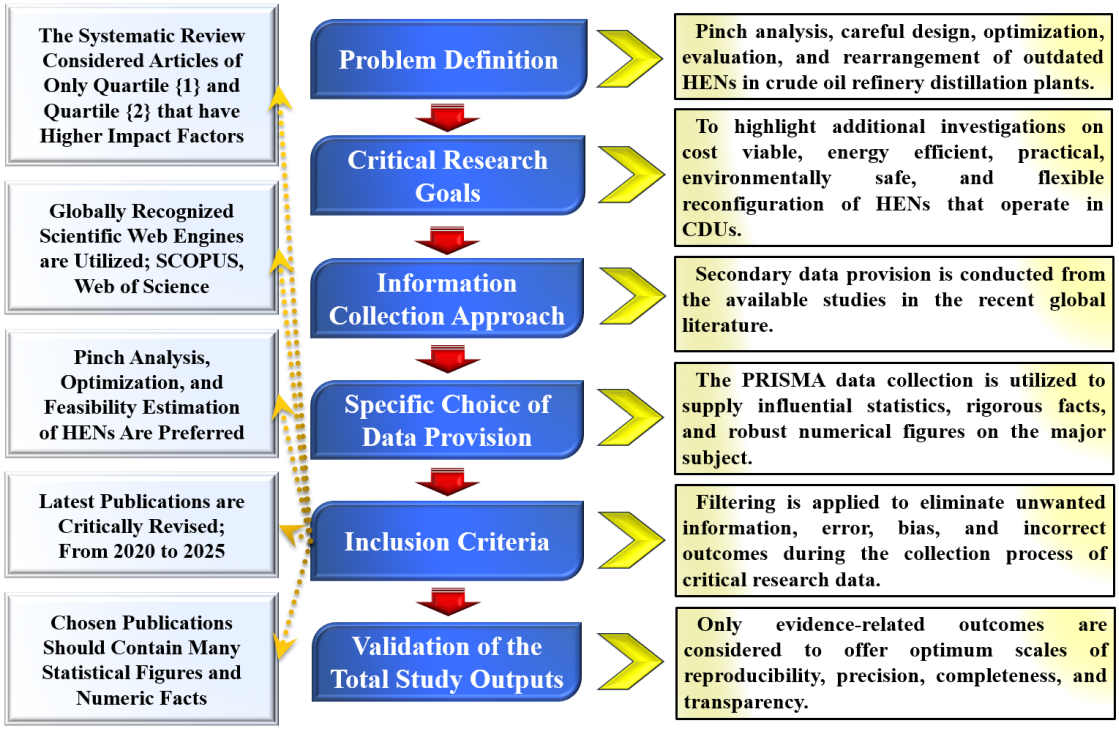


Figure 3. A flowchart of the major research methodology.

The most important phase of this work involved formulating and implementing a collection of data and filtering criteria, critically revising HENs synthesis research works, which are recently published in the last five years. The importance of these criteria is to eliminate flaws, bias, errors, and unwanted data that may contribute to low efficiency and quality in the overall obtained outcomes from the total publications reviewed in this study. After applying this filtering criteria, the overall results discussed and cited in the whole work will be verified and validated by considering the major validation principles related to the PRISMA approach.

3. Advanced Design Strategies to Optimize Critical Crude Oil Refinery Components

Rafeek [5] inspected a case study of a petroleum refinery plant, seeking to promote its exergy efficiency (ExE) and EE. The authors reported that the distillation process is considered a pivotal phase that is broadly utilized in many industries, particularly in crude oil refinery systems. They clarified that an efficient separation process is featured by its enhanced thermal performance and less energy consumption. In this respect, this research estimates the thermal effectiveness of the distillation process in a petroleum plant located in Northern Egypt. The major objective is to raise ExE and EE. ASPEN® HYSYS was utilized to achieve the study goals. The first and second laws of thermodynamics have been implemented. To validate the effectiveness and superiority of the HYSYS model, practical, actual data have been utilized in a comparative analysis. The major outcomes of the optimization and analysis processes, which concentrated on some critical components in the crude oil refinery, namely the distillation tower, showed that this component had the largest exergy destruction (reaching 44.5 GJ/hr, i.e., 41.8% of total exergy destruction). The investigation considered analyzing coolers, pumps, HEN, fired heater, and the Preflash unit.

It is imperative to remark that the reason for the larger exergy destruction in the distillation tower is owing to irreversibility properties connected to the phase separation. Conversely, the Preflash unit exhibit the maximum thermal energy performance, recording an ExE of 97.1% and a minimum total exergy destruction of 459 MJ/hr. The main research outcomes also confirmed that the HEN and the fired heater have exhibited robust EE, recording values of 91.6% and 92.7%, respectively. However, those two components contributed to no negligible values of thermal losses. On the other side, coolers showed the least ExE, i.e., 55.2%. It is responsible for about 33% of

the total exergy destruction in the crude oil plant. Simultaneously, parametric investigation uncovered that raising the overhead pressure would enhance the overall ExE by a proportion of 4.3%. In comparison, excessive pumping flow rates could result in greater irreversibility issues and minimal EE. The researchers explained that their findings are noteworthy since they provide valuable insights to help managers and professionals conduct enhancements in the thermal energy recovery and operational effectiveness in crude oil refinery plants, which can bring fostered scales of sustainability and EE.

