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# Exergy assessment of the separation train of a real production onshore oil and gas platform using Aspen Plus

*Prepared by*

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**DECLARATION**

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of MSc in Chemical Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signed:
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**Hamza Ramoul**

This ___23__ day of ______August____ 2022

## ABSTRACT

The petrochemical and chemical industries are among the most energy-intensive industries, accounting for more than a third of global industrial energy consumption. Rising raw material, infrastructure, and energy prices are squeezing profit margins in the chemical industry. The chemical industry is looking for more energy-efficient equipment and process design to reduce energy consumption. Exergy analysis can be a valuable approach for finding energy waste in such a situation. Exergy analysis can also be utilized to provide a high-level depiction of process change and environmental protection. This study investigated the separation trains of the ALRAR gas separation facility in Algeria, as well as prospective options for reducing exergy losses, and specifically answered the following research questions, which sections of the separation train suffer from high energy loss, and what are the potential solutions for boosting the exergy efficiency of the separation train, using a combination of both Aspen Plus and Aspen HYSYS simulations. This study aims to simulate the ALRAR separation train using Aspen Plus and Aspen HYSYS, conduct exergy analysis, pinpoint potential suggestions to improve the ALRAR separation train's energy efficiency, and state meaningful thermodynamic performance parameters for plant evaluation. The results show that the air coolers (E-101) and (E-105) in the ALRAR gas plant have significant exergy losses, while the heat exchangers (E-104) and (E-103) have low exergy efficiency. Moreover, the exergy analysis resulted in the formulation of actionable recommendations to improve the train's exergy efficiency. Additionally, this work made a notable contribution by demonstrating how to integrate exergy analysis with Aspen Plus and Aspen HYSYS, as well as how to compute physical exergy with Aspen HYSYS.

# ACKNOWLEDGEMENTS

I’d like to express my deepest thanks to Prof Jean Mulopo for suggesting this topic, which is interesting and fits my desires, I’m also grateful for his advices and guidance. I would like to extend my deepest gratitude to Dr. Jibril Abdulsalam who always believed in me and my abilities, I feel lucky to be one of his students. I must also thank the University of Witwatersrand for providing high-standard services.

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## NOMENCLATURE

| | |
|---|---|
| o | Ambient |
| Ai | air |
| C | heat capacity |
| Ch | chemical |
| D | Destruction |
| E | energy |
| Eva | evaporator |
| ex | specific molar exergy |
| Ex | Exergy |
| Exshore | exported to shore |
| f | fuel |
| Gen | generated |
| H | Enthalpy |
| Irr | irreversible |
| k | device |
| K | Boltzmann constant. |
| Ki. | Kinetic |
| l | lost |
| L | Heat load |
| m | molar flow rate |
| n | number of moles |
| ŋ | efficiency |
| P | Pressure |
| p | Product |
| Phy | physical |
| Po | Potential |
| Q | Heat flow |
| R | Universal gas constant. |
| Rev | reversible |
| S | Entropy |
| t | Time |

T Temperature

V volume

W Work

x mole fraction

ỵ destruction ratio

Ⴖ Carnot factor

ỵ Activity coefficient.

## 1. INTRODUCTION

Among fossil fuels, natural gas is the cleanest and most energy-efficient. This energy source includes a high concentration of methane as well as trace quantities of other hydrocarbons and acid gases. This fossil fuel is stored in reservoirs thousands of meters under the earth's surface. Natural gas is now in high demand in our everyday lives. It is widely used in energy generation, petrochemical goods, transportation, and so on. Natural gas, for example, generates 23.20% of the world's electricity (BP., 2020). Natural gas demand is steadily increasing; from 2014 to 2017, the annual growth rate was between 2% and 3%, but in 2018, consumption increased by 05.06%.

The world has been heavily reliant on oil in recent decades, but due to the greenhouse gases produced by oil combustion, many governments around the world have enacted strict legislation prohibiting the harmful gases generated by the industrial process. This led the oil companies to consider transitioning to a cleaner energy source, with natural gas being one of the most appealing options. Natural gas is composed of several elements, some of which are poisonous. To meet pipeline gas standards, this fossil fuel is often processed in a gas processing plant to make it stable and environmentally friendly.

Natural gas processing entails extracting crude, water, and solids from gas. The separation method necessitates the use of vessels, heaters, coolers, pumps, and valves. The vessels are "gravitational separators," with an inlet diverter, settling surface, mist extractor, and outlet valves. The first stage occurs in the inlet diverter, which uses the velocity of the feed gas and gravitational forces to separate gas from liquid. At this stage, vapor ascends to the vessel's top, and liquid descends to the bottom. The second separation takes place on the settling floor, where the liquid will settle down for some time, allowing water to settle on the bottom and oil to settle on top, and then they exit the separator separately through different outlet valves. The final separation takes place in the mist extractor, which is placed on the top and extracts tiny droplets of liquid from the vapor. The separation train requires a significant amount of energy, and some of it gets transformed into unusefulwork. This “waste’ of energy can be quantified by using Exergy analysis.

Exergy is described by Szargut et al. (1989) as "the maximum amount of work obtainable when an energy carrier is brought from its initial state to a state of thermodynamic equilibrium (an inert state) with the common substances of the natural environment using reversible processes," in other words, exergy is the amount of energy that can be converted into useful work. Exergy can be lost, as opposed to electricity, which is often conserved during a phase, and this is the primary cause of irreversible changes. Reversible change is described as a process that uses the same amount of energy when transitioning from an initial state "A" to a reference state "B" as it does when the transition from state "B" to state "A." These are idealized changes that do not exist in reality. The irreversible mechanism, on the other hand, cannot reverse (from state "B" to state "A") unless additional energy is applied.

The separation train in the South of Algeria needs a considerable amount of energy to separate oil and water from the feed gas. This energy is provided by a public utility. To minimize capital costs and increase the overall thermodynamic efficiency of the production train, two versions of the train will be simulated using Aspen Plus and Aspen HYSYS, and the separation train will be evaluated using exergy analysis. By investigating the train's exergy quality, the exergy losses and their causes inside the train will be discussed, allowing for more precise recommendations for improvements.

### 1.1. Research's relevance

The petrochemical and chemical industries are among the most energy-intensive, accounting for more than one-third of total manufacturing energy consumption. Rising raw material, infrastructure, and energy costs are tightening the chemical industry's profit margins. To reduce energy consumption, chemical industries are looking for more efficient equipment and better process design. Exergy analysis can be a useful tool for detecting energy waste in such a scenario. It also suggests modifications to the process or equipment to make it more energy-efficient. Exergy analysis may also be used to provide a high-level overview of process change and environmental protection. Major unit operations of the ALRAR gas separation plant (Algeria) will be investigated in this study, as with possible options to reduce exergy losses and, in particular, the following research questions: i) which sections of the separation train have significant energy degradation? and why is this the case? ii) what options are available to boost the separation train's exergy efficiency? iii) what thermodynamic parameters are efficient to assess the separation train?

## 1.2. Problem statement

The world's population's well-being is dependent on the continuous availability of energy resources. Natural gas and oil will continue to play an important role in the global energy system and in particular, natural gas is expected to gain market share in the short term. In Algeria, oil and gas extraction accounts for the majority of the country's overall value development. Increasing energy efficiency is one way to improve energy security and reduce greenhouse gas emissions. Increasing energy efficiency reduces energy demand and is generally acknowledged as an important policy choice.

However, the term "energy efficiency" is used in a variety of ways, and its exact definition varies depending on the context. Energy efficiency in industrial processes is related to thermodynamics energy analysis and is based on the first law of thermodynamics. The first law notes that energy is conserved, and all types of energy are viewed equally in thermodynamics energy analysis without providing further details on internal losses induced by irreversibilities, and process units.

Nonetheless, energy analysis and the first law are most commonly used to assess the energy efficiency of industrial processes. But, according to the second law of thermodynamics, entropy is produced in all actual processes. This means that the ability to do work is decreasing. This ability can be measured using a combination of the first and second rules, and can effectively be evaluated using exergy analysis.

Exergy analysis offers a better assessment of resource utilization than energy analysis and allows one to pinpoint where inefficiencies exist in a process: both external losses and internal irreversibilities. Exergy analysis appears to be a very efficient method in this regard, as it would allow for increased efficiency and reduced environmental impact of industrial processes.

Unfortunately, unlike enthalpy, this concept is difficult to grasp, and exergy analysis is rarely included in current process simulators such as gProms, Aspen Plus, Chemcad, and others. In this context, the primary goal of the research presented in this dissertation is to link exergy analysis to Aspen Plus and Aspen HYSYS and to demonstrate the utility of this approach for analyzing the exergy efficiency of a typical gas separation train.

## 1.3. Aim and Research Objectives

Exergy analysis's main aim is to evaluate the ALRAR separation train define and measure thermodynamic "imperfections" within chemical processes, and it is focused on both the first and second laws of thermodynamics, While energy analysis is based solely on the first rule.

However, there have been very few formulations of exergy balances on a real process to date. Furthermore, the integration of exergy analysis with current process simulators has not been completely realized. As a result, the study's objectives are to:

a) *Real case study of The ALRAR gas processing plant, then conduct exergy analyses of the ALRAR gas processing plant using Aspen Plus and Aspen HYSYS*

*b) Identify and discuss improvement potentials and draw broad conclusions;*

*c) Define meaningful thermodynamic performance parameters for plant evaluation.*

## 1.4. Research questions:

- Which units of the separation train suffer from high exergy loss?
- What are the potential solutions for boosting the energy efficiency of the separation train?
- What are the efficient thermodynamics parameters to evaluate the separation train?

## 1.5. Scope of research

This research was conducted under the following boundaries:

- Use of Aspen Plus and Aspen HYSYS to simulate the ALRAR separation train.
- Get the thermodynamic variables of streams, as well as their exergy values.
- Spot the areas that suffer from energy degradation from the results obtained.
- Provide potential solutions to improve the energy efficiency of the ALRAR separation train.

## 1.6. Research significance

Exergy analysis can be a useful tool to reduce the energy consumption of the petrochemical and chemical industry. This study shows how to evaluate a real case study ALRAR plant, then based on the analysis of the results, recommendations to improve the energy efficiency can be deduced. Using exergy analysis will lead to reducing the operating and capital cost of the petrochemical and chemical plant. The study can be a showcase model to use for other same cases.

## 1.7. Research organization

- **Chapter 1** includes general information about this study. It includes the following sections:
- Section 1: This section provides a general background of the research conducted.
- Section 2: Explains how this study can be used and useful in the real life.
- Section 3: States the problem beyond this research.
- Section 4: Cites the research questions.
- Section 5: States the boundaries of this study.
- Section 6: Defines the importance and the impact of this research.

- **Chapter 2** is divided into 3 parts:
- Brief of the literature done in the same area.
- Introducing information about energy and exergy analysis as well as the parameters used in this study.
- Information about process units such as Separators, heat exchangers, refrigeration, and air coolers are provided.
- A description of how to calculate the exergy of a stream in Aspen Plus and Aspen HYSYS.

- **Chapter 3** describes the structure of the ALRAR separation train, as well as the simulation cases.

- **Chapter 4** presents and discusses the results of:
- Energy balances.
- Exergy destruction.
- Exergy efficiency.
- Chemical exergy.
- Physical exergy and its compounds; and
- Exergy destruction ratio.

- **Chapter 5** summarizes the study's results as well as proposed remedies to improve the energy efficiency of the separation train**.**

## 2. LITERATURE REVIEW

The literature review conducted in this work falls into two categories: the first is concerned with evaluating and developing the exergy analysis methodology and associatedindicators to efficiently assess petroleum plants, and the second is concerned with evaluating anddeveloping the exergy analysis methodology and associated indicators to efficiently assess petroleum plants. The second group evaluated actual petroleum refineries. This chapter analyzed and critiqued the available relevant categories of literature.

De Oliveira and Van Hombeeck. (1997) conducted the first exergy analysis on a real petroleum platform. The authors were able to create a model of an offshore platform in Brazil using the HYSIM program. The system consisted of a separation, compression, and pumping train. They then constructed a standard methodology for evaluating any petroleum platform using the same trains, which they accomplish by giving the necessary equations. Their findings indicated that the heating and compression procedures require the most energy, while the separation train consumes the least. The low overall efficiency of exergy is explained by the integration of the combustion machine that generated the mechanical power.

The effectiveness of four small-scale liquefaction processes was investigated by (Remeljej and Hoadley., 2006). The processes consisted of a single mixed refrigerant (SMR), liquefied natural gas (cLNG), a new liquefied natural gas (LNG) scheme, and geo synthetic clay linear (GCL). The data was gathered from peer-reviewed journals. The study's goal was to examine the various processes on an equal footingto assess their energy efficiency and potential for improvement in terms of offshore appropriateness. During the modeling of the numerous processes, the study identified a limitation:the temperature of the final products in all processes was not the same, thus the conditions had tobe altered, reducing the efficiency of the design. Exergy analysis and the shaft-work targeting approach were employed to achieve the study's goal. Equation (2.1) was used to estimate the minimum amount of work required to produce LNG using exergy analysis.

$$W = \sum(H - T_0S)_{LNG} - \sum(H - T_0S)_{Feed} \qquad (2.1)$$

Where

H: Enthalpy.

$T_0$: Ambient temperature.

S: Entropy.

W: Work.

LNG: Liquefied natural gas.

The shaft-work targeting method was used to address the exergy loss and estimate the degree of optimization within the processes using the shaft-work Equation (2.2).

$$Ex = W_{rev} = \Delta He\Omega \quad (2.2)$$

Where

Ex: Exergy.

W: Work.

Rev: Reversible.

$\Delta He$: Change in Heat Load.

Ω: Carnot factor.

Temperature vs heat load plots were generated for each of the four processes, with the region between the two curves (hot and cold streams) representing the lost work. According to the study's conclusions, the SMR process requires the least amount of work, followed by the new LNG design and the two remaining processes. Secondly, a multistage compression approach should be implemented to reduce exergy loss throughout the process. A two-stage compression with intercooling would result in a 17% decrease in lost work for the SMR process, while a three-stage compression would result in a 27% reduction. Finally, the investigation found that the LNG exchanger accounted for 30% of work losses, while GCL, the new LNG scheme, and cLNG account for 20%, 10%, and 10%, respectively. Additionally, the study recommended the addition of an external chilling unit.

