

Exergy Analysis of a Crude Oil Distillation Unit for Enhanced Energy Efficiency and Sustainability

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Abstract This study presents a detailed exergy analysis of a crude oil distillation unit (CDU) using Aspen HYSYS simulation software. The primary objective is to evaluate the thermodynamic performance of the CDU, focusing on energy utilization, key areas of irreversibility, and overall system efficiency. The simulation model was validated against real plant data, demonstrating a high degree of accuracy in predicting flow rates and thermodynamic properties. The analysis reveals significant exergy losses, particularly in the distillation tower and coolers, which account for 41.8% and 33% of the total lost useful energy (exergy), respectively. In contrast, the preflash separator exhibits exceptional efficiency with minimal exergy loss. The findings highlight the potential for optimizing energy use in the CDU, particularly in components with high irreversibility and inefficient energy conversion. Specifically, improvements in the heat exchanger network could enhance heat recovery, while adjusting process parameters, such as reducing temperature gradients in the distillation column may lower avoidable losses. This study provides valuable insights for improving the design and operation of crude oil distillation units, contributing to enhanced energy efficiency and reduced environmental impact in the petroleum refining industry.

Keywords: Aspen HYSYS Simulation; Crude Oil Distillation; Energy Efficiency; Exergy Analysis;

Petroleum Refining; Thermodynamic Performance.

1 Introduction

Crude oil distillation is one of the most energy-intensive processes in the petroleum refining industry, playing a critical role in separating crude oil into its various fractions, such as naphtha, kerosene, gas oil, and fuel oil. The process involves heating crude oil to high temperatures and then separating the components based on their boiling points in a distillation tower [1–3]. Despite its importance, the crude oil distillation unit (CDU) is often associated with significant energy losses and inefficiencies, primarily due to the inherent thermodynamic limitations of the separation process [4–6].

Energy efficiency in the CDU is a critical concern for the petroleum industry, as it directly impacts operational costs and environmental sustainability [7–9]. The first law of thermodynamics, which focuses on energy conservation, has traditionally been used to analyze energy use in industrial processes. However, this approach does not account for the quality of energy or the irreversibilities that occur during energy conversion and transfer [10–12].

Exergy analysis, which incorporates both the first and second laws of thermodynamics, provides a more comprehensive understanding of energy utilization by quantifying the useful work potential of energy streams and

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identifying areas of inefficiency [13–15].

Several studies have investigated energy and exergy efficiency in crude oil distillation units. Osuolale and Anozie [16] analyzed crude distillation units (CDUs) in Nigerian refineries, revealing low exergy efficiencies (32–33%) despite high energy efficiencies (75–87%). Adjusting operating parameters improved exergy efficiencies significantly, with one atmospheric distillation unit (ADU) increasing from 33% to 74% and another from 32% to 61%. They highlighted major thermodynamic inefficiencies, suggesting optimization of pump-around flow and feed temperatures to enhance efficiency. Al-Muslim et al. [17] examined reference temperature effects on exergy analysis, finding that higher reference temperatures reduced exergy efficiency, particularly in one-stage distillation. They emphasized the need for realistic reference conditions and exergoeconomic optimization. Dincer and Rosen [18] compared energy and exergy efficiencies, noting atmospheric units performed worse than vacuum units. They suggested operational optimizations and solar energy integration for improvement. Yan et al. [19] identified key inefficiencies in CDU components and used pre-flash configurations with Sequential Quadratic Programming (SQP), improving exergy efficiency from 28.9% to 41.4% and reducing energy consumption by 28.7%. Tarighaleslami et al. [20] applied exergy analysis to the Tabriz refinery's atmospheric distillation column, achieving a 17.16% reduction in exergy losses and a 3.6% decrease in fuel consumption. Benali et al. [21] proposed separating light species in the preheating train to cut exergy destruction and fuel use by 21%.

In addition to conventional distillation methods, alternative energy-efficient techniques, such as multi-effect distillation (MED) have been explored. MED improves thermal efficiency by using the vapor generated in one distillation column as the heat source for the next, thereby reducing external heating requirements. This heat integration can be arranged in the direction of the mass flow or opposite to it, enabling efficient separation of multi component mixtures with reduced energy consumption [22]. Similarly, vapor compression distillation (VCD/MVC) reuses the latent heat of vapor by compressing it (mechanically or thermally) and reintroducing it as the heat source for the same cycle, significantly lowering energy consumption in small- to medium-scale systems [23]. Although these technologies are primarily applied in desalination and other thermal separation contexts, the underlying principles of energy reuse and internal heat integration are highly relevant to refining and inspire new

possibilities for hybrid systems.