Ibrahim [6] performed an analytical work, design, and optimization of a case study that expresses a CDU at a crude oil refinery plant in Al-Basra, Iraq. To achieve the study objectives, the authors utilized the ASPEN® HYSYS software. Three distinguished scenarios have been explored, namely (A) The original situation that contains four separation phases, (B) an improved design that integrates three separation phases, and (C) the proposed layout that integrates three separators with a stripping tower. The scholars took into account minimization of the operating costs, and a number of economic profitability indices. This was done by removing the fourth-stage separator by adjusting the pressure drop through the valves to enable the pressure rate to reach the atmospheric pressure value at the final separation phase. At the same time, an alternative separation technology was performed, helping raise the mass fraction of the crude oil from 0.829 to 0.980. The critical study outcomes confirmed that removing the fourth stage separator would supply remarkable economic feasibility with no compromising of the product quality. In addition, it was noted that the three-phase separation configuration in the second scenario would minimize the CAPEX by 20.75%. As a result, this has yielded in TAC savings of 969,550 USD. Simultaneously, the core research outputs affirmed that the three-phase separation provided the most economically viable solution, which corresponded to active minimizations in the CAPEX and TAC. Conversely, integrating a stripping tower in the third scenario has resulted in a minimization in the CAPEX by 87,500 USD; however, increases in some costs were noted. Besides, this scenario contributed to improvements in the separation efficiency due to the rise in the heat recovery in the crude oil mass fraction. Nonetheless, corresponding total expenses have risen.

Fidelis [7] conducted mathematical simulation and numerical optimization processes using the ASPEN® HYSYS software package, exploring opportunities to enhance the current EE, ExE, thermal performance, economic profitability, ecological impact, and operating conditions of current crude oil refinery plants in Nigeria. The scholars explained that promoting such measures is crucial for the Nigerian industrial sector and economy because efficient and high-performance petroleum refineries can contribute to significant energy savings and less adverse environmental influences to the local Nigerian nature. Therefore, their analysis and the retrofit process included a case study of the Aradel's Water-Box Cooler and CDU. The retrofit process considered implementing rearrangement of the best HEN configuration that can supply promoted levels of thermal efficiency. The results revealed that this rearrangement has contributed to minimization of the Heavy Fuel Oil (HFO) rundown temperature from 101.3 °C to 76.4 °C, helping ensure a remarkably stable and stable product storage conditions.

In addition, the optimization process has contributed to energy savings in the CDU by 8.1%. This process has simultaneously resulted in an increase in the overall yield of the crude oil distillation products of high demand, notably dual-purpose kerosene (DPK) and automotive gas oil (AGO) by 64.04% and 12.5%, respectively, supporting the refinery in matching common products that are greatly needed in the market. The pivotal insights obtained from the simulation and optimization outputs confirmed the significant practicality, feasibility, and reliability of such practices to implement, enabling better support of refinery decision makers to enhance the thermal performance and operational efficiency of their plants, while improving its safety.

Anagani conducted an analytical optimization work through which various performance indices and feasibility variables of a crude oil distillation unit have been explored. The author relied on the ASPEN® HYSYS software package. The major objective of this doctoral study was to examine and identify thermal energy losses and locations where excessive or inappropriate energy

consumption takes place. This step is imperative since excessive energy consumption and thermal losses may contribute to larger GHG emissions and pollution of the local environmental system. The author conducted a thorough overview of the literature. Then, a petroleum refinery plant was explored and simulated by the ASPEN® Plus software Weiss [8]. illustrated a crude oil refinery plant that was utilized in marine industry to produce heavy fuels. This process is considered an energy intensive. Therefore, a careful energy analysis and optimization of the thermal performance are influential and important. Pinch and sensitivity analytical works were carried out to identify the most suitable energy requirements of the plant. Specifically, the pinch analysis was performed to distinguish the most appropriate configuration of the HEN utilized at this plant. Simultaneously, the sensitivity analysis was implemented to investigate the impact of changing the variables correlated to the best HEN configuration. and the outputs revealed a superior HEN configuration that has enhanced thermal performance, less GHG emissions, and great economic feasibility relying on the pinch analysis. The temperature difference has been also optimized.

Hussain [9] implemented numerical optimization and mathematical simulation to design and analyze a new column sequencing necessary to operate in a crude oil distillation tower at Al-Basrah crude oil refinery plant. The authors elucidated that adopting such strategies for crude oil refineries in Iraq is considered substantial and imperative because efficient consumption of fossil fuel can enhance refinery plant's thermal performance, EE, economic profitability, and reduce its negative environmental impact. Within this framework of background, the scholars introduced a breakthrough strategy, recognized with "marginal vapor flow (MVF)" to carry out an optimization of the distillation tower sequence in the crude oil refinery plant, providing more concentration to the third distillation unit at Al-Basra Petroleum Refinery Plant. To achieve the major research objectives, simulations have been run by the ASPEN® HYSYS Version 11 platform. Through the simulation process, the needed overall energy consumption was estimated. It was also compared to the optimum sequence that was suggested by the MVF approach. Moreover, a state-of-the-art adoption of the downward minimization formula was exploited to help choose light and heavy products.