Nguyen et al. (2013) modeled a plant that included the following components: a production manifold, a separation train, oil pumping and export, gas recompression and purification, gas compression and export, wastewater treatment, seawater injection, power generation, and heat recovery, and miscellaneous utilities (e.g. sewage) (Figure 5). The separation train consisted of gravity separators, throttling valves, and heaters. Three-phase separators split the incoming fluidinto the first two stages, while a two-phase separator and an electrostatic coalescer regulated the last step. The data were gathered from a variety of free sources - all of which dealt with North Sea plants. The study simulated six case studies with varying reservoir fluid contents: the first three examples replicated an oil processing plant with associated free gas. The water contents and molar flow rates of these three examples were different. The remaining three scenarios simulated units that process various types of oil – black oil, near-critical oil, and condensate. The study replicated the six scenarios using the same process and operating parameters as in the real-world scenarios using Aspen Plus for the processing system (except for the glycol system and the power generation unit). For the glycol system, Aspen HYSYS was used.

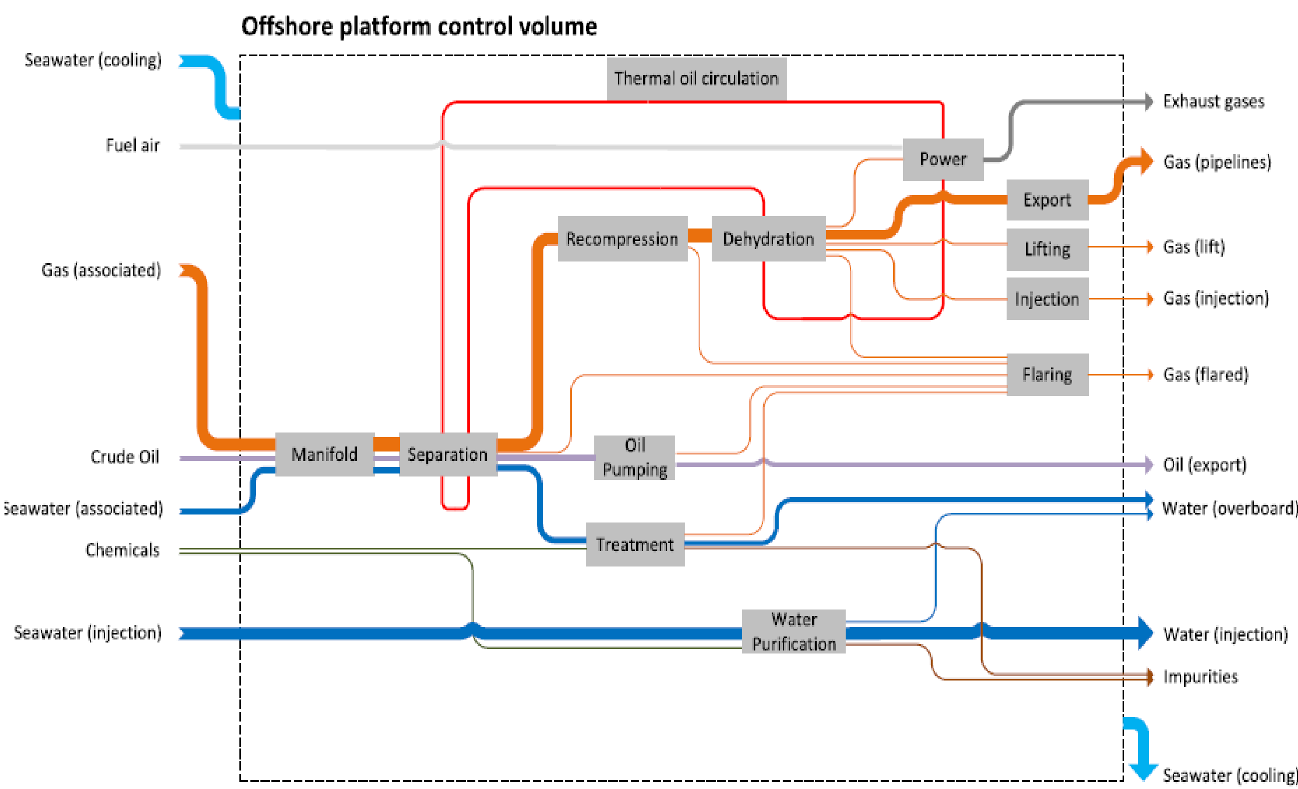


**Figure 2.5** Conceptual layout of processes on the North Sea oil and gas platforms (Nguyen et al., 2013).

The study used the following thermodynamic parameters to evaluate the cases:

Exergy destruction by means of Equation (2.3):

$$Ex_{destrcution} = \sum Ex_{in} - \sum Ex_{out} = \sum \left(1 - \frac{T_0}{T_k}\right) Q_k - W_{cv} + \sum m_{in} e_{in} - \sum m_{out} e_{out} \quad (2.3)$$

Where

Ex: Exergy.

$T_0$: Ambient temperature.

$T_k$: Temperature of the device.

$Q_k$: Heat flow.

W: Work.

ex : mass exergy.

Exergy loss:

$$Ex_{loss} = \sum Ex_{rejected} \quad (2.4)$$

The exergy destruction ratio :

$$\gamma_d = \frac{Ex_{d,k}}{Ex_d} \quad (2.5)$$

Where

$\gamma_d$: Exergy destruction ratio of a device.

$Ex_{D,k}$: Exergy destructed within a device “k”.

$Ex_D$: Total exergy destructed within a process “k”.

Exergy efficiency:

$$\eta_{Ex} = \frac{E_{p,k}}{Ex_{f,k}} \quad (2.6)$$

Where

$\eta Ex$: Exergy efficiency.

$Ex_{p.k,}$: Exergy product from the device.

$Ex_{t,\ k:}$ Exergy of fuel consumed by the device.

Exergy loss ratio:

$$\gamma_l = \frac{Ex_{l,k}}{Ex_l} \quad (2.7)$$

Where

$\gamma_l$: Exergy loss ratio.

$Ex_{l,k}$: Exergy lost by the device.

$Ex_l$: Total exergy loss.

The results of the exergy analysis showed that the gas turbine (GT) and heat recovery system destroyed 62-68% of the total exergy destructed, while the oil, gas, and water processing plant had a share of 35-38%. The study explained the significant exergy destructed in the utility plant by the effect ofexergy of mixing of gas and combusted air and the combustion by itself. The exergy destruction ratio showed that the production manifold and the gas compression train were the biggest exergy contributors to total exergy destructed, followed by the gas recompression and separation systems.

The study explained the considerable exergy loss in the production manifold by the decrease in the streams' pressure and determined that the compressors' poor performance and anti-surge were the primary sources of exergy loss in the gas compression system. In the case of the gas recompression system, the differing compositions and temperatures of the streams that combined at the entrance contributed to the destruction of the system's exergy, resulting in its irreversibility. However, the study did not explain the exergy destruction in the separation train.

Exergy losses were observed in flared gas, discharged seawater, wastewater, and gas turbine exhaust gas. A clear contribution of this study is that it demonstrated how to apply the exergy approach to evaluate a petroleum refinery. Additionally, it provided petroleum plant managers with a detailed view of a plant's energy use over the span of a reservoir's life.

Voldsund et al. (2013) modeled and appraised a North Sea oil and gas platform which is presented in Figure (2.6). The study examined the effectiveness of exergy analysis as a method for evaluating oil and gas processing on an offshore platform. The plant was divided into a production manifold, a separation train, a gas recompression train, a gas reinjection train, an oil export pumping station, and a fuel-gas treatment station.

The separation train was composed of three stages, each of which featured gravity separators; the pressure at the inlet first stage was 71 bar. Three-phase separators were used in the first two stages, while a two-phase separator and an electrostatic coalescer were used in thelast step. Apart from separating the oil, gas, and water, the separation train was responsible for lowering the inlet pressure to 2.8 bar, allowing for the separation of more gas. According to the study, the average number of production days from 2009 to 2011 was used as process data (the days when shutdowns and disturbances took place were not considered). The facility was modeledusing the simulator software Aspen HYSYS, and the Peng-Robinson equation of state was used to determine the thermodynamic properties. The COSTALD method was used to determine the liquiddensities.

The study considered the intake composition as provided by the oil plant and assumed no modification had occurred over time. The study used exergy calculations to determine the exergy in material streams and developed user variables using visual basic code in Aspen HYSYS. Calculation of physical exergy was performed using the same algorithm as reported in (Abdollahi-Demneh et al., 2011). Temperature and pressure-based exergies were estimated using a modified version of the physical exergy code. The mixing component of the chemical exergy was computed through the development of their code, but the pure component portion was omitted. Additionally, potential and kinetic exergies were overlooked.

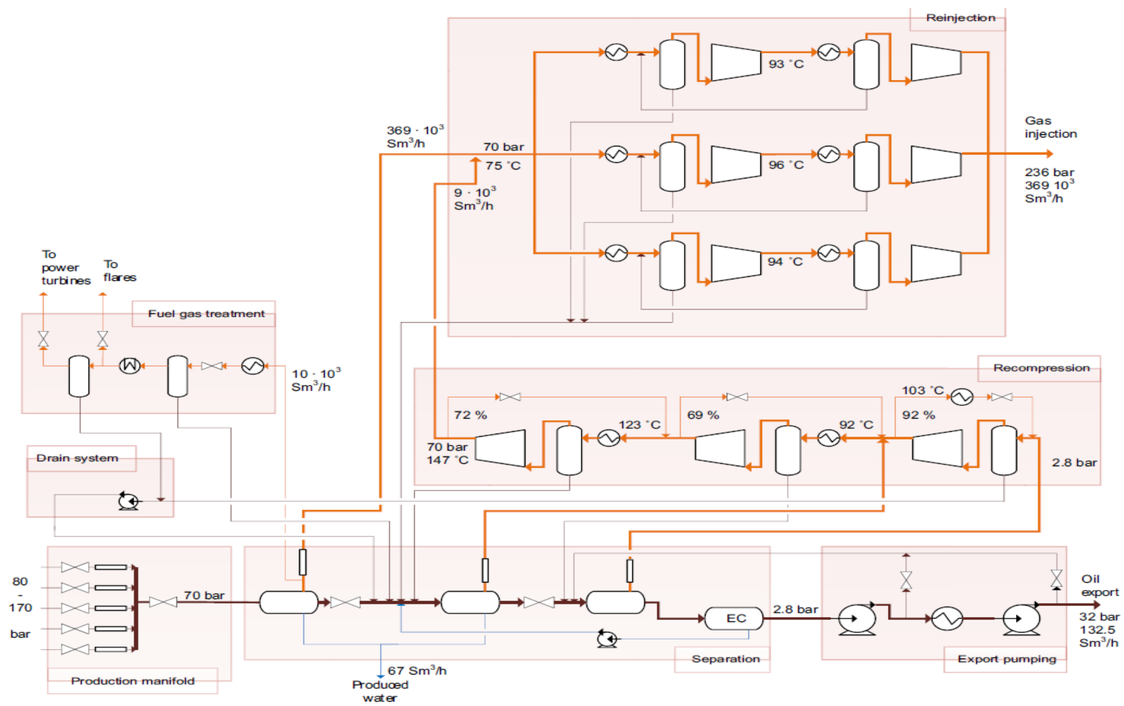


**Figure 2.6** Process flowsheet of the oil and gas processing of the studied production day. Gas streams are orange and oil, condensate, or mixed streams are brown, and water streams are blue (Voldsund et al., 2013).

The study classified all thermal exergy that exits the system as exergy destroyed, rather than exergy lost. The following thermodynamic parameters were used:

- Specific power consumption, which the study defined as the amount of energy consumedper unit of oil produced and is proportionate to $CO_2$ emissions.
- Exergy efficiency Equation (2.6).
- The efficiency defect (exergy destruction ratio), is defined in Equation (2.5).

The study's findings (Figure 2.7) indicated that the reinjection unit was the most exergy destructor, followed by the production manifold and finally the recompression unit. Compressors,coolers, and valves were identified as the equipment responsible for these exergy losses in the study. The primary causes of these exergy losses were inefficient compressors, anti-surge recycling surrounding compressors, and cooler design flaws.

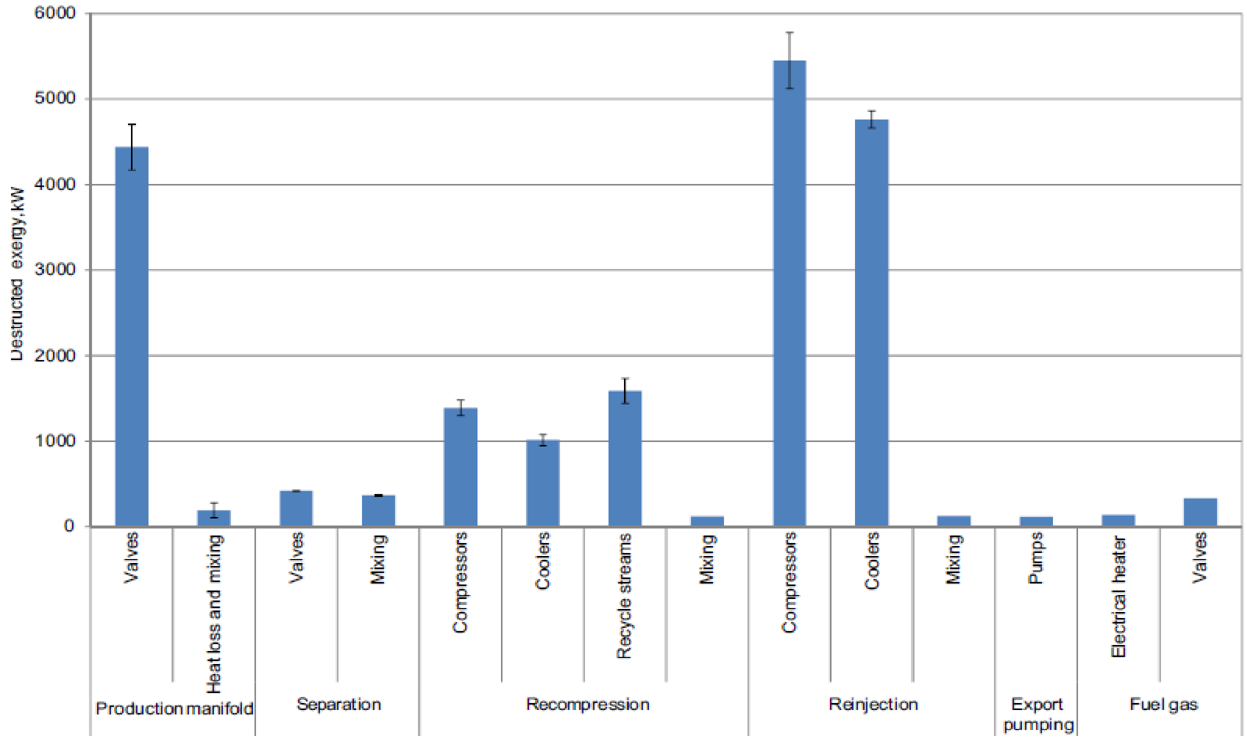


**Figure 2.7** The major contributions to exergy destruction are distributed on the type of processunit (Voldsund et al., 2013).