Despite these advancements, there remains a substantial gap in optimizing CDU operations using a combined approach of energy and exergy analysis. The objective of this study is to perform an energy and exergy analysis of a crude oil distillation unit using Aspen HYSYS simulation software. The study aims to identify the thermodynamic losses and inefficiencies in the system, calculate the exergy efficiency of the system, and provide insights into the optimization of crude oil distillation units.

The novelty of this study lies in its comprehensive approach to analyzing both energy and exergy in a crude oil distillation unit. Unlike earlier studies that often focus on theoretical models or simplified systems, this work integrates a high-fidelity Aspen HYSYS simulation with real operational data to ensure accurate and industrially relevant outcomes. While previous studies have focused on energy analysis, this work incorporates exergy analysis to provide a deeper understanding of the thermodynamic inefficiencies in the system. Moreover, Aspen HYSYS offers advanced thermodynamic property modeling, rigorous equipment specifications, and process optimization capabilities, making it a powerful tool for capturing the complexity of CDU operations more effectively than many other platforms, such as MATLAB or Excel-based models. Additionally, the use of Aspen HYSYS for process simulation and validation against real plant data ensures the practical relevance of the findings. The findings of this study are expected to provide valuable insights for engineers and researchers working on the design and optimization of crude oil distillation units. By identifying the components with the highest exergy destruction, this study offers a roadmap for improving energy efficiency in the petroleum refining industry, thereby supporting global efforts toward sustainable development, particularly aligning with United Nations Sustainable Development Goals (SDG 7: Affordable and Clean Energy, and SDG 13: Climate Action), ultimately contributing to more sustainable and cost-effective operations

2 Martial and Methods

To assess thermodynamic properties, such as enthalpies, entropies, and exergies of various streams, the Aspen HYSYS program was used to perform the process simulation of the crude oil distillation unit. The simulation process began by clearly defining the problem, establishing process boundaries, and identifying operating conditions. The next step was to select the input units of parameters (SI units). Following that, a fluid package was chosen, where

the Peng–Robinson equation of state was selected due to its suitability for modeling hydrocarbon systems and its widespread use in petroleum refining operations. After that, the crude oil feedstock was characterized based on data obtained from experimental laboratory analyses. Pseudo components were generated from TBP (True Boiling Point) distillation data, including molecular weight, density, and boiling range, to represent the complex mixture of hydrocarbons in crude oil. Before entering the distillation tower, the crude oil undergoes a series of heat integration steps through a network of heat exchangers. This heat recovery system significantly enhances energy efficiency by reducing external heating demand. The preheated crude is then routed to a preflash separator, which removes light vapors and lowers the vapor load on heater. The remaining topped crude is further heated in the main heater to reach the target temperature for atmospheric separation.

The main atmospheric distillation tower is modeled with 36 theoretical stages. The internal configuration consists of valve trays on stages 1 to 22, bubble-cap trays on stages 23 to 30, and baffle trays with 40% open area from stages 31 to 36. The tower includes two side strippers: one for gas oil with 4 valve trays, and another for kerosene with 6 valve

trays. Steam enters the bottom of the tower to enhance vaporization and reduce hydrocarbon partial pressures, thereby facilitating separation without the use of a reboiler. The overhead system includes a partial condenser operating at 47.55 °C and 0.4 bar, condensing lighter fractions from the overhead vapor. The condenser, modeled as a horizontal shell-and-tube exchanger, removes 58.30 MW of heat and delivers 366.73 kmol/h of reflux. It has a shell diameter of 1.193 m, length of 1.789 m, and an internal volume of 2.00 m³, with 1.00 m³ of operational liquid holdup.

The pressure drop values across trays and equipment were obtained from the original process design specifications of the industrial distillation unit. The simulation was conducted under adiabatic conditions, assuming negligible heat losses to the surroundings. All key parameters, including feed inlet positions, product draw-off points (naphtha, kerosene, gas oil, and fuel oil), and boundary conditions, were explicitly defined within the simulation framework. For the exergy analysis, ambient reference conditions were set at 25 °C and 101 kPa. **Fig. 1** highlights the simulation model for the crude oil distillation unit constructed in the Aspen HYSYS program.