Critical research outcomes revealed influential contributions and rationale obtained from the integration of ASPEN® HYSYS with MVF technology to optimize petroleum refinery distillation tower sequences. Specifically, the ASPEN® HYSYS software helped precisely model main processes occurring at the distillation column. At the same time, the MVF technique has facilitated identifying the optimal tower sequences referring to marginal amounts of the vapor flow rates. On the other hand, it was clearly noted that within the inspected sequences, sequence number nine has exhibited the least overall MVF, recording 1,393.4 kmol/hr, implying its optimality. In comparison, sequence number two has showed the greatest overall MVF with a value of 4,827.3 kmol/hr, indicating the lowest preferable situation. The simulation outcomes related to the optimum sequence obtained from the MVF technique showed a significant reduction by 35% in the total energy consumption compared to the original operating scenario at real conditions. In contrast, the simulation findings linked to the lowest preferable scenario exhibited a considerable increase in energy consumption by 32% compared with real operating conditions.

As a whole, the current work underscores the influential role of the MVF technology in performing active optimization of various distillation sequences to achieve fostered EE, supplying actionable strategies to improve current operations in petroleum refinery plants; therefore, minimizing the resulting operating costs and total energy consumption that can, in turn, alleviate adverse ecological impacts and raise sustainability measures.

Domingos [10] carried out mathematical simulations and numerical optimization related to an atmospheric distillation column, analyzing parametric correlations that create influential insights that provide better understanding concerning operational performance of the overall distillation process in a crude oil refinery plant. The authors reported that petroleum refineries contain a collection of units that operate to fractionate raw heavy crude oil into lighter greater-value products. One of the imperative units in the crude oil plant, which contribute to very large

exergy destruction compared with other components in the plant is the distillation tower. Accordingly, the scholars analyzed this unit, which consists of multiple elements incorporated inside the distillation tower. These various components are important to facilitate a concurrent thermal and mass transfer between fluid phases, including liquid-to-vapor phases, while attaining optimum thermodynamic equilibrium between these phases.

mathematical simulations and numerical optimization considered a number of key variables, notably the amounts of side stream flow rates, reflux constraints, the rates of steam injection, temperature values, and the rate of feed flow. The authors utilized ASPEN® HYSYS version 8.8 to achieve the goals of their research. Pivotal study findings confirmed that it was possible to achieve the targets of the objective function, helping ensure a diesel production amount of 2,900 metric tons/day. This result expresses approximately a threefold rise in the production process compared to the original level with no optimization. Therefore, a conclusion can be reached that such optimization and simulation procedures can support petroleum refinery operators in achieving considerable sustainability and enhancements, contributing to maximization of EE and thermal performance to thermal processes. Figure 4 indicates a correlation between the diesel flow and reflex ratio with each of temperature and the steam flow.

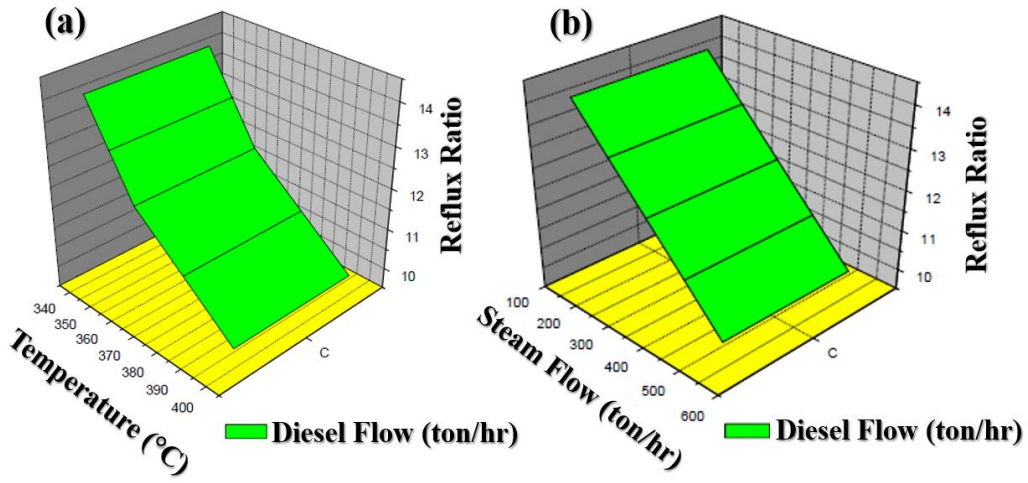


Figure 4. Diesel flow rates influenced by: (a) both temperature and reflux ratio and (b) both steam flow and reflux ratio.