Nguyen et al. (2014) assessed the energy and exergy consumption of an offshore petroleum plant located in the Norwegian Sea. The plant was composed of the following components: a production manifold, a separation train, an oil export train, a gas recompressing and treatment train, a fuel-gas handling system, condensate treatment, produced water treatment, water handling and seawater injection, and a flaring and venting system. The plant could operate in two modes: the first, termed "Low-energy production mode," was designed for use while the oil is being stored. The second, designated "High-energy production mode," was established for loading and transporting oil to the shore. The analysis uses Aspen Plus and Aspen HYSYS to simulate the process, and their model included the following three Equations of states (EOS): The Peng-Robinson model, the non-random two-liquid model, and the schawertzen-Truber-Renon model.

Nguyen et. (2014) calculated the exergies of the streams using the approach described by (Kotas., 1988).

The following thermodynamic criteria were used in their study:

- Energy efficiency is defined by Equation (2.8).

$$\eta_E = \frac{E_{out}}{E_{in}} \quad (2.8)$$

Where

$\eta E$: Energy efficiency.

$E_{out}$: Energy outflow.

$E_{in}$: Energy inflow.

- The energy waste ratio is defined by Equation (2.9).

$$\delta_E = \frac{E_f}{E_{exshore}} \quad (2.9)$$

Where

$\delta_E$: Energy waste ratio.

$E_{f.}$: Energy flow.

$E_{exshore}$: Exergy to shore.

- The specific power consumption.

- The exergy efficiency using Equation (2.6).

- The exergy destruction ratio using Equation (2.5); and

- The exergy waste is calculated in the same manner as energy waste (Equation 2.9) but on an exergy basis.

The plant received around 3870 ± 100 MW of energy in total, the majority of which came from well streams, with minor contributions from other sources such as power and heat from triethylene. The majority of this energy was exported to the shore, with only a small amount being lost in the form of wastewater

As per the energy analysis, the overall power consumption ranged between 18 and 26 MW. The study identified the gas treatment section as the largest energy consumer, accounting for 44 – 66% of total energy demand, with compressors and heating demand being the largest energy consumers within this section, while the separation train was the lowest energy consumer and second-largest heat consumer in the two production modes. The plant had a lower energy efficiency than the benchmark, but a higher energy intensity and waste.

The plant in consideration received 3870 ± 100 MW of exergy. The exergy destruction on a low–energy production day was 15,290 kW, or 79% power usage. Exergy losses occurred mostly in the water rejected to the sea, waste gas streams – vented and flared gas -, and cooling water loss.
The kinetic and potential exergies were overlooked in this study, though it was noted that in practice, destruction in potential and kinetic exergy would have significance.

The investigators presented a graph containing the exergy destruction of each system within the plant (Figure 2.8); that shows that the gas treatment system was the most exergy destroyer, followed by the oil loading system (when it is operational); if not, the gas recompression system is the second most exergy destroyer, while the separation train was ranked fifth.

The exergy destruction ratios of the plant’s major equipment resulted in the identification of the plant’s weakestequipment in terms of exergy destruction, which were (in decreasing order) coolers (heat exchangers), compressors, and anti-surge recycling. The investigators ascribed this to the inefficiency of gas compressors and the large temperature difference between hot gas and colling water in heat exchangers.

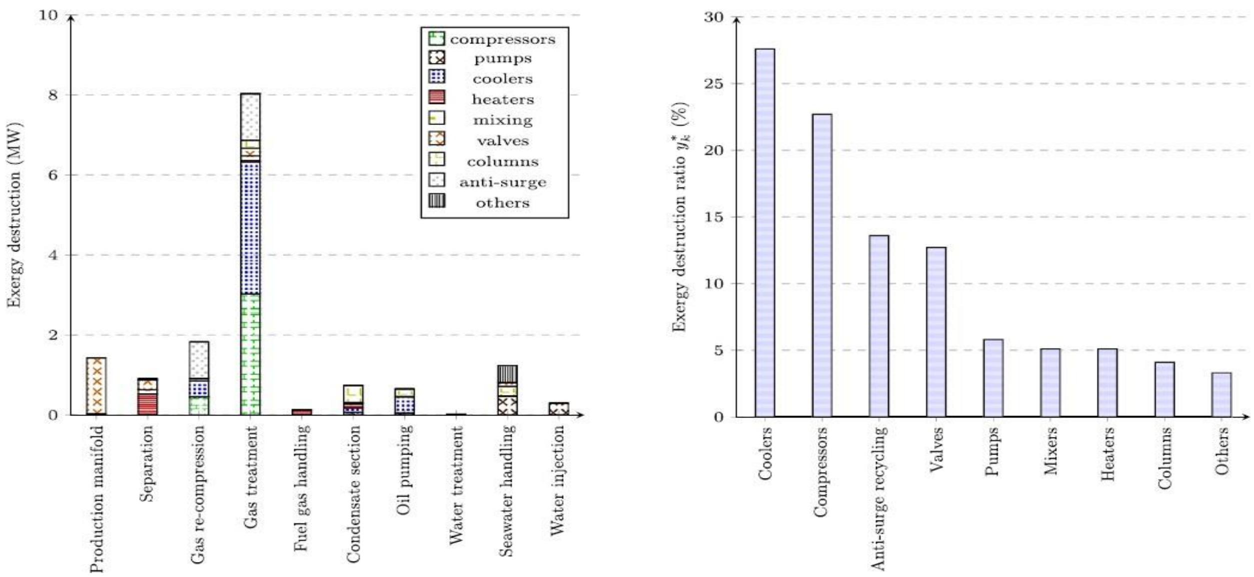


**Figure 2.8** Exergy destruction share and ranking, sorted by processes (left) and components(right) (Nguyen et al., 2014).

The investigators believed that the current design cannot be improved in terms of energy consumption unless more efficient loading pumps are deployed and losses in the pipelines are reduced, both of which are currently impractical. To increase the exergy efficiency of the separation train, the study recommended adding more separator stages and/or replacing the first stage separator with a separator operating at a higher pressure.

They recommended adding expanders to the production manifolds. The researchers concluded by recommending the adoption of exergy indicators, but not the particular energy consumption, which they considered a misleading measurement. In summary, this study demonstrated an effective method for performing an exergy analysis on a petroleum plant.

Vatani et al. (2013) performed a standard exergy study, followed by an advanced exergy analysis, on five distinct liquified natural gas (LNG) processes. The study sets out to achieve the following: i) a comparison of the five LNG processes in terms of irreversibilityand exergy efficiency; ii) demonstrate how to perform an advanced exergy study on a high-energyoperation.

Compressors, multistage heat exchangers, and air coolers were the primary components of all the processes evaluated. Aspen HYSYS was used to simulate the processes, with Peng–Robinson–Stryjek–Vera (PSVR) serves as the equation of state.

Advanced exergy analysis is composed of four components; these four components can be classified into two groups, as follows:

- The first category is concerned with avoiding exergy destruction within a device; as previously stated, this category is divided into two components: avoidable and unavoidable exergy destruction.

- The second category is based on the effect of an irreversible device on subsequent devices within the same process; this category is divided into endogenous and exogenous exergy degradation. Endogenous exergy destruction occurs when the device under matter causes irreversibility. While exogenous exergy destruction refers to the irreversible effects of the other devices on the device under consideration.

Each device's exergy destruction and exergy efficiency were estimated using the Equations summarized in Table (2.2). The findings of the standard exergy study revealed that compressors have the lowest exergy efficiency in all of the investigated processes. However, the results of exergy destruction indicated that compressors were either the leading or second-largest consumers of exergy in all operations. The air coolers came in second place in the CR3 and mixed fluid cascade (MFC) processes, while the heat exchanger came in first place in the single mixed refrigerant (SMR)-APCI and second place in the SMR-LINDE processes. Advanced exergy study revealed that the majority of devices possessed endogenous exergy destruction. Compressors experienced avoidable exergy destruction, whereas heat exchangers experienced unavoidable exergy destruction. This work provided a clear approach for performing advanced exergy analysis and guided engineers and process designers on how to decrease the inefficienciesassociated with high-energy processes.

Sánchez et al. (2015) used energy and exergy parameters to evaluate a Floating Production Storage and Offloading (FPSO). The FPSO can operate in three distinct modes, depending on the crude oil composition extracted: when the crude oil contains the greatestamount of water and carbon dioxide, when the crude oil contains the greatest amount of Basic sediment-water (BSW), and when the crude oil contains the greatest amount of oil and gas. The purpose of this study was to investigate an FPSO by performing energy and exergy analysis and then evaluating how energy and exergy were distributed throughout the FPSO's systems. Figure (2.9) depicts the plant that was examined. The study went into considerable detail on how each mode operates, and here is a summary:

- In the first mode of operation, crude oil is separated in the separation train, and the gas is dried and then injected into the reservoir. The gas turbine is fueled externally – air or fuel gas. Following the separation of the crude oil and dehydration of the separated gas, a fraction of the latter is transferred to a $CO_2$ membrane for carbon dioxide extraction, and the remaining fraction is injected into the reservoir with the $CO_2$ removed. The third mode is identical to the second mode, except that there is nogas injection into the reservoir.

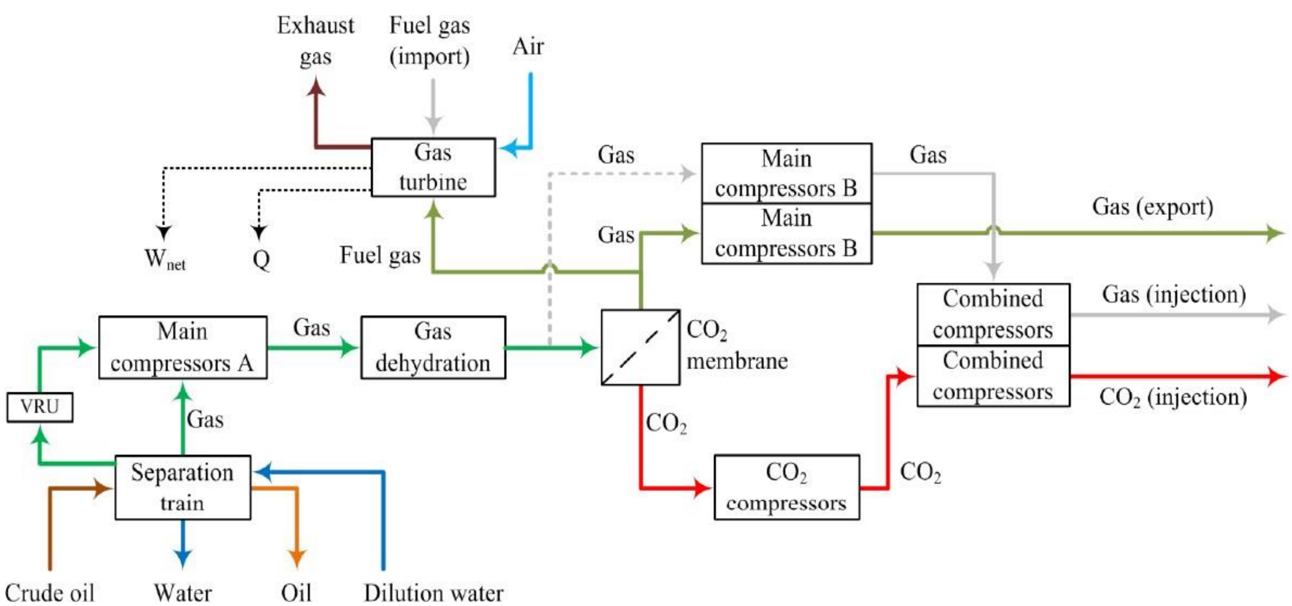


**Figure 2.9** The plant simplified schematic diagram (Sánchez et al., 2015).

Aspen HYSYS was used to simulate the plant under evaluation. This analysis included some assumptions, one of which was that all three modes would operate at the same mass flow rate. Using the first law of thermodynamics, the work examines the distribution of energy during the energy conversion process. They made no mention of kinetic or potential energy in their analyses and instead relied on the following thermodynamic indicators:

- Energy and exergy efficiency (see Table 2.1)

- Exergy destruction (see Equation 2.3)

- Specific exergy destruction: defined as the ratio of the exergy destructed within a device to the equivalent oil produced.