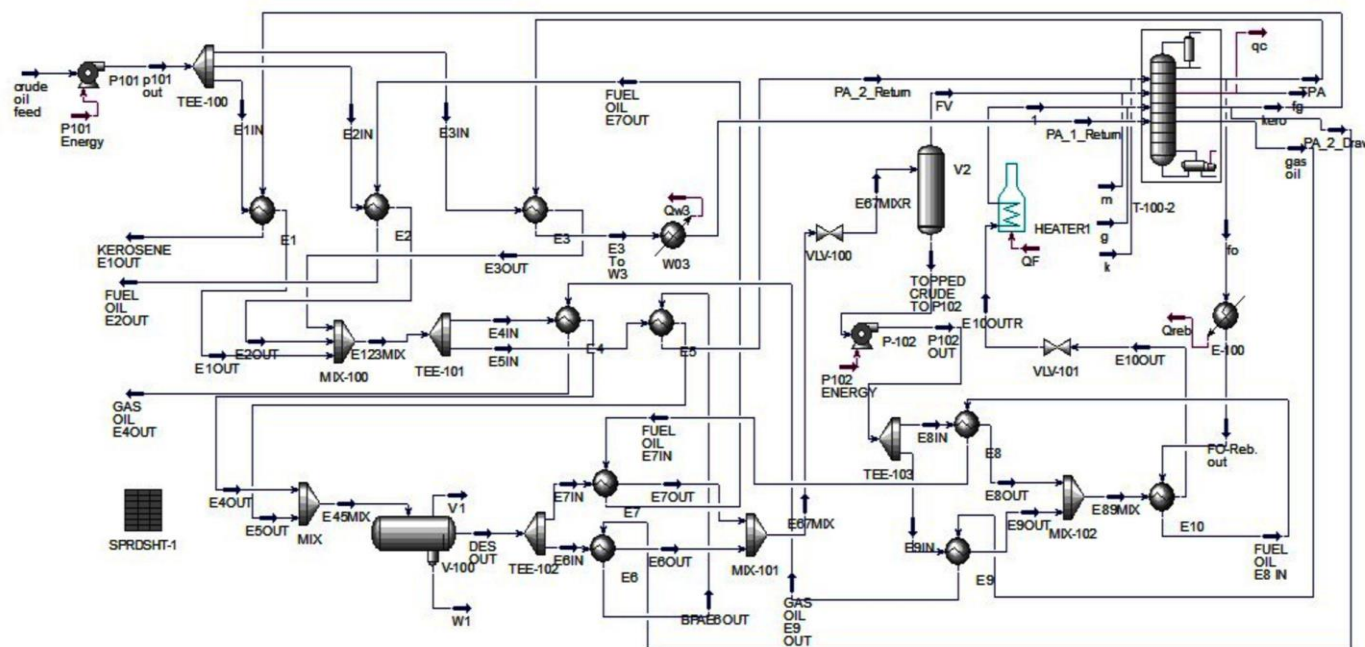


Fig. 1 Simulation model on Aspen Hysys

3 Thermodynamic and performance Analysis

Thermodynamic balance equations are used to assess energy and exergy losses, as well as the irreversibility present within a system or its components. Energy loss refers to the energy that is rejected to the environment,

while energy analysis, based on the first law of thermodynamics, focuses on the conservation of energy. However, energy analysis does not account for the inefficiencies or irreversibilities that occur during thermodynamic processes. Therefore, it is limited in identifying where inefficiencies occur. In contrast, exergy

analysis, which incorporates both the first and second laws of Thermodynamics, offers a more comprehensive evaluation by identifying the maximum useful work obtainable from a system and quantifying losses due to irreversibility. This dual approach allows for more precise targeting of inefficiencies within the crude oil distillation unit.

3.1 Governing Thermodynamic Equations

Three commonly used equations are applied for thermodynamic analysis in the case of control volume systems: conservation of mass, conservation of energy and entropy generation equations, to apply these equations and to calculate the exergy loss, exergy efficiency and heat added, assumptions are made to derive the modelling equations as follows [24,25]:

- Steady state, steady flow conditions.
- Negligible changes in kinetic and potential energy.
- Reference conditions are: $T_o = 25^\circ\text{C} = 298.15\text{ K}$, $P_o = 101\text{ KPa}$.

Mass and Energy Balances

- **Conservation of Mass:**

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \quad (1)$$

Where:

$\dot{m}$ stands for mass flowrate, Subscripts i and e represent inlet and outlet conditions, respectively.