Olugbenga [11] applied both simulation and optimization procedures of a crude oil refinery plant to investigate the stabilization process at this plant. The scholars utilized Response Surface Methodology (RSM) and ASPEN® HYSYS to conduct energy saving modifications that can contribute to less GHG emissions and better sustainability. They clarified that the stabilization procedure in the crude oil refinery includes eliminating remarkably volatile hydrocarbons, like propane, ethane, and methane, while raising the fraction of heavier hydrocarbon products in the fluid. Following the production process, the dissolved gas in the crude oil should be removed to avoid shrinkage in the storage tanks. It is imperative to remark, in this context, that maintaining optimum value of the Reid vapor pressure (RVP) in the range between 10-12 psia at the atmospheric temperature is considered important. In this respect, this work performed an analytical analysis of the stabilization process of the crude oil refinery by recycling the condensate into the separator feeds. Referring to the general production, the stream composition and procedure conditions have been attained and recorded from real-time data.

As mentioned above, both RSM and ASPEN® HYSYS simulation software to conduct optimization of this stabilization process to provide enhanced thermal efficiency and performance. The HYSYS model has precisely reproduced mass transfer and thermodynamic characteristics of

the process, supplying an influential foundation of such inspections. To leverage RSM's empirical analysis potential, a number of critical variables has been examined, including pressure, temperature, and flow rare. These indices influence the values of the RVP and total energy consumption. The major simulation and optimization outcomes affirmed complex interdependencies besides optimum variable configurations. The integrated optimization strategy RSM and ASPEN® HYSYS has established a rigorous system to optimize the stabilization process of the crude oil refinery. The results also revealed a value of 7.75 psia of the RVP. More importantly, this optimization and simulation procedures have promoted the economic profitability of the oil and gas sector by connecting software suggestions to crucial sustainability goals.

Lian [12] conducted a retrofit analysis and investigation of the acid gas sweetening procedure in a crude oil refinery. The authors utilized the exergy analysis strategy. In this context, they explained that in spite of the increasing rates of R&D and investigations in the natural gas and petrochemical industries over the last decades, the process optimization and analysis of the energy consumption still formulate a challenging knowledge gap. So, their work relied on exergy investigation and process simulation to examine the bottlenecks of general acid gas sweetening procedure at crude oil refineries. To achieve this objective, the ASPEN® HYSYS platform was exploited.

Some optimization approaches have been created and discussed. Firstly, a state-of-the-art low temperature absorption, considering a lean solvent temperature that reached 15 °C was created and integrated into the cold energy recovery of sweet gas. This step has enhanced the absorption efficiency and minimized the circulation rates of the lean solvent. Secondly, a modified heat pump distillation process was created. It combined split flow feeding strategy. Through the simulation and optimization analytical procedures, the critical study outcomes revealed that the total energy consumption and the operating expenses have been minimized by 22% and 14%, respectively, for the absorption process. The results also confirmed that when the modified regeneration process has been considered, the resulting energy recovery and EE have been enhanced. Additionally, it was realized that the TAC, the overall energy consumption, and the operating expenses have been minimized by 13.1%, 30%, and 19.3%, respectively.

Abo-Mousa [13] conducted graphical analysis and simulation and optimization procedures to revamp the existing Suez Oil Petroleum Refinery Plant located in Suez, Egypt, which was considered the case study of this work. The scholars gave more focus on refining and renovating the current distillation tower because of its greatest exergy destruction and largest thermal energy consumption compared to other components in the refinery. They took into account variant operational constraints. They also aimed at raising the target temperature value of different crude oil streams before they enter the furnace. In this context, the authors expressed that a remarkable progress has been done to enhance the design and analysis of CDUs throughout the latest decade. Prevalent useful strategies of these analytical approaches involve mathematical programming strategies and pinch tactics.

More recently, graphical tools have been also created and implemented to help provide some revamping and renovating scenarios of existing CDUs, suggesting possible enhancements styles and optimization of their thermal performance, ecological impacts, and operational costs. These profiles are practical since they can distinguish energy inefficiency issues; therefore, performing necessary modifications to maximize EE. Accordingly, this study has implemented graphical retrofit strategy on the CDU related to the case study, cited above. The CDU utilizes two ways of operation, including (A) without and (B) with naphtha stabilizer. When the naphtha stabilizer is not utilized, the process reformer would operate to reform all naphtha fluids without stabilization. Comparatively, when the naphtha stabilizer operates, LPG can be separated from the naphtha fluid.

To conduct a retrofit of the current preheat train, a graphical-related renovation strategy was

adopted. This revamping approach was initiated by making mathematical simulation of the current HEN data by the ASPEN® HYSYS software tool. This step was followed by making verification against actual information. Also, the thermal performance of the HEN was examined by the two graphical axes that include T_{hot}-T_{cold} profiles. After that, the graphical approach was harnessed to recognize heat exchangers along the pinch and identify the possible modifications that can be considered to enhance the thermal EE and minimize the total fuel consumption. The core research outcomes revealed that the graphical strategy has identified some probable and feasible modification actions on the CDU and the petroleum plant, contributing to the following advantages:

(A) achieving energy savings of 21.1% when the stabilizer is utilized and operates. However, extra CAPEX of 0.81 million USD and reductions in TAC of 0.82 million USD, with a PBP of 1 year,

(B) accomplishing energy savings of 0.42 million USD and CAPEX of 0.33 million USD when the reformer operates and is utilized.