**Table 2.1** Energy and Exergy efficiency equations adapted from (Sánchez et al., 2015).

| | Separation | Compression | Gas turbine |
|---|---|---|---|
| Energy efficiency | - | $\eta_{comp} = \frac{\sum H_{out} - \sum H_{in}}{W_{in}}$<br>$H_{outt}$: enthalpy flow rate of the outlet fluid<br>$H_{in}$: enthalpy flow rate of the inlet fluid<br>$W_{in}$: inlet power | $\eta_{GT} = \frac{w_{net}}{m_{fuel} \cdot LHV}$<br>$W_{net}$: net output<br>$m_{fuel}$: mass flow rate of the fuel<br>LHV: Lower heating value. |
| Exergy efficiency | $\eta_{B,S} = \frac{\Delta B_{ch} + \sum_{out} B_{ph}}{\sum_{in} B_{ph} + \sum B_H^Q + W_{in}}$<br>$\Delta B_{ch}$: chemical exergy increment<br>$B_{ph}$: Physical exergy flow rate<br>$B_H^Q$: thermal exergy | $\eta_{comp} = \frac{\sum B_{out} - \sum B_{in}}{W_{in}}$<br>$B_{out}$: exergy flow rate of the outlet fluid<br>$B_{in}$: exergy flow rate of the inlet fluid | $\eta_{GT} = \frac{w_{net}}{B_{fuel}}$<br>$B_{fuel}$: exergy flow rate of the fuel |

The analysis includes a table (showing the power consumed during the separation process for each mode – primarily pumps and compressors – as well as the heat and thermal exergy necessary for the separation process and fuel heating in each mode. The data revealed that the separation train required the most heat and thermal exergy of the three operational modes. According to the study, this was mostly owing to the necessity of warming the feed and diluting water during the first stage. Mode 3 had the highest demand for power, heat, and thermal exergy, which was explained by the additional energy and exergy required to separate and process the crude oil's higher oil and gas content.

The power consumption and contribution percentages for each piece of equipment implemented in the three modes revealed that medium pressure compressor (MC)-A consumed the most power in all three modes, while the separation process consumed the least. As previously indicated, the excessive powerconsumption in mode 3 was caused by the enormous volume of oil and gas in the input.

Exergy destruction computations found that the gas turbine (GT) was the highest exergy destroyer in all three operational modes. Regardless of GT, the indication of relative exergy destruction revealed that the largest exergy destroyer in each mode was MC-A in mode 1, separation process in mode 2, and MC-B in mode 3. The authors ascribe the large loss of exergy within the separation system to the heat process of the crude oil, as well as the noticeable fall in pressure, which adversely affected the physical exergy. The gas cooling process was the principal cause of exergy loss in the compression system. By factoring in the heat used in the separation process and power consumption and comparing the results to the results of the relative exergy destruction, it was concluded that the ranking of the floating production storage and off-loading (FPSO) systems were not the same when only the exergy criterion wasused, as well as when heat and power requirements were considered. Calculating the exact exergy consumed by each system in each of the three operational modes, it was revealed that approaching the reservoir's end-of-life, the FPSO consumes the most exergy to process the same quantity of oiland gas.

The exergy efficiency results showed that GT had the lowest exergy efficiency of the three operational modes, which they ascribe to the combustion that occurred within this equipment. Furthermore, the results suggested that the separation process's exergy efficiency was highest in mode 1 and lowest in mode 2. There was no clear relationship between exergy efficiency and crude oil concentration, and the exergy efficiency of the compression process was largely governed by the gas process parameters and gas composition. Through two tallies, the work underscored the crucial use of metrics in evaluating an FPSO plant: The first objective was to determine the effectiveness of specialized exergy destruction while comparing identical systems running in diverse operational modes. The second objective was to prioritize compressors to optimize FPSO systems and operations.

Mehrpooya et al. (2016) studied the thermodynamic performance of a South Pars ethane recovery plant. The study employed standard exergy analysis and advanced exergy analysis – a novel thermodynamic tool based on standard exergy analysis that addresses avoidable, unavoidable, exogenous, and endogenous exergy destruction within the equipment – respectively. The following performance factors were considered in their study:

- Exergy destruction, using Equation (2.10):

$$Ex_D = T_0 S_{gen} \tag{2.10}$$

Where

$Ex_D$: Exergy destruction

$T_0$: Ambient temperature

$S_{gen}$: Entropy generated

- Exergy destruction ratio using Equation (2.5).

- Exergy destruction rate: and

- The exergy efficiency of the refrigeration cycle was calculated using Equation (2.11):

$$\eta_{Ex} = \frac{\Delta Ex_{eva}}{W} \tag{2.11}$$

Where

$\eta Ex$ : Exergy efficiency

$\Delta Exeva$: Change in Exergy of evaporation.

W: Work

- Exergy efficiency equations of the remaining devices are summarized in Table (2.2).

**Table 2.2** Expressions of exergy destruction and exergy efficiency used (Mehrpooya et al., 2016).

| **Units** | **Exergy destruction** | **Exergy efficiency** |
|---|---|---|
| Compressors and expanders | $Ex_d = Ex_{in} - Ex_{out} = \sum (m.e)_i + W - \sum (m.e)_o$ | $\eta_{Ex} = \frac{\sum Ex_{in} - \sum Ex_{out}}{W}$ |
| Air coolers | $Ex_d = Ex_{in} - Ex_{out} = \sum (Ex_{i,in} + Ex_{air,in} + W) \sum (Ex_{i,out} - Ex_{air,out})$ | $\eta_{Ex} = \frac{\sum Ex_{out} + Ex_{air,out}}{\sum Ex_{in} + W}$ |
| Heat exchangers | $Ex_d = Ex_{in} - Ex_{out}$ | $\eta_{Ex} = 1 - [\{\frac{\sum Ex_{out}}{\sum Ex_{in}}\}_{hot} - [\{\frac{\sum Ex_{out}}{\sum Ex_{in}}\}_{cold}]$ |
| Pumps | $Ex_d = Ex_{in} - Ex_{out} = \sum (m.e)_i + W - \sum (m.e)_o$ | $\eta_{Ex} = \frac{\sum Ex_{in} - \sum Ex_{out}}{W}$ |
| Expansion valves | $Ex_d = Ex_{in} - Ex_{out} = \sum (m.e)_i - \sum (m.e)_o$ | $\eta_{Ex} = \frac{e_o^{\Delta T} - e_i^{\Delta T}}{e_i^{\Delta P} - e_o^{\Delta P}}$ |
| Separators, drums, and mixers | $Ex_d = Ex_{in} - Ex_{out} = \sum (m.e)_i - \sum (m.e)_o$ | $\eta_{Ex} = \frac{\sum Ex_{out}}{\sum Ex_{in}}$ |
| Cycle/process | Summation of the irreversibility of all devices | $\eta_{Ex} = 1 - \frac{Total\ irreversibility\ of\ cycle}{Total\ consumed\ er\ in\ cycle}$ |

The plant under consideration was designed to recover ethane and heavier hydrocarbons from a feed gas via a refrigeration cycle, demethanizer column, and deethanizer column. The authors used Aspen HYSYS to simulate the plant using the Peng–Robinson–Stryjek–Vera equation of state. Before doing the exergy analysis, Mehrpooya *et al* (2016) conducted an energy analysis using the following equation to determine the coefficient of performance (COP) (COP = 2.054).

$$COP = \frac{Q_c}{W} = \frac{\text{absorbed heat in low-temperature}}{\text{net consumed power}} \tag{2.12}$$

Where

COP: Coefficient of performance

$Q_c$: Heat absorbed in low-temperature

W: Work

The computation of chemical and physical exergy, as well as the destruction of total exergy, revealed that the cooling tower and heat exchanger consume the most energy. To go deeper and arrive at a more accurate solution, the study used advanced exergy analysis, which determined that the irreversibility in the heat exchanger and cooling tower is endogenous and irreversible, implying that the aforementioned equipment cannot be upgraded. On the other hand, the irreversibility within the compressor is endogenous and avoidable, which implies that exergy loss can be avoided or minimized, hence improving the plant's thermodynamic performance in terms of exergy efficiency. The study established that increasing a device's irreversibility reduces the energy consumption of other devices connected to it. Pressure is the most critical parameter in the refrigeration process since it has a considerable effect on the amount of energy consumed by the operation.

## 2.1. Thermodynamic analysis

### 2.1.1. Energy analysis

Although energy cannot be created or destroyed, it can be transferred from one form to another, according to the first law of thermodynamics. Energy can be transferred from one point to another or from one body to another (Ghasem & Henda., 2012). Furthermore, the rate of changeof total energy in the control volume equals the rate at which energy flows into the control volume,less the rate at which energy flows out of the control volume, plus the rate at which energy is addedas heat flow across the control surface, less the rate at which energy is lost as work done by the system (Denn., 2012). Thus, energy can be divided into three types: kinetic energy (Eki), -potentialenergy (Epo), and internal energy (U). The energy evolution in a closed system – where there is no exchange of matter – can be described using Equation (2.13).

$$Q - W = \Delta U + \Delta E_{ki} + \Delta E_{Po} \qquad (2.13)$$

Where:

Q: Heat.

W: Work.

$\Delta U$: Change in Internal energy.

$\Delta E_{ki}$: Change in Kinetic energy.

$\Delta E_{Po}$: Change in Potential energy.

"Q" is the thermal energy that flows into/out of the closed system, due to the temperature difference. Note that the temperature (heat) flows from zones with high temperatures to zones with low temperatures.

"W" is the energy that flows due to any operating forces such as torque or/and applied forces. In the case of chemical processes, the work may come from compressors, pumps, moving turbines, and moving pistons. Note that the work is positive when it is done by the system.

Kinetic energy is related to the motion of the system. If the system is at rest (no acceleration) so $E_{ki} = 0$.

Potential energy is associated with the position of the system.

Note that in this study the kinetic energy and potential energy are not considered. So the energy evolution of a system is defined using Equation (2.14).

$$Q - W = \Delta U \qquad (2.14)$$

Given,

$$\Delta H = \Delta E + P\Delta V \qquad (2.15)$$

Where

$\Delta H$: change in Enthalpy.

$\Delta E$: change in energy.

P: Pressure.

$\Delta V$: Change in volume.

For a closed system, the volume is constant ($\Delta V=0$), so the Equation (2.15) is reduced to:

$$\Delta H = \Delta E \quad (2.16)$$

Taking into account that the evolution of a closed system equals the change of the internal energy:

$$\Delta E = \Delta U \quad (2.17)$$

The Equations (2.16) and (2.17), give

$$\Delta H = \Delta U \quad (2.18)$$

The energy change of a closed system can be expressed using Equation (2.19).

$$Q - W = H_{out} - H_{in} \quad (2.19)$$

Where

$H_{out}$: Enthalpy in.

$H_{in}$: Enthalpy out.

Note that the thermal energy ``Q`` can be transferred in three ways: conduction, convection, and radiation.

Conduction means the transfer of heat energy by the direct contact of atoms or matters. For example two streams in a mixer.

Convection refers to the transfer of thermal energy between fluids and/or gases across a solid surface. For example heat transfer in a heat exchanger.

Radiation indicates the transfer of heat by rayons for example the heat transferred from the sun.

Therefore, the heat transfer is specific to the nature of the equipment.

More details about heat transfer such as in heat exchangers are detailed in Section (2.3).

### 2.1.2. Exergy analysis

The second law of thermodynamics introduces an extensive variable called "Entropy" as a physical state attribute. This attribute is proportional to the system's number of particles, internal energy, and volume. Entropy relates to a system's capacity for energy distribution among its particles (Sato., 2004), Entropy is sometimes referred to as "disorder" or "randomness" and as a result, it may be defined as follows:

$$S = Kln\Omega(\mathrm{N}, \mathrm{V}, \mathrm{U}) \tag{2.20}$$

Where

S: Entropy.

K: constant.

Ω: Carnot factor

The creation of entropy is defined as follows:

$$dS = dS_{rev} + dS_{irr} \tag{2.21}$$

$$dS_{rev} = \frac{dQ_{rev}}{T} \tag{2.22}$$

$$dS_{irr} = \frac{dQ_{irr}}{T} > 0 \tag{2.23}$$

Where

S: Entropy.

Rev: Reversible.

Irr: irreversible.

Q: Heat.

From the energy conservation equation, and the equation of change of entropy (irreversible process), Equation (2.24) is obtained:

$$dU = TdS - PdV - TdS_{irr} \tag{2.24}$$

Where

U: Internal energy

T: Temperature

P: Pressure

S: Entropy

Irr: irreversible

One should note that the irreversible entropy is always positive (always increases).
As seen in Equation (2.24), if a process occurs at a constant entropy (dS=0) and a constant volume (dV=0), this will result in a decrease in the internal energy of the system (Gunderson., 2011).
There are two other critical notions in discussing thermodynamics: reversibility and irreversibility. A reversible process allows for forward and backward movement of the system while maintaining the system and its surroundings in a quasi-equilibrium condition. In other words, a reversible change occurs without adding additional energy to the system. Reversible processes are ideal processes that do not exist, however, a few closely reversible changes do exist (Szargut et al., 1989).Irreversible changes, which occur in the majority of real-world processes, are those that require additional energy to reverse Gunderson (2011). As can be seen in equation (2.23) a change in entropy must be greater than zero. The latter has a detrimental effect on internal energy.

The second law of thermodynamics asserts that spontaneous processes that occur in one direction do not arise spontaneously in the opposite way (Nevers., 2013). Exergy is a notion that was established in the 1950s; the phrase was coined by "Rant" and is composed of two Greek words: (-erg) meaning "work," and (-ex) meaning "released." Numerous meanings have been offered to the concept of exergy. Exergy was defined as "the amount of available energy; its capability to be converted into various forms of energy; and, most importantly, the capacity for work that is used with a given system of energy carriers in our normal environment on the earth (Sato., 2004). Exergy can also be defined as the maximum amount of work that can be achieved when anenergy carrier is brought into thermodynamic equilibrium (an inert state) with common natural substances through reversible processes (Szargut et al., 1989). On the other side, "exergy" has been defined as "the least amount of work necessary to produce a materialor a form of energy from its inert reference condition" (Sato., 2004).