- **Conservation of Energy:**

$$\sum_i \dot{E}_i + \dot{Q}_{cv} = \sum_e \dot{E}_e + \dot{W}_{cv} \quad (2)$$

Where:

$\dot{E}$ stand for energy rate of stream, $\dot{Q}_{cv}$ denotes heat rate enter the control volume, $\dot{W}_{cv}$ the work done by the control volume.

Exergy Balance Equation

The general exergy balance for a control volume is given by [26] [27]:

$$\sum_i \dot{E}x_i + \sum_j \left(1 - \frac{T_o}{T_j}\right) \dot{Q}_{cv} = \sum_e \dot{E}x_e + \dot{W}_{cv} + \dot{I}_{cv} \quad (3)$$

Where:

$\dot{E}x_i$ represents the exergy rate related to the inlet streams, $\dot{E}x_e$ represents the exergy rate related to the outlet streams, $\left(1 - \frac{T_o}{T_j}\right) \dot{Q}_{cv}$ is the exergy rate associated with heat transfer, $\dot{W}_{cv}$ denotes the exergy rate related to work transfer and $\dot{I}_{cv}$ irreversible exergy loss. This equation

enables evaluation of system losses and component-level inefficiencies.

3.2 Specific Exergy Calculation

Assuming that the kinetic and potential exergy are negligible (meaning the difference in work done or energy values of a component and the potential or kinetic exergy across it is minimal, the total specific exergy of a material flow through a system can be divided into physical exergy and chemical exergy, as demonstrated in [26]

$$ex = ex_{ph} + ex_{ch} \quad (4)$$

In case of environment relative evaluation, the physical exergy is represented as [26] :

$$ex_{ph} = (h - h_o) - T_o(s - s_o) \quad (5)$$

Where:

h, s represent the specific enthalpy and specific entropy, respectively.

T is the temperature, and o refer to the reference state.

And molar chemical exergy for mixture given as [28] :

$$\dot{e}_{om} = \sum_i x_i \dot{e}_{oi} + RT_o \sum_i x_i \ln \gamma_i x_i \quad (6)$$

Where:

x_i refers to component mole fraction, $\dot{e}_{oi}$ refer to molar exergy, γ_i is the activity coefficient and R is the molar gas constant.

The exergy efficiency of subunit is calculated from [29] :

$$\psi_{EX,subunit} = \frac{\dot{E}x_{ntp}}{\dot{E}x_{nts}} \quad (7)$$

Where:

$\dot{E}x_{ntp}$ is the net exergy produced, and $\dot{E}x_{nts}$ is the net exergy supplied

And the overall exergy efficiency can expressed as a function of total exergy loss $\dot{E}x_{L,T}$ and total exergy supplied $\dot{E}x_{S,T}$ from the following equation [29]:

$$\psi_{EX,overall} = 1 - \frac{\dot{E}x_{L,T}}{\dot{E}x_{S,T}} \quad (8)$$

4 Model Validation

In process simulation, validating a model against real data is a fundamental step to ensure its accuracy and reliability. Accurate simulations are important for optimizing industrial operations and making data-driven decisions. Aspen HYSYS is commonly used for such purposes due to its capability to model complex systems in detail. To assess the performance of the Aspen HYSYS model, a comparison was made between the simulated

values and the actual measured data. This validation process includes not only flow rates but also key exergy-related parameters, such as temperatures and pressures.

Table 1 presents the results of the flow rate comparison, showing a strong agreement between the simulated and real data. For instance, the simulated main feed flow rate of 348.25 m³/hr is nearly identical to the real value of 349.9 m³/hr, with a difference of only 1.65 m³/hr. Similarly, the simulated kerosene flow rate of 32 m³/hr closely matches the real value of 31.6 m³/hr, demonstrating a high degree of precision. The fuel oil flow rate in the simulation was 189.6 m³/hr, while the actual measurement was 174 m³/hr, showing a slight overestimation, but still within a reasonable range for model validation. This corresponds to a relative deviation of approximately 9%, which is acceptable in industrial simulation studies involving complex thermodynamic behavior. To assess how this deviation might influence the exergy analysis, a sensitivity assessment check was performed. The results confirmed that the overall trends in exergy efficiency and exergy destruction remain stable and consistent, and the conclusions of the study are unaffected by this discrepancy particularly the identification of the distillation tower and coolers as major contributors to exergy loss. This is because the fuel oil stream contributes a relatively smaller portion to the total exergy balance compared to other major units like the distillation tower. Furthermore, the simulated gas oil flow rate of 61.69 m³/hr is virtually identical to the real data of 61.5 m³/hr, highlighting an exceptional level of agreement. Overall, the results presented in **Table 1** and visually confirmed in **Fig. 2** indicate that the Aspen HYSYS simulation model closely mirrors the actual data, providing strong confidence in its accuracy and suitability for further process analysis and optimization