The critical outcomes of this graphical approach and ASPEN® HYSYS simulation process affirmed considerable scales of flexibility and capability to support engineers and crude oil refinery managers and operators in performing such revamping and renovation practices to enhance thermal performance and reduce corresponding operating costs.

Okechukwu [14] implemented mathematical simulations and numerical optimization processes to provide enhanced economic feasibility and minimal energy consumption of a CDU investigated in the case study of the Port-Harcourt Crude Oil refinery. To achieve the study goals, the author utilized the ASPEN® HYSYS software package, which helped conduct a pinch analysis. The scholar focused on reconfiguring HEN to achieve less TAC. Various operating variables have been considered, namely specific heat recovery, the flow rate of the heat capacity, and inner and outer temperature values. The author obtained some critical statistics to investigate and obtain the least TAC, notably Grid Diagrams, Grand Composite Curves, Composite Curves, and the minimal approach temperature.

Relying on the optimization procedures carried out in the ASPEN® HYSYS platform, it was found that the minimal temperature difference that can achieve very low heating and cooling demands in the CDU was 20 °C. The least cooling and heating energy requirements reached 2.16 $\times 10^8$ kJ/hr and 7.70 $\times 10^7$ kJ/hr, respectively, indicating a reduction of 114% of thermal energy needs compared to the existing CDU. In addition, it was realized that the overall number of heat exchangers required in the HEN in the CDU accounted only to 18 compared to 24, which is currently utilized in the CDU. Resultantly, these reduction trends have recorded an overall minimization in the TAC by 207.9%. These insights provide active validation of this software package in conducting such optimization tasks to achieve practical reductions in the TAC and operating costs, which is considered very noteworthy and imperative.

Jaja [15] carried out an optimization process of a crude oil distillation unit. The authors took into account the analysis of a case study that expresses the Port Harcourt Refining Company. They formulated an HYSYS model of this case study. The investigated HYSYS model consisted of three mixers, three heaters, one heat exchanger, one desalter (3-phase separator), two-phase separator, and the major fractionating column. The raw crude oil was explored and characterized relying on the ASPEN® HYSYS version 8.8. The created HYSYS model was simulated considering the industrial plant information provided by the Port Harcourt Refining Company. The HYSYS model supplied component mole fractions of 0.2517, 0.0547, 0.2687, 0.1572, and 0.2667, for Atmospheric Residue, Heavy Diesel Oil (HDO), Light Diesel Oil (LDO), Kerosene, and Naphtha, respectively. When compared to the mole fractions of the plant, which are 0.2550, 0.0530, 0.2650, 0.1560, and 0.2710, an ultimate deviation of 3.2% was attained.

Through the HYSYS mode, the ASPEN® software was also capable of predicting the temperature besides the tray of withdrawal for atmospheric residue, HDO, LDO, kerosene, and

naphtha corresponding to temperature values of 320 °C (of Tray 48), 310 °C (of Tray 35), 215 °C (of Tray 25), 206 °C (of Tray 12), and 120 °C (of Tray 1), respectively. A comparative analysis was conducted with the crude oil plant information, offering an ultimate deviation of 23.2%. In addition, the HYSYS model was optimized referring to Sequential Quadratic Programming (SQP), taking into account the operating conditions as the critical boundary constraints. The core PhD outputs confirmed that the optimization process helped raise the overall mass flow rate of Naphtha from 7.5×10^4 kg/hr to 7.7×10^4 kg/hr. Similarly, the kerosene product flow has increased from 5.2×10^4 kg/hr to 5.2×10^4 kg/hr. Also, the LDO product flow rate has risen from 1.105×10^5 kg/hr to 1.112×10^5 kg/hr. Moreover, the HDO flow rate has upgraded from 2.97×10^4 kg/hr to 2.98×10^4 kg/hr. Finally, the atmospheric residue flow rate remained at a value of 3.16×10^5 kg/hr. The outcomes also revealed that the optimal mole fraction rates of the five products, respectively, were 0.2584, 0.0528, 0.2635, 0.1540, and 0.2713. At the same time, the resulting optimal temperatures have recorded amounts of 327 °C, 317 °C, 257 °C, 221 °C, and 129 °C, respectively.

3. Results and Discussion

4. HENs Retrofit and Synthesis using ASPEN® Energy Analyzer

The ASPEN® software has also some submodules, notably ASPEN® Energy Analyzer, which can be exploited to identify the best combination between different heat exchangers in a HEN to offer optimum operational efficiency, enhanced thermal performance, and promoted cost viability.

Basir [16] carried out a pinch analysis, and optimization, design, and simulation of HEN, seeking to examine the best HEN configuration in a biodiesel production system from waste cooking oil (WCO) that could supply ultimate scales of energy savings, economic profitability, and thermal performance by identifying opportunities to make an active energy recovery from this process. The authors explained that pinch analysis and HEN reconfiguration are considered two influential analytical tools that can identify chances for efficient energy recovery and cost savings. In turn, these active outcomes from these two approaches can offer critical strategies to alleviate adverse environmental impacts of the biodiesel production system, enhancing its sustainability rates. To achieve the major study goals, the scholars utilized ASPEN® Plus software and ASPEN® Energy Analyzer platform. Specifically, ASPEN® Plus computer tool was implemented to conduct mathematical simulations of the biodiesel production process, offering an in-depth modeling and understanding of the thermodynamic characteristics related to the investigated process.