Exergy is a state function that is related to the entropy, temperature, pressure, and enthalpy of the system in the matter. The highest amount of exergy is conserved in reversible processes. Affinity (free enthalpy change) is a thermodynamic quantity that reflects the maximum amount of work energy that may be obtained when an energy carrier is taken from an initial condition to its equilibrium state. In contrast to affinity, the final equilibrium state of exergy is decided by the conditions of the surrounding environment (dead state, inert reference state), which is defined by thermal, mechanical, and chemical equilibrium with the environment. In contrast to the energy idea, which, as established by the first law of thermodynamics, is always preserved in a system.

Exergy can be wasted as a result of energy being transferred to unintended reservoirs. In other words, some energy is converted to inefficient forms of energy. This loss of exergy is classified into two categories: internal "destruction" losses and exterior "external losses" (Szargut et al., 1989). Internal exergy losses are associated with the internal components of the system; they manifest themselves within the system's control boundary. External exergy lossesoccur as a result of the process's waste products being discharged into the environment". Internal exergy loss, according to the same previous authors, can be classified into two types based on theirability to be reduced. The first type is referred to as "technical exergy loss," and this sort of loss can be minimized by enhancing the equipment's performance (Szargut., 2005): whereas the secondis referred to as "structural internal exergy loss (Szargut., 2005). This form of exergy loss cannot be reduced unless the system's structure or fundamental principle is altered.

By and large, the exergy of a stream in the matter is structured around four elements via Equation (2.25).

$$Ex = Ex^{ch} + Ex^{ph} + Ex^{Po} + Ex^{Ki} \quad (2.25)$$

Where,

$Ex^{ch}$: Chemical exergy

$Ex^{ph}$: Physical exergy.

$Ex^{Po}$: Potential exergy

$Ex^{Ki}$: Kinetic exergy.

When the system is not in motion, its relative position is overlooked. So Potential exergy and kinetic exergy will be dropped (which is the case in this study).

The exergy of said stream is classified as follows: physical exergy, and chemical exergy. Figure (2.10) simplifies the elements that comprise a stream's exergy.

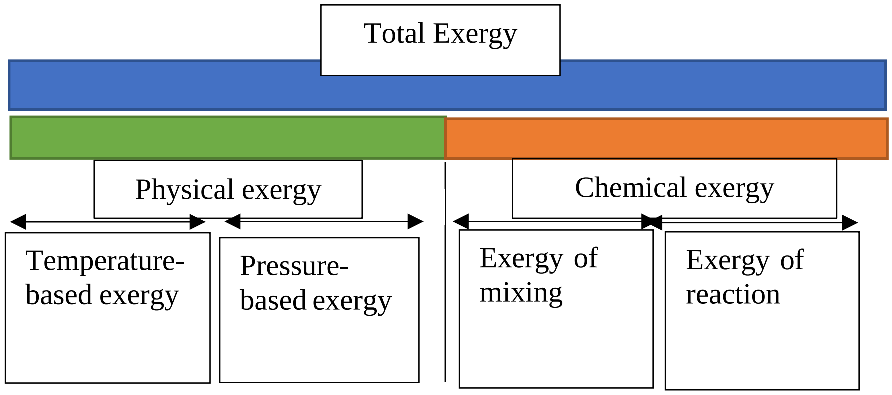


**Figure 2.10** Simplified illustration of a stream's exergy

#### 2.1.2.1. Physical exergy

Physical exergy is determined by the state determined by the ambient temperature $T_0$ and pressure $P_0$.

Equation (2.26) defines the physical exergy:

$$ex_{phy} = \Delta h - T_0 \times \Delta s \quad (2.26)$$

Where

$ex_{phy}$: Specific physical exergy.

$\Delta h$: Change in specific enthalpy.

$T_0$: Ambient temperature.

$\Delta s$: Change in specific entropy.

The physical exergy ($Ex_{phy}$) is expressed by the Equation (2.27):

$$Ex_{phy} = H_{phy} - H_{0,phy} - T_0(S - S_{0,phy}) \quad (2.27)$$

Where

$Ex_{phy}$: Physical exergy.

$H_{phy}$: Physical enthalpy.

$H_0$: Physical enthalpy at ambient conditions.

$T_0$: Ambient temperature.

S: Entropy.

$S_{0,phy}$: Physical entropy at ambient conditions.

Note that the physical exergy is similar to that Gibbs free energy as represented by Equation (2.28):

$$G = \Delta H - T \times \Delta S \tag{2.28}$$

Where

G: Gibbs free energy.

H: Enthalpy.

T: Temperature.

S: Entropy.

The physical exergy is divided into two parts: the first one is pressure-based exergy, and the second one is temperature-based exergy.

The pressure-based exergy can be calculated using one of the Equations (2.29), (2.30), (2.31).

$$Ex_{pressure} = [H(T_0, P) - H(T_0, P_0)] - T_0 \times [S(T_0, P) - S(T_0, P_0)] \tag{2.29}$$

Where

$Ex_{pressure}$: Pressure-based exergy.

H: Enthalpy

$T_0$: Ambient temperature

P: Pressure

$P_0$: Ambient pressure.

S: Entropy.

$$Ex_{pressure} = nRTln\frac{P}{P_0} \tag{2.30}$$

Where

$Ex_{pressure}$: Pressure-based exergy.

R: gas constant.

P: Pressure.

$P_0$: Ambient pressure.

$$Ex_{pressure} = -T_0(S - S_0) \quad (2.31)$$

Where

$Ex_{pressure}$: pressure-based exergy.

$T_0$: Ambient temperature.

S: Entropy.

$S_0$: Entropy at ambient temperature and ambient pressure.

Temperature-based exergy is expressed using Equation (2.32), or Equation (2.33):

$$Ex_{temperature} = [H(T, P_0) - H(T_0, P_0)] - T_0 \times [S(T, P_0) - S(T_0, P_0)] \quad (2.32)$$

Where

$Ex_{temperature}$: Temperature-based exergy

H: Enthalpy

$T_0$: Ambient temperature

P: Pressure

$P_0$: Ambient pressure

$$Ex_{temperature} = c_p \left[ T - T_0 \times \left(1 + ln \frac{T}{T_0}\right) \right] \quad (2.33)$$

Where

$C_p$: Heat capacity at pressure constant.

T: Temperature.

$T_0$: Ambient temperature.

### 2.1.2.2. Chemical exergy

The chemical exergy of a stream refers to the amount of work that may be achieved by bringing each of its constituents from the starting state to the dead state -thermal and chemical equilibrium with the environment. Chemical equilibrium is a state in the progression of reversible chemical reactions in which no net variation in the quantities of reactants and products occurs. Equation (2.34) defines the chemical exergy of a mixture.

$$Ex_{0Chemical} = \sum_i x_k ex_{0k} + RT_0 \sum_k x_k ln\gamma_k x_k \quad (2.34)$$

Where

$Ex_{0,\ Chemical}$: Chemical-based exergy.

$x_k$: Molar fraction of the kth component in the considered substance.

$ex_{0k}$: Specific molar exergy of the kth component.

R: Universal gas constant.

$T_0$: Ambient temperature.

$\gamma_k$: Activity coefficient of the kth component.

The first term in equation (2.34) calculates the chemical exergy of each of the constituents when they are in pure form whereas the second term calculates the exergy of mixing. The exergy of mixing is always negative, and it is the result of the mix of components without a reaction taking place. Morris & Szargut. (1986) report values for reference species' standard chemical exergy.

## 2.2. Separation train

In gas processing facilities, the separation train is the principal and one of the most critical trains. The separation train's aims are as follows: i) gas separation from crude oil, water, hydrocarbon condensate, and suspended solids. ii) removing condensable and recoverable hydrocarbon vapors from the gas. iii) gas treatment to eliminate condensable water that could form hydrates in subsequent trains (Campbel., 1992). Separators, coolers (air coolers, heat exchangers), and pumps or/and compressors comprise a conventional separation train. The purpose of coolers and/or pumps is to lower the temperature of the fluid, allowing for the separation of more gas and heavier hydrocarbons. Figure (2.12) illustrates the phase evolution of a typical natural gas.

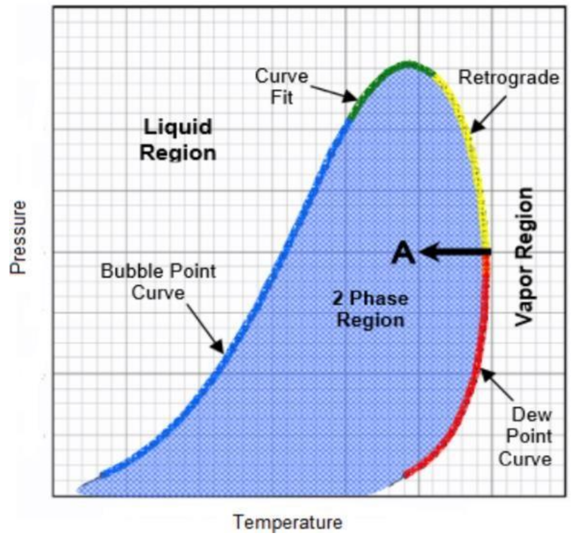


**Figure 2.12** Typical envelope of natural gas (Hajiw., 2014).

Natural gas phases are temperature and pressure-dependent, as illustrated in Figure (2.12). Separators come in a variety of configurations. Gravitational separators and centrifugal separators are the most often used separators (Mokhatab et al., 2018). Gravitational separators areclassified into two types: vertical separators and horizontal separators. Mokhatab et al. (2018), and Stewart et al. ( 2008) describe the gravity separator in detail: The primary separation of gas from liquid occurs when the gas stream enters the separator and collides with the entrance diverter due to the rapid shift in the fluid's velocity. Following the first separation, the separated liquid phase settles in the gravity settling part, which then undergoes the second separation. This is accomplished by giving enough time for the oil to rise to the top and the waterto fall to the bottom, and then separating the two stages using separate control valves. The third separation is mostly governed by the mist extractor attached to the separator's top, which eliminatesany remaining liquid droplets in the vapor phase prior to the gas exiting through the separator's top. Conventional horizontal gravity separators and vertical gravity separators are depicted in Figures (2.13) and (2.14), respectively.

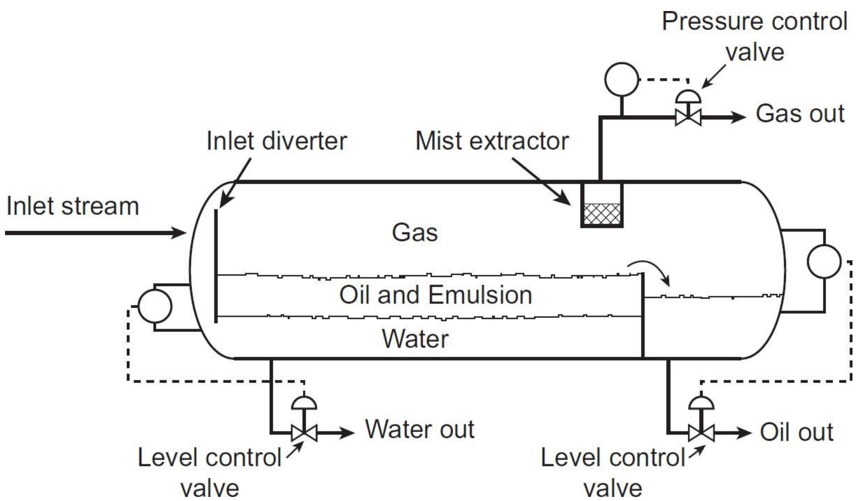


**Figure 2.13** Horizontal gravity separator (Mokhatab et al., 2018).

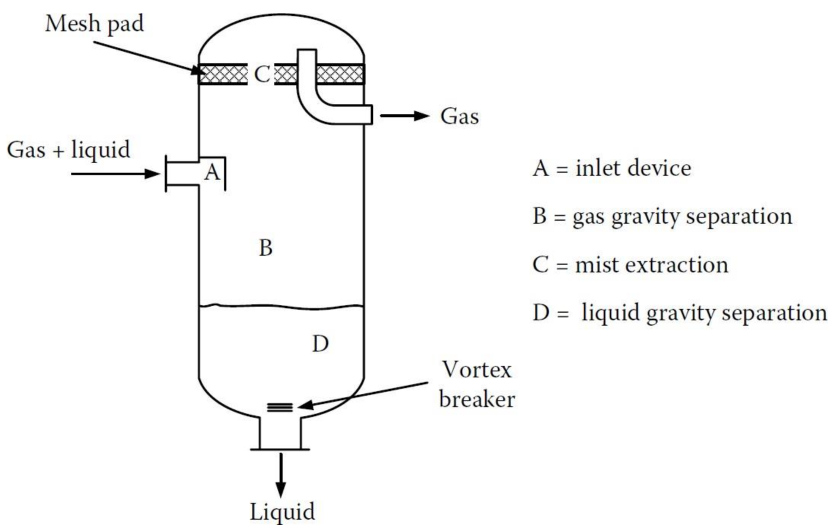


**Figure 2.14** Typical vertical separator (Kidnay et al., 2006).

A typical separation train consists of two to three stages, commonly each stage operates at a lower pressure than the previous stage. Figure (2.15) simplifies the three separation stages.