Table 1: Difference between simulated and real flowrates

Comparison parameter	Real flowrate [m ³ /hr]	Simulated flowrate [m ³ /hr]	% Deviation
Main feed	349.9	348.25	-0.47%
Kerosene	31.6	32	+1.27%
Fuel oil	174	189.6	+8.97%
Gas oil	61.5	61.69	+0.31%

To further confirm the model's accuracy, temperatures were also validated. **Table 2** summarizes the differences between the simulated and real temperatures. The top temperature simulation of 113.8°C shows a deviation of only 0.87% from the real value of 112.9°C. The bottom temperature of 313.5°C is similarly close to the actual measurement of 311.4°C, with a deviation of 0.67%. However, the kerosene temperature of 181.2°C deviates by 3.42% from the real value of 175.2°C, indicating a need for further investigation in this area. **Fig. 3** provides a visual representation of the real versus simulated temperatures.

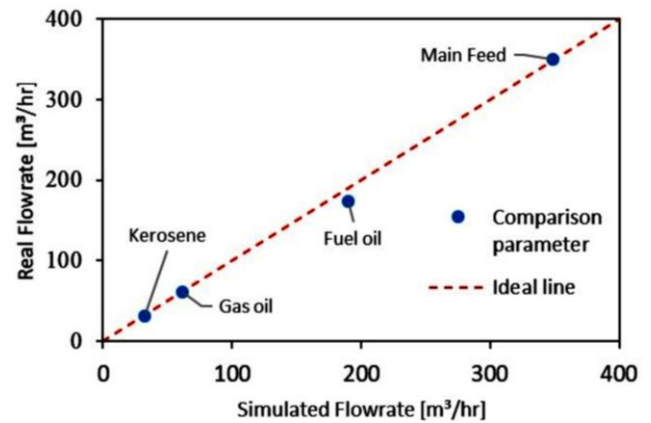


Fig. 2 model validation: real vs. simulated flowrates

Table 2: Difference between simulated and real temperatures

Comparison parameter	Simulated Temperature [°C]	Real Temperature [°C]	% Deviation
Top	113.8	112.9	0.87
bottom	313.5	311.4	0.67
Kerosene	181.2	175.2	3.42
Gas oil	249.04	248.1	0.37
Crude oil from heater	343	335	2.38

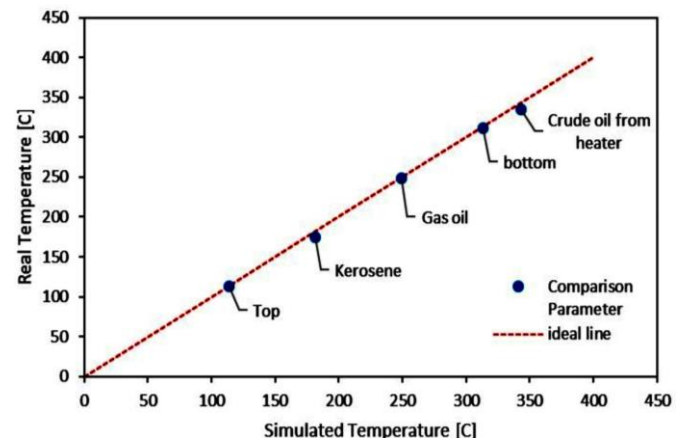


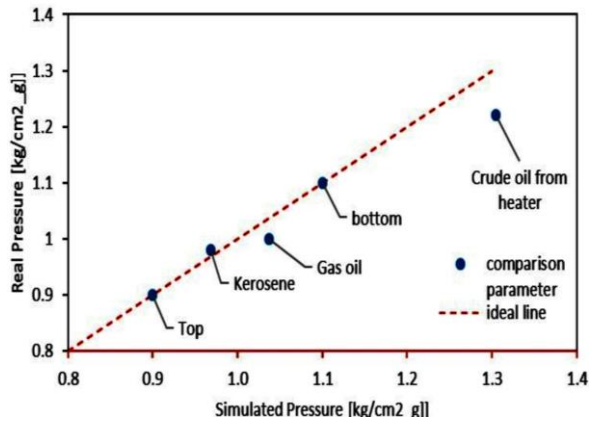
Fig. 3 model validation: real vs. simulated temperature