Comparatively, the ASPEN® Energy Analyzer platform was exploited to apply a pinch analysis, which is imperative to categorize the values of the pinch temperatures and evaluate the minimal cooling and heating thermal energy demands. The core research outputs revealed that the pivotal pinch temperature values were 40 °C, 115 °C, 125 °C, 165 °C, and 177 °C. Additionally, it was observed that the minimal thermal energy needed for the hot utility was 1.04×10^6 kJ/hr, while the minimal heat amount needed for the cold utility reached 7.96×10^6 kJ/hr, indicating critical chances to improve the EE. Practically, the results confirmed that the new HEN configuration would achieve significant energy savings in the hot utility and cold utility by 3.203 MW and 3.306 MW, respectively. In turn, these insights can highlight active savings in the TAC by 295,146 USD and 23,808 USD for hot and cold utilities, respectively.

Alznati [17] performed a pinch analysis, optimization, and analysis of HEN. The authors exploited ASPEN® Energy Analyzer platform. Their case study expressed a natural gas sweetening unit (NGSU) in Libya. The researchers concentrated in their study on exploring the heat integration process in the HEN. They also focused on reducing the total energy consumption to minimize the resulting operating costs of the crude oil refinery in which the NGSU operates. Their work relied on two stages. Through the first phase, ASPEN® HYSYS software tool was implemented to create a number of imperative flow diagrams of the NGSU. In the second phase, ASPEN® Energy Analyzer platform was exploited to estimate the pinch temperature and cold and hot utilities. The second software, i.e., ASPEN® Energy Analyzer platform, was also applied to achieve feasible and practical energy savings, which can be translated by active economic

profitability and less consumed fuel; therefore, less needed costs to obtain steam to heat up the cold fluids. The core simulation and optimization outcomes revealed that the optimal hot pinch temperature was 108 °C, while the cold pinch temperature was 98 °C. Besides, the thermal energy needs of the cold utility reached 4.7×10^7 kJ/hr, while those thermal energy amounts needed for the hot utility were 1.3×10^7 kJ/hr.

Sadek conducted a retrofit analysis, design, and optimization of a HEN, operating in a crude oil refinery plant. To achieve these tasks, ASPEN® HYSYS and ASPEN® Energy Analyzer software tools. The authors reported that these software tools are remarkably valuable and feasible to identify thermal energy losses and inefficient configurations of HENs that could waste much expenses and fuel. In this context, they explained that the current HEN design wastes not less than 776% of thermal energy, which is considered a massive ratio. Therefore, their retrofit analysis, design, and optimization aimed to reduce the total thermal energy consumption, utilized surface area, and financial expenses of the current HEN arrangement. Relying on the simulation and optimization procedures carried out in both ASPEN® HYSYS and ASPEN® Energy Analyzer submodule tools, it was realized that six valid retrofit HEN configurations have been obtained. The HEN arrangement with the least PBP has been chosen. In addition, the resulting energy savings from the chosen HEN configuration reached about 600% compared to the original HEN design, reaching a PBP of approximately 0.72 years.

Muharja [18] harnessed ASPEN® Energy Analyzer software tool, spreadsheet, and the Peng-Robinson formula to reconfigure a HEN functioning at a Paiton Steam Power Plant, at East Java, Indonesia, which is chosen as the case study of this work. The authors focused on adopting proactive strategies to minimize the overall energy consumption and TAC. They elucidated that heat recovery in such industrial facilities is considered greatly valuable because of much savings in operating costs and GHG emissions that can be achieved from these analytical energy investigations and optimization processes.

A comparison was carried out to attain the lowest surface area of the optimum HEN and ultimate energy recovery, considering a temperature range of 10 °C to 19 °C. Grid diagram was utilized to optimize the best HEN arrangement. The core simulation and optimization findings affirmed that the TAC has been reduced at a temperature difference of 16 °C. In addition, this optimization work has brought total financial savings of 14.3%, which are reflected in active minimizations in TAC, CAPEX, and operating costs. More importantly, it was found that the obtained ultimate thermal energy recovery has reached nearly 286,706 kW, while the overall surface area of the HEN amounted to 138.8 square meters. These imperative insights are influential to minimize the overall financial expenses and raise the crude oil company's competitiveness in the local market.

Pethe [19] carried out numerical simulations and optimization procedures to distinguish the most viable and practical HEN utilized in the CDU of the Kaduna Crude Oil Refinery Plant. To accomplish the necessary research objective, the submodule ASPEN® Energy Analyzer software tool was exploited. This software enables engineers to choose the best HEN configuration, taking into consideration many constraints and boundary conditions that are crucial to minimize the operating costs, adverse environmental impacts, and enhance thermal performance and heat transfer efficiency. The scholars utilized the pinch analysis in this software to conduct such choice process. They formulated Composite plots, Grand-Composite curves, and Alpha profile. They also implemented a comparative analysis related to the values of the TAC. The major research outcomes revealed that the pinch temperature rates were 2,640 °C (in the hot pinch) and 2,440 °C (in the cold pinch).