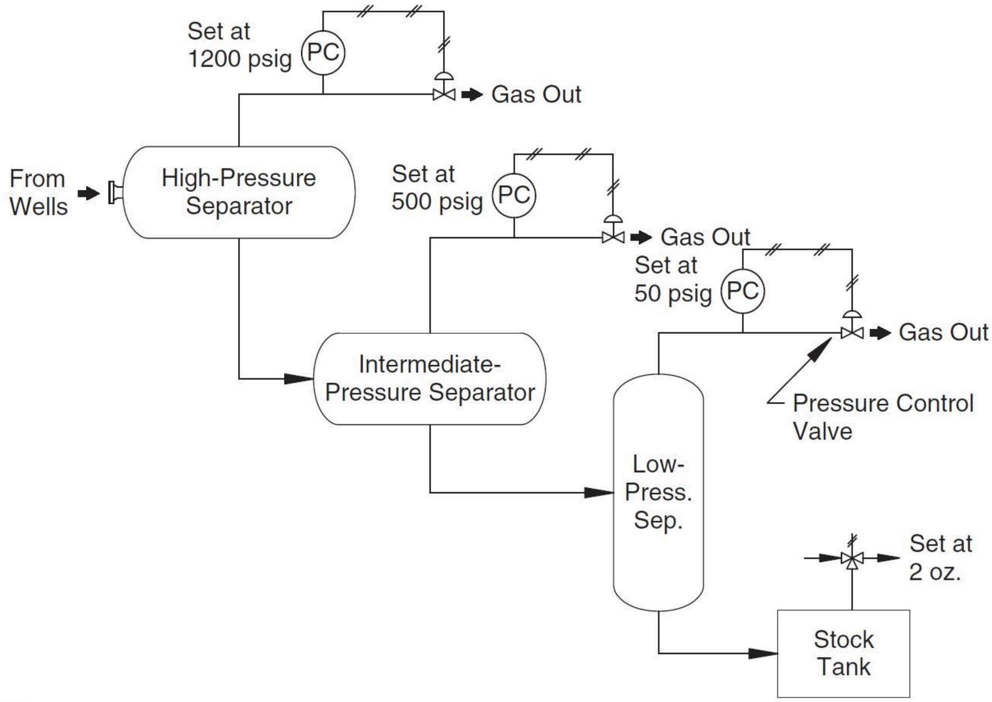


**Figure 2.15.** Typical separation stages (Stewart et al., 2008).

## 2.3. Heat exchanger

Heat exchangers are devices where thermal energy is exchanged between two or more process streams at different temperatures. Before introducing the types and typical structure of heat exchangers that exist, it is important to understand the principal theory of heat transfer between process streams across a surface, and the factors involved. The principal theory of heat transfer in a heat exchanger (including air coolers) across a surface is defined by Equation (2.35).

$$Q = UA\Delta T_m \tag{2.35}$$

Where

Q: Heat transferred per unit time.

U: The overall heat-transfer coefficient.

A: Heat transfer area.

$\Delta T_m$: The mean temperature difference.

The overall heat-transfer coefficient (U) is mainly affected by the overall resistances which are the sum of many individual resistances. individual film coefficient resistance is a term signified by the material's capacity to reduce the passage of temperature through it. The relationship between the overall heat-transfer coefficient and the individual resistances is given by Equation (2.36):

$$\frac{1}{U_0} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(\frac{d_o}{d_i})}{2K_w} + \frac{d_o}{d_i} \times \frac{1}{h_{id}} + \frac{d_o}{d_i} + \frac{1}{h_i} \qquad (2.36)$$

Where

$U_o$: The overall coefficient is based on the outside area of the tube.

$h_o$: Outside fluid film coefficient.

$h_i$: Inside fluid film coefficient.

$h_{od}$: Outside dirt coefficient.

$h_{id}$: inside dirt coefficient.

$d_0$: tube outside diameter.

$d_i$: tube inside diameter.

$k_w$: Thermal conductivity.

The individual resistances are mainly dependent on:

- Physical properties of the fluids.
- Physical properties of the material of the shell and tubes.
- Fluid flow rate.
- The physical arrangement of the heat-transfer surface.

Therefore the energy efficiency of heat exchangers is significantly affected by the individual resistances.

Shell- and tube exchanger is by far the most heat exchanger and equipment used in the chemical industry. here is a brief of its structure; Shell and tube exchanger is structured of several tubes contained in a cylindrical shell. the ends of the tubes are fitted into a tube plate. The baffles are provided in the shell to direct the fluid flow and support the tubes. Rods and spacers hold the assembly of baffles and tubes (Towler & Sinnot., 2012).

Couper et al. (2005) introduce the types of heat exchangers:

- Double-pipe exchanger (simplest one)
- Shell and tube exchangers (used for applications) such as food industry, chemical industry, and petrochemical industry.
- Plate and frame exchangers.
- Spiral heat exchangers.
- Compact (plate-fin) exchangers.

Fouling factor is a term that refers to corrosion, dirt, the deposit of products reaction, and/or organic growth that takes place in the heat exchangers during the latter's lifetime (Couper et al., 2005). The deposited material will generally have low thermal conductivity. Therefore, it will reduce the heat-transfer rate between the process streams, so the heat exchangers' energy efficiency. Due to the negative effect of the fouling, it is quoted as heat-transfer resistance. The value of the fouling is almost impossible to predict, so its value is based on past experiences. The fouling factor obligates designers to oversize the heat exchanger so its negative impact will be reduced, but at the same time, this action can be costly.

Another aspect to consider when it comes to the heat exchanger's energy efficiency is the pressure drop. The main cause of pressure drop in heat exchangers is the passage of the fluids through the tubes. The arrangements of the shells and the tubes are responsible for the pressure drop rate, which decreases the heat exchanger's energy efficiency (Couper et al., 2005).

## 2.4. Refrigeration

Refrigeration is a general term that refers to any process that lowers the temperature of a matter which can be solid, gas, or liquid. There are two methods of refrigeration: Natural and mechanical. Natural refrigeration means cooling a matter without any artificial devices, an example of natural refrigeration is the use of ice to refrigerate the matter under consideration (cooling foodstuff). Mechanical refrigeration employs a refrigerant, which is a fluid with the ability to absorb heat. In addition to process units such as evaporators, condensers, compressors, and throttling devices. Sometimes some auxiliary devices are employed (Towler & Sinnot., 2012).

The principal theory of mechanical refrigeration is as follows:

- The evaporation: The refrigerant evaporates by absorbing the heat from the matter which is in the matter to be cooled in a heat exchanger.
- Compression: In a compressor, the refrigerant gets compressed so both its temperature and pressure increase, at that time the refrigerant changes its phase from saturated vapor to complete superheated vapor.
- Condensation: in this process, the refrigerant changes its phase from superheated vapor to liquid, this is achieved by extracting the thermal energy absorbed in the evaporator and the work energy that was taken from the compressor.
- Expansion: The refrigerant gets expanded in a throttling valve by reducing pressure through an isenthalpic process.

Mechanical refrigeration was first introduced in 1755 by a Scottish physician "William Cullen" who was able to make ice from water by reducing its pressure this is a simple process, but it is mechanical refrigeration as an air pump was used to reduce the pressure "2". But in 1834 Jacob Perkins was able to patent and construct a vapor-compression machine. From that time till now the refrigeration systems invented are the following:

- Vapor-compression refrigeration systems.
- Absorption refrigeration systems.
- Air-standard refrigeration systems.
- Jet ejector refrigeration systems.
- Thermoelectric refrigeration.
- Thermoacoustic refrigeration.

# 3. CASE STUDY AND METHODOLOGY

## 3.1. Field overview

### 3.1.1. Geographic Location

The STAH region is located 1800 km south of ALGIERS, 800 km south of OUARGLA, and 400 km north of ILLIZI, to which it is officially attached. To the east, the STAH region is bordered by Libya, while to the west, the national route N = 3 IN-AMENAS-DEBDEB passes alongside it. The region's southern limit is naturally formed by a large cliff that unfolds stunning panoramas from the border to the jump of the mouflon. Although the desert-like environment of STAH has huge thermal amplitudes, the relief's average height of about 700 m lessens the severe seasonal temperatures. Temperature extremes range from 45 °C in the summer to -5 °C in the winter, with daily temperature variations of up to 25 °C. There is heavy rainfall there, with 100 mm of rain falling annually from November to January. The normal winds are north-northeast and south-southwest, and they blow from February to May, with gusts exceeding 180 km per hour.

### 3.1.2. ALRAR field characteristics

- Date of discovery: 1961
- Date of entry into service: 1984 for ALRAR East and 1997 for ALRAR West
- Producer reservoir: Devonian F3
- Average depth: 2550 m
- Initial pressure: 228 bar
- Initial temperature: 130 °C
- Water salinity: 200 g/l
- Production: gas and condensate.

### 3.1.3. Raw material

ALRAR's gas treatment facilities are supplied by:

- 22 ALRAR East producing wells.
- 13 ALRAR West producing wells.
- Liquids recovered from STAH / MEREKSEN gas.

## 3.2. ALRAR natural gas facility

### 3.2.1. Facility overview

The raw gas coming from the producing wells is completely collected at the production manifold, part of which feeds train 04: 5.922 MMSm3 / day. The other part is sent to the V-403 broadcaster to fairly feed the other three trains. Figures (3.1) and (3.2) are the blocks flow diagrams of ALRAR natural gas treatment and recycling facilities.

#### 3.2.1.1. Process description

Figure (3.3) is the process flow diagram of the ALRAR separation train. The ALRAR feed gas enters the ALRAR inlet separator (V-101) at a pressure of 68.9 bar(g) and a temperature of 100 °C. The gas escapes from the top of the (V-101), then passes through the feed gas line, and the liquid hydrocarbons are collected from the bottom, while water is discharged into the oily water treatment unit. The liquid hydrocarbons coming from the (V-101) are cooled by an air cooler (E-105) to a temperature of 60 °C, and 27 °C in the propane refrigerant (E-104), while the pressureis reduced to 34.3 bar(g). The gas from (V-101) is mixed with regeneration gas which comes froman external train. The mix is first cooled to 60 °C by a cooler (E-101), then to 48 °C by subjectingit to heat exchange with residual gas in the heat exchanger (E-102), and lastly to 27 °C by passing it through the propane refrigerant (E-103), the pressure is decreased to 64.8 bar(g). The cooled gas enters a high-pressure separator (V-102) at 27 °C and 64.8 bar(g). The gas separated is sent to a dehydration process, the water is sent to the oily water treatment unit, and the liquid hydrocarbons leaving are mixed with the stream from (E-104) and directed to the separator (V-103). The separated gas from (V-103) is sent to a chill down and expansion process, water is sent to the oily water treatment unit, and the hydrocarbon liquids are sent for further processing.

**Table 3.1** Equipment involved in the inflows and outflows streams.

| | | | |
|---|---|---|---|
| **Streams** | ALRAR<br>WATER1 | FEEDGAS<br>WATER2 | FUELGAS<br>TOPUMP<br>WATER3 |
| **Equipment** | Separator(V-101) | Separator (V-102) | Separator (V-103) |
| **Volume “m3”** | 8.649 | 6.305 | 0.2335 |

| | | | |
|---|---|---|---|
| **Diameter “m”** | 1.527 | 1.372 | 0.4572 |
| **Length “m”** | 4.572 | 4.445 | 1.372 |
| **Head height “m”** | 0 | 0 | 0 |
| **Boot height “m”** | 1.524 | 1.372 | 0.4572 |
| **Boot diameter “m”** | 0.58 | 0.4572 | 0.1524 |