Pressure validation was conducted as well, and

Table 3 outlines the results. The simulated top pressure of 0.89997 kg/cm²_g is very close to the real pressure of 0.9 kg/cm²_g, resulting in a negligible deviation. The bottom pressure shows an even smaller deviation of -2.2E-05. However, the simulated kerosene pressure of 0.96855 kg/cm²_g deviates by -1.2%, and the crude oil from the heater shows a more significant deviation of 7.0%. **Fig. 4** illustrates the comparison between real and simulated pressures.

Table 3: Difference between simulated and real pressures

Comparison parameter	Simulated pressure [kg/cm ² g]	Real pressure [kg/cm ² g]	% deviation
Top	0.89997	0.9	-3.7E-03
bottom	1.10000	1.1	-2.2E-05
Kerosene	0.96855	0.98	-1.2E+00
Gas oil	1.03713	1	3.7E+00
Crude oil from heater	1.30482	1.22	7.0E+00

**Fig. 4** Model validation: real vs. simulated pressures

5 Results and discussion

5.1 distillation tower

To provide a clear understanding of the exergy dynamics within the distillation tower, systematic calculations of exergy for both inlet and outlet streams were performed, ultimately leading to the determination of exergy destruction and efficiency.

Crude oil feed is one of the inlet streams that has the following specifications:

- Mass flow rate: 2399 kg/h
- Specific enthalpy: -2380 kJ/kg
- Specific entropy: 2.916 kJ/kg-C
- Specific exergy = 17.52 kJ/kg

The total exergy out encompasses all outlet streams, including fuel gas, kerosene, gas oil, fuel oil, naphtha, water draw, and the condenser duty, leading to a cumulative total exergy output of 5.0×10^7 kJ/hr. The exergy destruction within the distillation tower is calculated by taking the

difference between the total exergy input and the total exergy output, resulting in an exergy destruction of 44,459,906 kJ/hr.

The exergy analysis of various components in the distillation plant, as presented in **Table 4**, highlights the differences in energy efficiency across the system. The distillation tower, with an exergy efficiency of 52.8%, is responsible for the highest exergy destruction at 44,459,906 kJ/hr, representing 41.83% of the system's total exergy loss. This highlights the inherent inefficiencies in the separation process, primarily due to thermal and pressure losses.

The exergy efficiency of the distillation tower is then determined by dividing the total exergy output by the total exergy input and multiplying by 100, which yields an exergy efficiency of approximately 52.88%.

The exergy analysis of the distillation tower underscores significant inefficiencies that warrant attention. With an exergy efficiency of 52.88% and notable exergy destruction, optimizing the design and operational parameters of the distillation tower could enhance overall energy utilization and reduce losses. This analysis serves as a foundation for identifying potential improvements in the distillation process. Furthermore, the contribution of the distillation tower to overall system exergy destruction is significant, accounting for 41.83% of total exergy loss across all components.

Table 4: Exergy efficiency and destruction for major process units in the system

Unit	Exergy efficiency %	Exergy destruction [kJ/hr]	Exergy destruction %
Distillation tower	52.8	44,459,906	41.83
Preflash	97.1	459,274	0.43
Heater	92.7	6,650,170	6.26
HEN	91.6	19,663,164	18.49
Pumps	92.6	106,681	0.10
Coolers	55.2	34,963,411	32.89
Total		106,302,606	100

5.2 Preflash separator

In contrast, the preflash separator demonstrates exceptionally high exergy efficiency at 97.1%, with a very small exergy destruction of only 459,274 kJ/hr, contributing just 0.43% to the total exergy loss. This highlights the highly efficient operation of the preflash unit, where most of the input energy is retained in useful products. The high efficiency of this component can be attributed to favorable operating conditions (i.e., mild temperatures and pressures), minimal phase change requirements, and simple design with low internal irreversibilities. The preflash separator's minimal exergy destruction is a significant strength,

indicating that it operates near optimal conditions, with little wasted energy. The relatively low exergy loss in this component stands out as an ideal model for other parts of the system, suggesting that efficient separation and process optimization in this unit lead to minimal energy loss. Its performance serves as a benchmark for evaluating other sections of the plant.