Simultaneously, it was found that the cold utility thermal energy requirements were 2.46×10^8 kJ/hr, which is related to the needed cooling water. On the other hand, the thermal energy needs related to the hot utility reached 2.02×10^8 kJ/hr at the furnace. Besides, it was realized that the achieved heat recovery of the suggested scenario was 4.178×10^8 KJ/hr. Also, a reduction in the

hot utility was achieved, reaching roughly 26.9% of the total target heating load. Comparatively, the cold utility energy reduction accounted to nearly 22.8% of the initial target heat load. Also, it was found that the minimal number of heat transfer units, including heat exchangers, heaters, and coolers has risen, contributing to an increase by 38.1% in the CAPEX, which is over the initial target CAPEX.

Udochukwu [20] followed and performed simulation and optimization approaches to examine the best HEN design and configuration in a Catalytic Reforming Unit (CRU) operates at a crude oil refinery in Nigeria. To achieve the major study goal, ASPEN® Pinch (Energy Analyzer) submodule tool of Version 11.1 was harnessed. Crucial Composite, Balanced Composite, and Grand Composite profiles have been created to identify inner and outer temperatures and related enthalpies that may correspond to greater or lower thermal energy consumption. Therefore, promoted design of the HEN configuration can be obtained that prevent thermal losses. The minimum operating temperature was 15 °C, while the pinch temperature reached 149.5 °C. The cold and hot utility targets amounted to 22,440 kW and 37,094 kW, respectively. In addition, the scholars implemented the problem table algorithm (PTA) to explore the precision of the rates, functioning as a sensitivity analytical tool.

This model revealed that similar exact values have been attained with a variance of only 0.4%. From the optimization process conducted for the HEN, it was observed that the optimum HEN arrangement provided the least heat recovery, reaching 55,465 kW. However, the overall number of heat exchangers has risen from 18 to 21, while the overall surface area reached 1,996 square meters. The power law formula was also exploited to identify the HEN expenses and attain the lowest TAC. Correspondingly, the CAPEX reached 5,918 USD/annum, the energy cost amounted to 2,892 USD/annum, and the TAC accounted to 57,443 USD/annum. These insights and numerical figures illustrate that the Pinch analysis by the ASPEN® Energy Analyzer has the potential to alleviate negative ecological impacts and reduce many operating expenses of the CRU and HEN.

Mrayed [21] administrated modeling, mathematical simulations, and numerical optimization of a CDU in a crude oil refinery plant. Their major research objective was to improve the thermal efficiency, and achieve a greater heat recovery, and a large economic profitability of the system. To achieve these study objectives, the authors utilized ASPEN® HYSYS to model and optimize the CDU. They also implemented ASPEN® Energy Analyzer through which a pinch analysis and a retrofit have been done to the HEN operating at this CDU. The authors, remarked, in this context, that thermal energy losses are inevitable in the process, particularly when critical CDU equipment and major devices are outdated and have low efficiency. In this respect, the pinch analysis can support engineers in conducting a retrofit of the HEN by minimizing the thermal energy losses. This approach has proved its successful outcomes and effectiveness in many industrial applications and large utilities.

To validate and prove the viability of the suggested HEN configuration and retrofit process, a baseline scenario was proposed. This scenario, i.e., the case study helped identify the ultimate probable energy savings, which can be attained. The pinch analysis was conducted by the ASPEN® Energy Analyzer and ASPEN® HYSYS software tools to recognize the optimal energy that can achieve enhanced energy recovery with minimal CAPEX. Another alternative HENs configuration was explored relying on the same pinch analytical platform. All analytical processes have been applied referring to the existing heating and cooling utilities in the refinery plant. Figure 5 indicates two schematic diagrams of the HENs before and after the modification process.

The pivotal research outputs confirmed that approximately 67.5 MW of ultimate heating and cooling utility could be recovered in comparison with the current utility load, which was 148.6 MW. As a result, this energy recovery has contributed to roughly 45% energy savings in the thermal energy utility requirements. Simultaneously, it was found that possible savings in the carbon dioxide emissions would reach a maximum value of 1,079 kg per hour related to a feasible

and practical scenario, while these savings could equal up to 7,840 kg per hour related to the grass rooting retrofit option