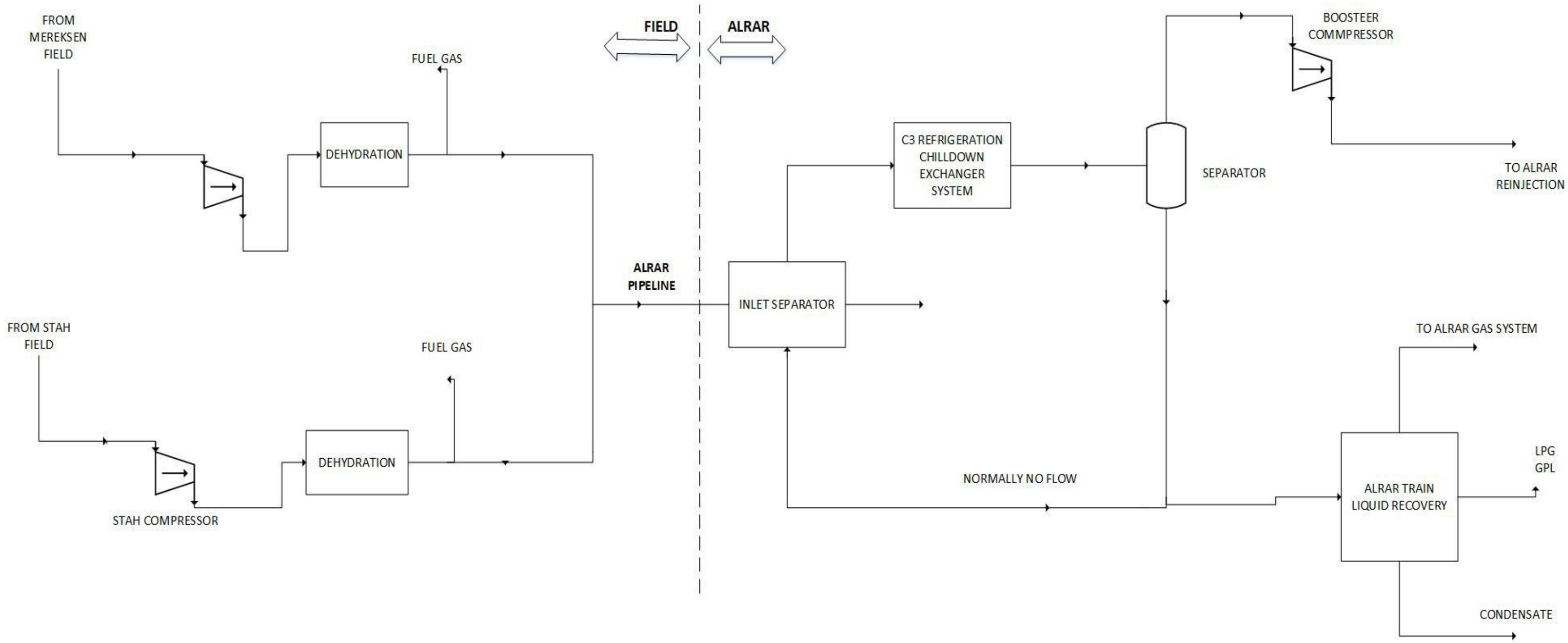


**Figure 3.1**. ALRAR block flow diagram.

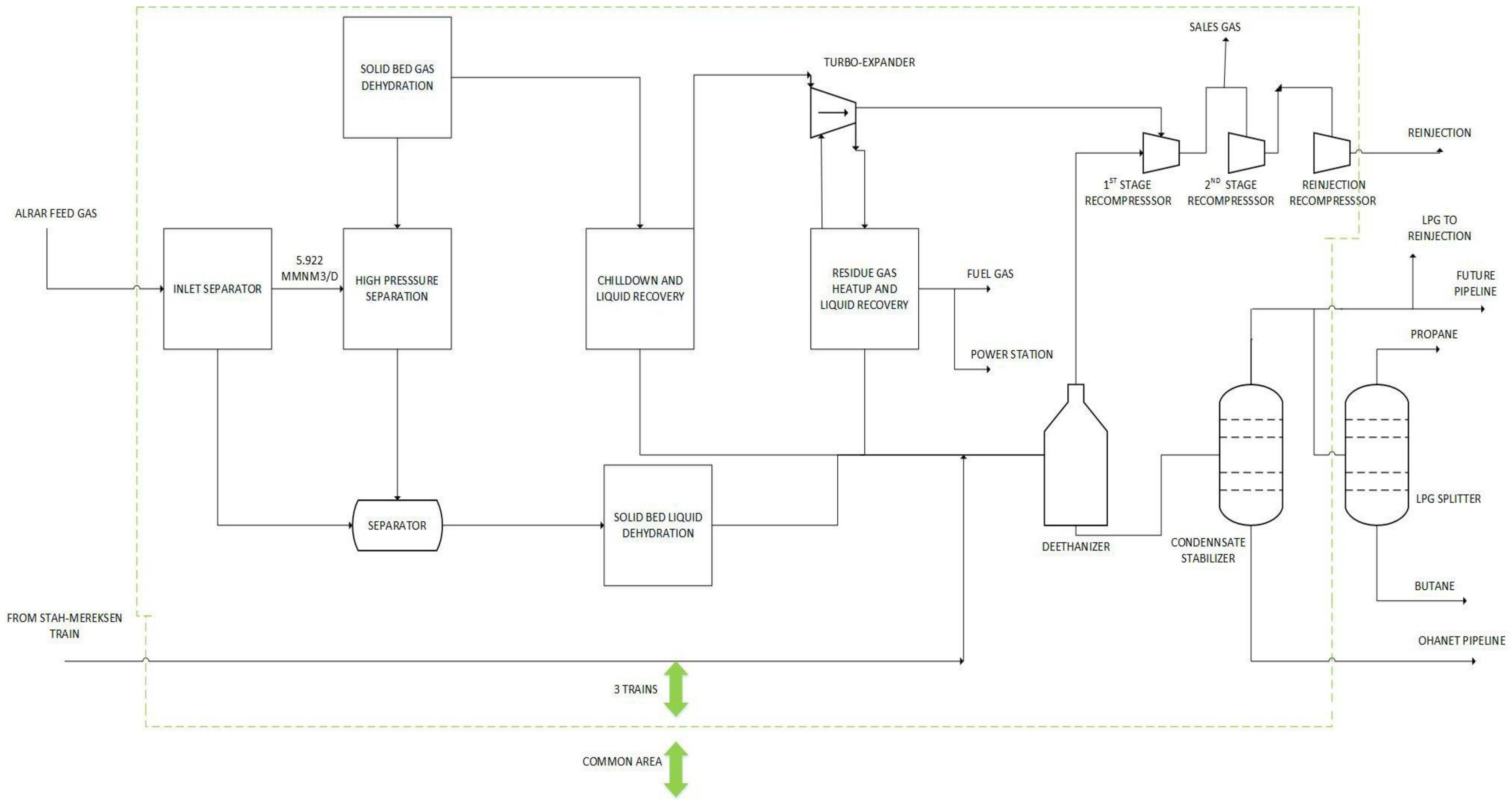


**Figure 3.2** ALRAR block flow diagram.

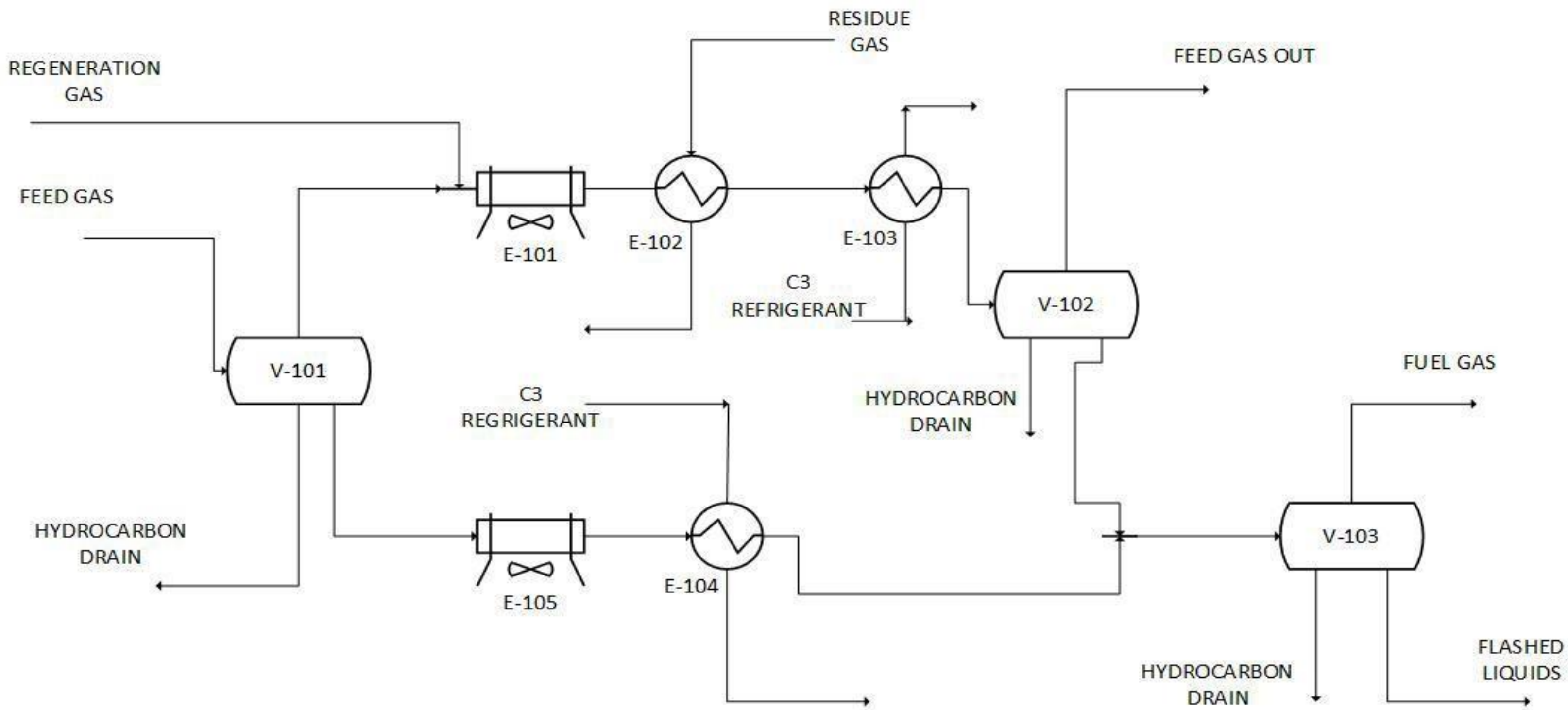


**Figure 3.3.** Separation train process flow diagram.

## 3.3. Methodology

### 3.3.1. Data

The data were acquired from "Sonatrach" which is the company responsible for running the ALRAR facility. The streams' characteristics and compositions can be seen in the appendix. The plant considered in this work was designed more than 30 years ago, and it is running to the present day.

### 3.3.2. Thermodynamic parameters

- **<u>Exergy destruction:</u>**

Note that the exergy destruction and the exergy efficiency of devices depend on the type of equipment in the matter.

The following equations were used to calculate the exergy destruction within the equipment of the ALRAR separation train.

**Air coolers:**

$$Ex_d = Ex_{in} - Ex_{out} = \sum(Ex_{i,in} + Ex_{air,in} + W) \sum(Ex_{i,out} - Ex_{air,out}) \quad (3.2)$$

Where

$Ex_d$: Exergy destruction.

$Ex_{air,in}$: Exergy of air entering the air cooler.

$Ex_{air,out}$: Exergy of air leaving air cooler.

$Ex_{i,in}$: Exergy of the stream "i" entering the air cooler.

$Ex_{i,out}$: Exergy of the stream "i" leaving the air cooler.

$Ex_{in}$: Exergy entering the device.

$Ex_{out}$: Exergy leaving the device.

W: Work.

**Separators, heat exchangers, and mixers:**

$$Ex_d = Ex_{in} - Ex_{out} \quad (3.3)$$

Where

$Ex_{in}$: Exergy entering the device.

$Ex_{out}$: Exergy leaving the device.

- **Exergy efficiency:**

The exergy efficiencies of the devices within the separation train in the matter were calculated using the equations provided in this section.

**Air coolers:**

$$\eta_{Ex} = \frac{\sum Ex_{out} + Ex_{air,out}}{\sum Ex_{in} + W} \quad (3.4)$$

Where

$\eta Ex$: Exergy efficiency.

$Ex_{out}$: Exergy leaving the air cooler.

$Ex_{air,}$ out : Exergy of air stream leaving the air cooler.

W: Work.

**Heat exchangers:**

$$\eta_{Ex} = 1 - [\{\frac{\sum Ex_{out}}{\sum Ex_{in}}\}_{hot} - [\{\frac{\sum Ex_{out}}{\sum Ex_{in}}\}_{cold}] \quad (3.5)$$

Where

$\eta Ex$: Exergy efficiency.

$Ex_{in}$: Exergy entering the device.

$Ex_{out}$: Exergy leaving the device.

- **Exergy destruction ratio:**

The exergy destruction ratio was calculated in this study in the same manner as Equation (2.5).

### 3.3.3. Simulation

The simulators software Aspen plus V10 and Aspen HYSYS V11 were used to simulate the separation train under study. Peng-Robinson was used as Equation of state (in both simulators software). The latter-mentioned equation is highly suitable for oil and gas plants simulations.

#### 3.3.3.1. Separation train ASPEN PLUS flowsheet

In this section, a description of the separation train Aspen Plus flowsheet is given.

ALRAR feed gas (stream ALRAR) is initially fed into a HORIZONTAL FLASH3 (called V-101), andthe flashed gas (stream FEED-GAS) is mixed with vapor regeneration (stream VAP-REG) in a mixer (called MIX-1), the product from the latter mixer (stream TO-E101) is sent to an air cooler (called E-101), the cooled gas (stream TO-E102) is sent to a heat exchanger (called E-102), where it is cooled by heat exchange with residual gas (stream CLD-RG), the cooled gas is then sent to a heat exchanger (called E-103), where it gets cooled from propane refrigerant (stream CLD-PRPN), finally, the gas is fed into a VERTICAL FLASH3 (called V-102). The flashed gas (stream FEEDGAS) is sent for further processing. The flashed liquids (stream LIQUIDS2) are mixed with (steam TO-MIX2) in a mixer (called MIX-2).

The flashed liquids (stream FEED-LIQ) from the VERTICAL FLASH3 (called V-101) are sent to an air cooler (called E-105), and the cooled liquids (stream TO-E104) are subjected to heat exchange in a heat exchanger (called E-104) with propane refrigerant (stream CLC-PRPN). The cooled liquids (stream TO-MIX2) are mixed with the previously flashed liquids (stream LIQUIDS2) in amixer (called MIX-2). The products (stream TO-V103) from the mixer (called MIX2) are fed into VERTICAL FLASH3(called V-103), from where flashed gas (stream FUEL-GAS) is sent for further processing. The flashed liquids (stream TO-PUMP) are sent for further processing, while the separated water (stream WATER-3) is sent to the oily water treatment unit for further processing.

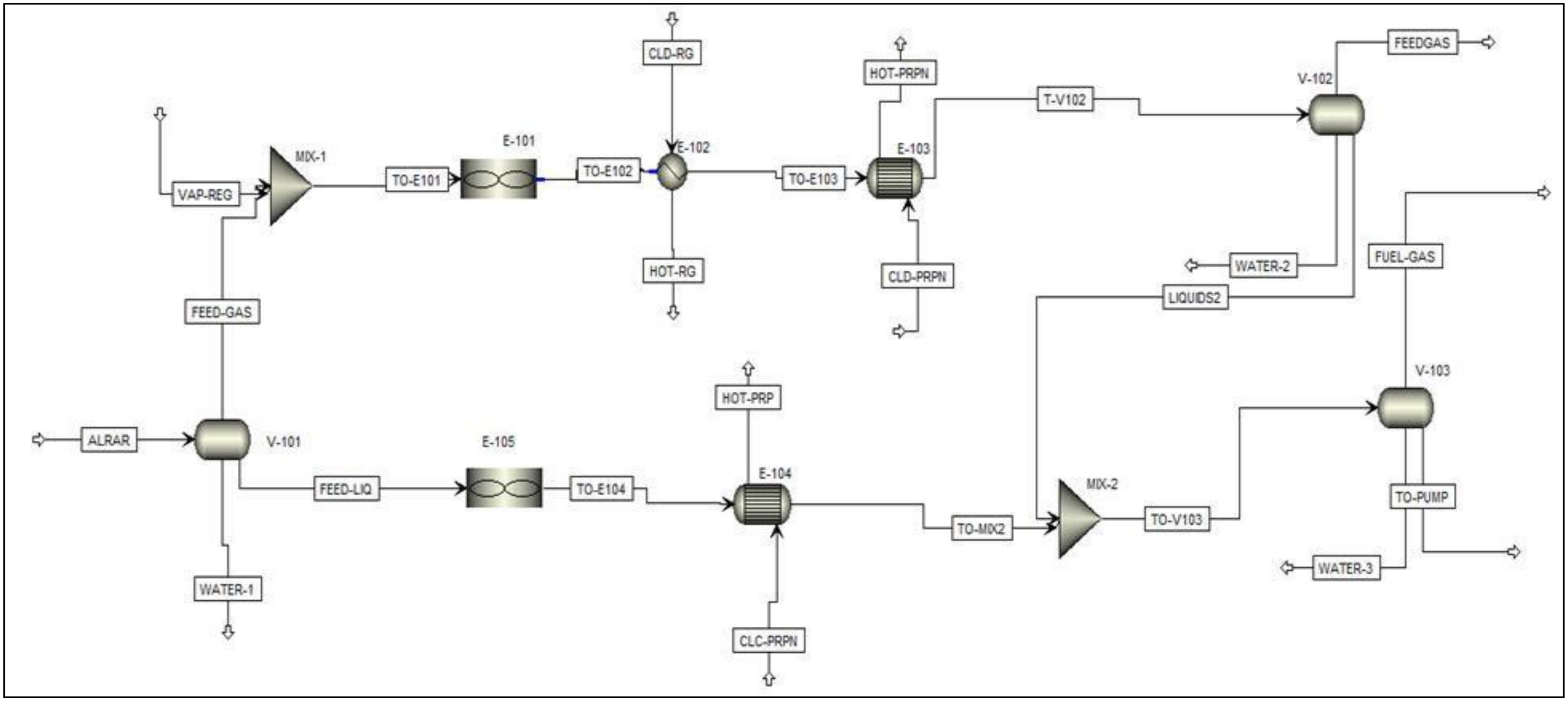


**Figure 3.4**. ASPEN PLUS process flowsheet.

#### 3.3.3.2. Separation train Aspen HYSYS flowsheet

In this section, a description of the Aspen HYSYS process flowsheet (Figure 3.5) is given.