5.3 Heater and heat exchanger network (HEN)

The heater and heat exchanger network (HEN) also demonstrate relatively high exergy efficiencies of 92.7% and 91.6%, respectively. However, they account for notable portions of the overall exergy destruction. The heater, with an exergy destruction of 6,650,170 kJ/hr, represents 6.26% of the total exergy loss, indicating that despite its high efficiency, it still incurs significant losses in heating the crude oil. The HEN, with an exergy destruction of 19,663,164 kJ/hr, accounts for 18.49% of the total exergy loss, as shown in **Fig. 3**. This large share of exergy destruction in the HEN highlights the importance of optimizing heat recovery and minimizing losses in the thermal integration of the process, especially in the recovery of waste heat from hot streams to preheat cold streams.

5.4 Pumps and Coolers

Other components, such as the pumps and coolers, show varying degrees of energy efficiency. The pumps, with an exergy efficiency of 92.6% and a minimal exergy destruction of only 106,681 kJ/hr, contribute just 0.1% to the total exergy loss, making them highly efficient compared to other parts of the system. On the other hand, coolers have a much lower exergy efficiency of 55.2%, resulting in substantial exergy destruction of 34,963,411 kJ/hr, which accounts for 32.89% of the total exergy loss. The poor performance of the coolers is likely due to large temperature differentials and irreversible heat rejection to the environment, which do not contribute to useful work. Design improvements or implementing heat recovery systems could help mitigate these losses.

5.5 Summary of unit performance

The conducted exergy analysis offers a clear and structured understanding of how individual units contribute to the overall thermodynamic behavior of the distillation process. By evaluating the exergy efficiencies and destruction levels of each component, it is possible to identify where the system operates effectively and where significant energy losses occur. This assessment enables a comparative overview of unit performance and highlights areas with the greatest potential for efficiency improvements.

A consolidated view of the numerical results is presented in Table 4, which outlines the exergy efficiency, destruction rate, and relative contribution of each unit. This tabulated summary supports the interpretation of trends and performance discrepancies across the system, setting the foundation for the following discussion of visual results. Additionally, **Fig. 5** shows that the preflash separator, heater, HEN, and pumps operate at relatively high exergy efficiencies (>90%), with the preflash separator achieving the highest efficiency at 97.1%. This performance reflects minimal irreversibilities, likely due to favorable operating conditions and effective energy utilization. In contrast, the distillation tower and coolers exhibit considerably lower efficiencies (52.8% and 55.2%, respectively), signaling significant energy degradation and potential for optimization.

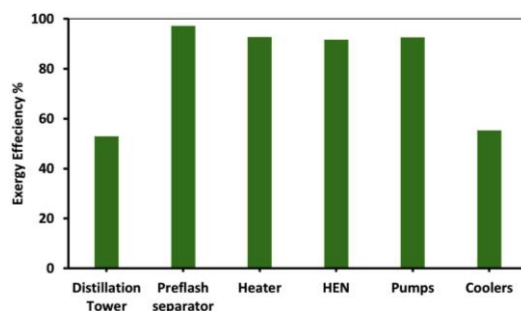


Fig. 5 Exergy efficiency of major process units

Also, **Fig. 6** provides a clear view of each unit's share of the total exergy destruction. It reveals that the distillation tower and coolers together account for nearly 75% of all exergy losses, making them the most inefficient components in the system. This finding reinforces the need to prioritize these units in future design modifications, particularly through heat recovery or process integration strategies.

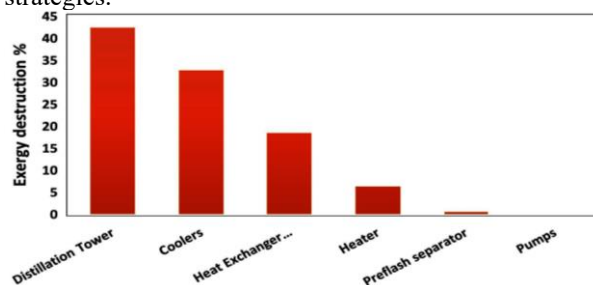


Fig. 6 Percentage of total exergy destruction contributed by each unit.

The distribution of absolute exergy destruction values depicted in **Fig. 7** supports the trends observed in efficiency and percentage loss. The distillation tower is responsible for the highest destruction rate (44,459,906 kJ/hr), followed by the coolers (34,963,411 kJ/hr) and HEN (19,663,164 kJ/hr). These figures highlight the critical role these units play in reducing overall plant performance and provide a

quantitative basis for process improvement.