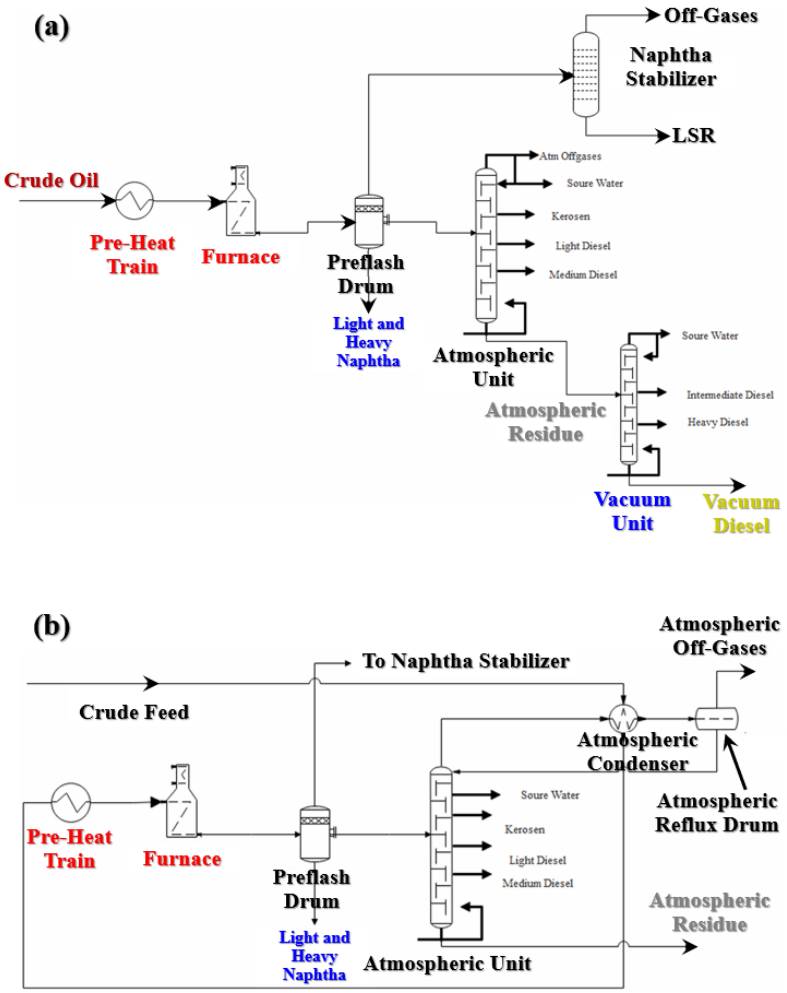


Figure 5. A schematic of the HEN (a) before and (b) after the modification process.

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Ogbonnaya [22] implemented simulations, optimization, and pinch analysis of a HEN, focusing on modifying heat exchangers with paths and loops to enhance their thermal EE, thermal performance, and cost viability. To achieve the major objectives of their work, the scholars utilized ASPEN® Energy Analyzer software package. Through their implemented simulation, synthesis, and optimization procedures to modify the current HEN arrangement, the authors focused on lessening the TAC. They adopted a blend of conventional pinch mechanisms that relied on mathematical programming besides the optimization approach. Composite Curves and Grand Composite Profiles have been created. Simultaneously, super-targeting, looping frameworks, linear programming, and MILP have been harnessed in the pinch analysis and optimization of the best HEN design.

A number of case studies have been considered from the available literature and solved using the ASPEN® Energy Analyzer. Then, these solutions have been compared to provide sufficient validation and effectiveness of the proposed HEN configuration. It was found that the resulting HEN arrangement had a superior thermal performance and EE. Also, the path and loop optimization brought four feasible TAC values out of five problems considered in their work. Furthermore, it was realized that the pinch analysis implemented by the ASPEN® Energy

Analyzer is greatly proactive and efficient compared to other traditional methods existing in the current literature.

4. Conclusions

This systematic review has been conducted to bridge some research voids in the current literature. A PRISMA data collection approach was adopted to achieve the study goals and provide necessary answers to the major research questions. Multiple validation and filtering criteria were applied and considered to eliminate flaw, bias, and errors and enhance the overall quality, value, and effectiveness of the overall outcomes obtained from the literature. Relying on the major data collection approach adopted in this work, the major research outcomes can be summarized in the following:

1- The ASPEN® software package, including the ASPEN® HYSYS submodule, offered a number of breakthrough solutions and practical contributions that supported petroleum engineering experts and analysts in overcoming old-fashioned linear programming mechanisms and investigation methods that are time-consuming, imprecise, and complex,

2- The ASPEN® Energy Analyzer submodule platform has supplied technological innovations reflected in promoted pinch analysis of old-style HENs with low efficiency and poor heat transfer performance, contributing to various favorable advantages for crude oil managers, like energy and annual cost savings,

3- Synthesis, retrofit, design, optimization, simulations, pinch analysis, and thermal performance and economic profitability estimations of primary crude oil components, like CDUs and HENs have recorded considerable enhancements and feasible outcomes by ASPEN® software tool since of its capability in managing operational dynamics, uncertainties, complexities, and nonlinearities existing while the system is operated.

The viable implications of this research can be summarized in supplying outstanding suggestions, proposed workable solutions, functional recommendations, and holistic, procedural plans of action, enabling crude oil decision makers and petroleum operators to achieve satisfactory savings in the TAC by eliminating sources of energy wastes and conducting active heat recovery; therefore, raising the overall sustainability and positive environmental impacts, and managing a common troublesome issue, reflected in excessive fuel bills due to outdated system components in the crude oil refinery. So, crude oil actors can match critical sustainability goals necessitated and implemented globally.

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