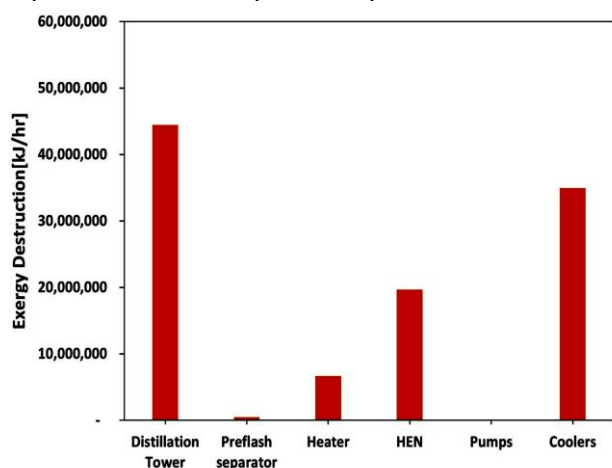


Fig. 7 Absolute exergy destruction for each unit.

6 Conclusion and Future Work

This study conducted a detailed energy and exergy analysis of a crude oil distillation unit (CDU) using Aspen HYSYS simulation software. The simulation model was validated against real plant data, demonstrating a high degree of accuracy in predicting flow rates and thermodynamic properties. The analysis revealed significant exergy losses across various components of the CDU, with the distillation tower and coolers accounting for the majority of the exergy destruction. Specifically, the distillation tower was responsible for 41.8% of the total exergy loss, while the coolers contributed 33%. These findings highlight the inherent inefficiencies in the separation and cooling processes, which are critical areas for potential optimization. The preflash separator, on the other hand, exhibited exceptional efficiency with minimal exergy loss, serving as a model for efficient operation within the system. The heater and heat exchanger network (HEN) demonstrated relatively high exergy efficiencies, though they still accounted for notable portions of the overall exergy destruction. The pumps, with their minimal exergy loss, were identified as highly efficient components.

This study has some limitations that should be acknowledged. The simulation model assumes steady-state operation, neglecting dynamic behaviors, such as startup, shutdown, and process disturbances. Additionally, although pressure drops and heat losses are not explicitly modeled, the pressure drop assumptions applied in the simulation are based on actual unit design specifications, ensuring a realistic representation of column hydraulics and stage-wise behavior. Accounting for environmental heat losses in future studies may further refine efficiency predictions.

The findings highlight the importance of optimizing heat exchange networks to improve heat recovery and minimize waste energy. Additionally, refining process parameters,

such as reducing temperature gradients in distillation columns, can significantly enhance overall energy efficiency. For example, optimizing tower operating pressures, pump-around return temperatures, and side draw flow rates can reduce internal irreversibility and improve separation performance. Moreover, this study not only identifies inefficiencies but also points toward actionable improvement strategies. For example, improvements in heat recovery directly address the high exergy destruction observed in the coolers, while column optimization strategies could reduce losses in the distillation tower. A detailed analysis of the distillation section has also revealed that targeted operational changes, such as reducing top reflux ratios or adjusting draw tray locations can reduce energy demand while maintaining product quality.

Future research should aim to expand upon the current findings by addressing both operational and structural inefficiencies in crude oil distillation systems. Given the significant exergy destruction observed in the cooling section, integrating advanced heat recovery systems represents a promising pathway to reduce thermal losses and improve energy utilization. Similarly, the adoption of real-time process control and optimization strategies could enhance operational responsiveness, particularly in mitigating inefficiencies arising from process disturbances and transient conditions. To address inherent limitations in conventional separation processes, the exploration of alternative column configurations, such as dividing wall columns and membrane-assisted hybrid systems should be prioritized for their potential to improve separation performance while reducing energy demand. These directions are directly informed by the specific inefficiencies identified in this study and provide a focused basis for technological advancement. In addition, dynamic simulation tools should be employed to capture time-dependent behavior not represented in steady-state models, and future work should incorporate environmental and economic assessments to evaluate the practical feasibility of integrating renewable energy sources, such as solar-assisted heating, within suitable refinery contexts.

In conclusion, this study not only confirms known inefficiency patterns but also provides clear pathways for improvement and future innovation. It offers valuable insights into the thermodynamic performance of a crude oil distillation unit and provides a roadmap for optimizing energy use in the petroleum refining industry. The findings have practical implications for engineers and researchers working on the design and operation of CDUs, contributing to more sustainable and cost-effective refining processes.

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