ALRAR feed gas (stream ALRAR) is initially fed into a VERTICAL THREE-PHASE (called V-101), and the flashed gas (stream FEED-GAS) is mixed with vapor regeneration (stream VAP-REG) in a mixer (called MIX-1), the product from the latter mixer (stream TO-E101) is sent to an air cooler (called E-101), the cooled gas (stream TO-E102) is sent to a heat exchanger (called E-102),where it is cooled by heat exchange with residual gas (stream CLD-RG), the cooled gas is then sent to a heat exchanger (called propane refrigerant E-103), where it gets cooled. Finally, the gas is fed into a VERTICAL THREE-PHASE (called V-102). The flashed gas (streamFEEDGAS) is sent for further processing. The flashed liquids (stream LIQUIDS2) are mixed with(steam TO-MIX2) in a mixer (called MIX-2).

The flashed liquids (stream FEED-LIQ) from the VERTICAL THREE-PHASE (called V-101) are sent to an air cooler (called E-105), and the cooled liquids (stream TO-E104) is cooled by passing a heat exchanger (called propane refrigerant E-104). The cooled liquids (stream TO-MIX2) are mixed with the previously flashed liquids (stream LIQUIDS2) in a mixer (called MIX-2). The products (stream TO-V103) from the mixer (called MIX2) are fed into VERTICAL THREE-PHASE (called V-103), from where flashed gas (stream FUEL-GAS) is sent for further processing. The flashed liquids (stream TO-PUMP) are sent for further processing, while the separated water (stream WATER-3) is sent to the oily water treatment unit for further processing.

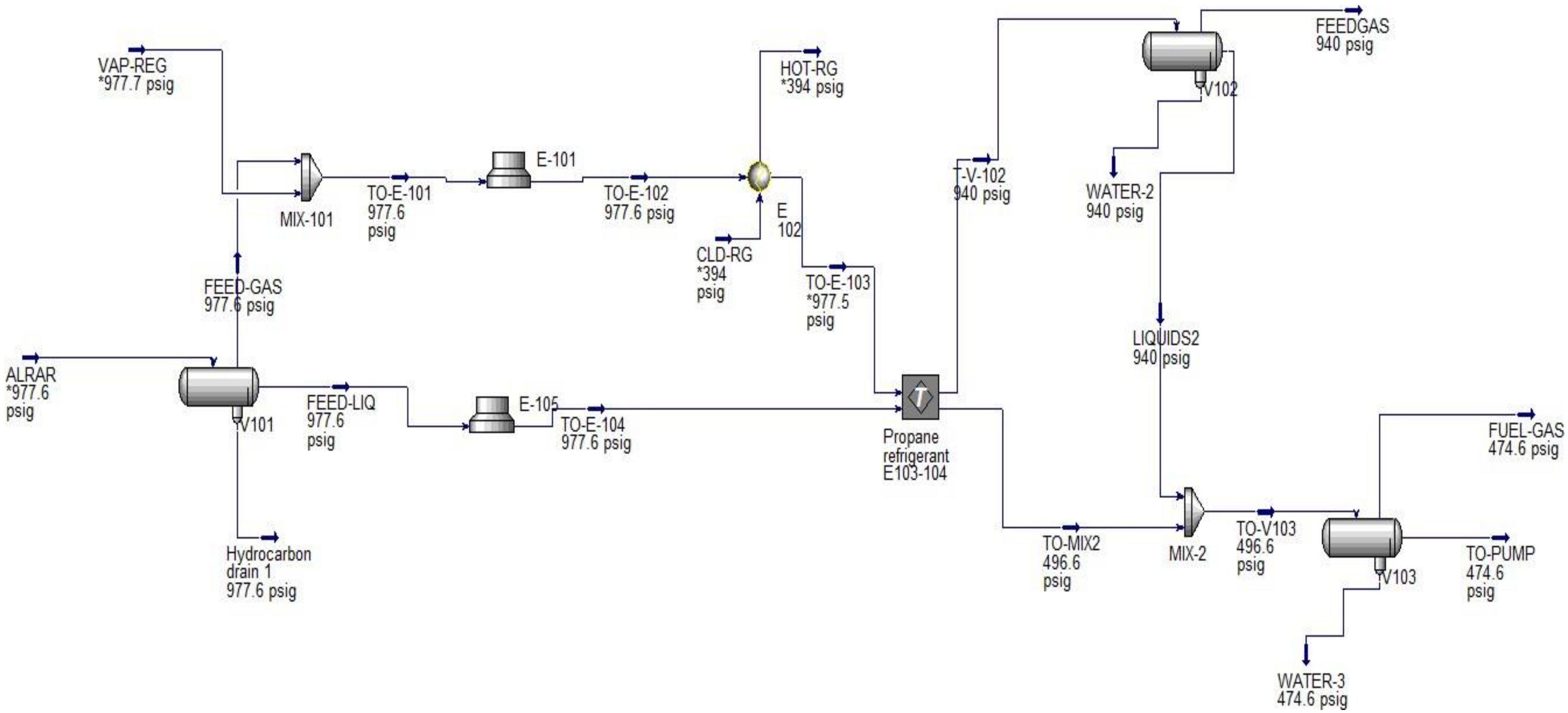


**Figure 3.5** Aspen HYSYS process flowsheet

### 3.3.4. Exergy Computing

The total exergy of each stream was calculated using both simulators Aspen Plus V10 and Aspen HYSYS V11. The total exergy of each stream was calculated in both: i) Aspen Plus V10 where some configurations have to be set to let the software calculate and display the exergy results; ii) Aspen HYSYS V11 where the mass exergy of each stream is automatically displayed. This section describes how to determine the total exergy of each stream in Aspen Plus V10 and Aspen HYSYS V11. A code in Aspen HYSYS was used to determine the physical exergy of streams. This section also explains how to compute the physical exergy of each stream.

#### 3.3.4.1. Total exergy calculation

***i)* Aspen Plus V10**

Below are the steps on how the total exergy of each stream was estimated using Aspen Plus V10:

- Go to the “Simulation” menu on the left side, then select the “Calculations Options” tab from the “Setup” folder see Figure (3.6).

- At the bottom of this page, there are two fields named "Exergy reference environment temperature" and "Exergy reference environment pressure". In the case of this study, the ambient temperature and ambient pressure are 20 $^{o}$C and 1 atm, respectively.

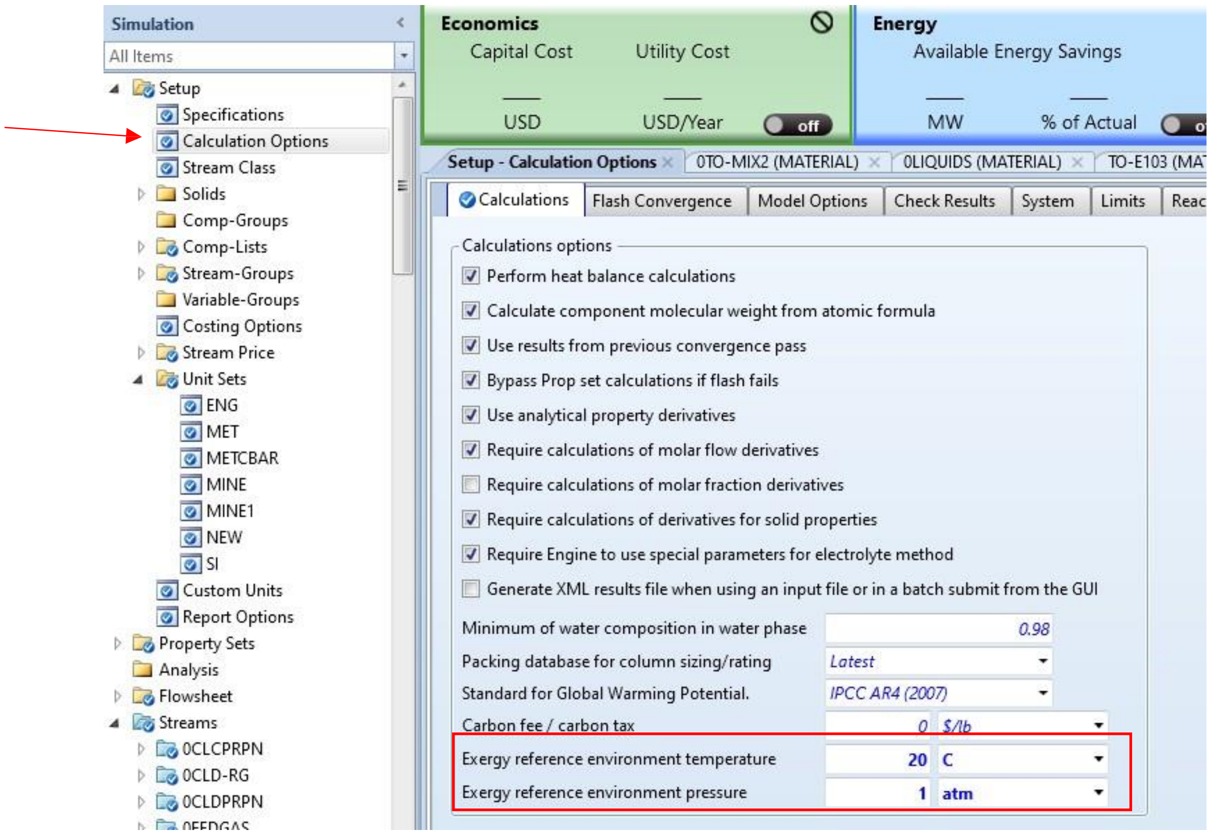


**Figure 3.6** Aspen Plus V10 calculation page.

- On the "Simulation" menu on the left side, select "Property Sets", then add a new value see Figure (3.7).
- Add the following options: "EXERGYFL", "EXERGYML", and "EXERGYMS".
- The unit of each option can be specified under "Units".

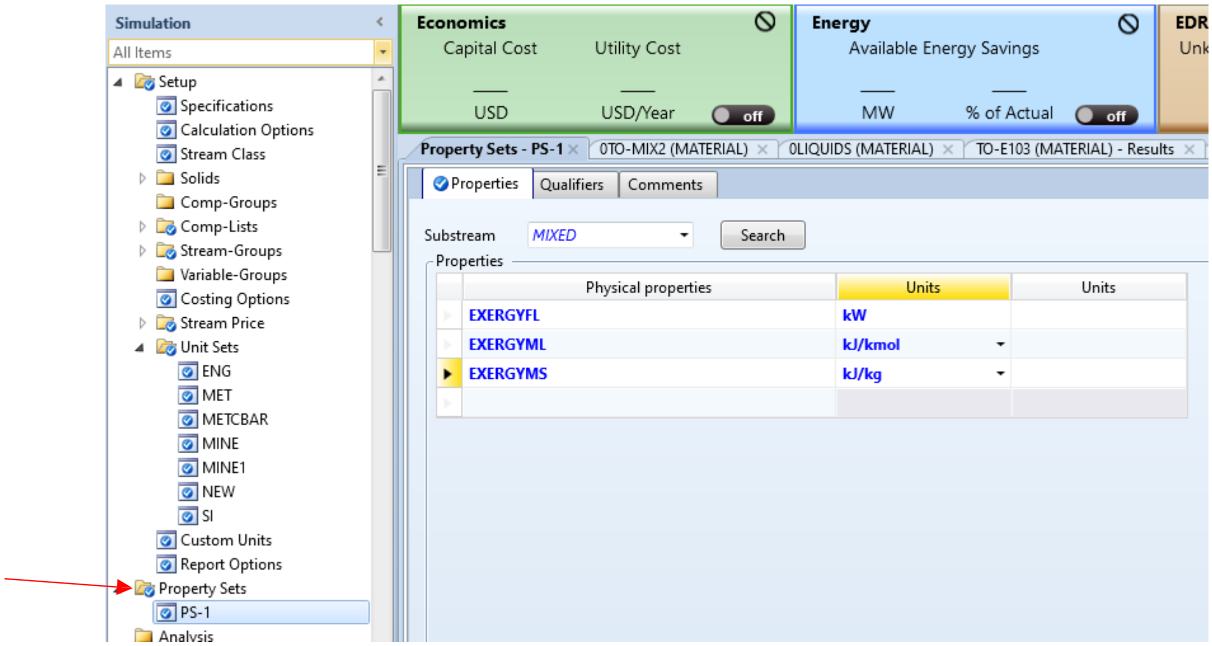


**Figure 3.7** Aspen Plus property sets.

- Under the "Setup" folder in the "Simulation" menu on the left side, select the "Report Options" tab see Figure (3.8).
- Click on the "Streams" tab, then select the "Property Sets".

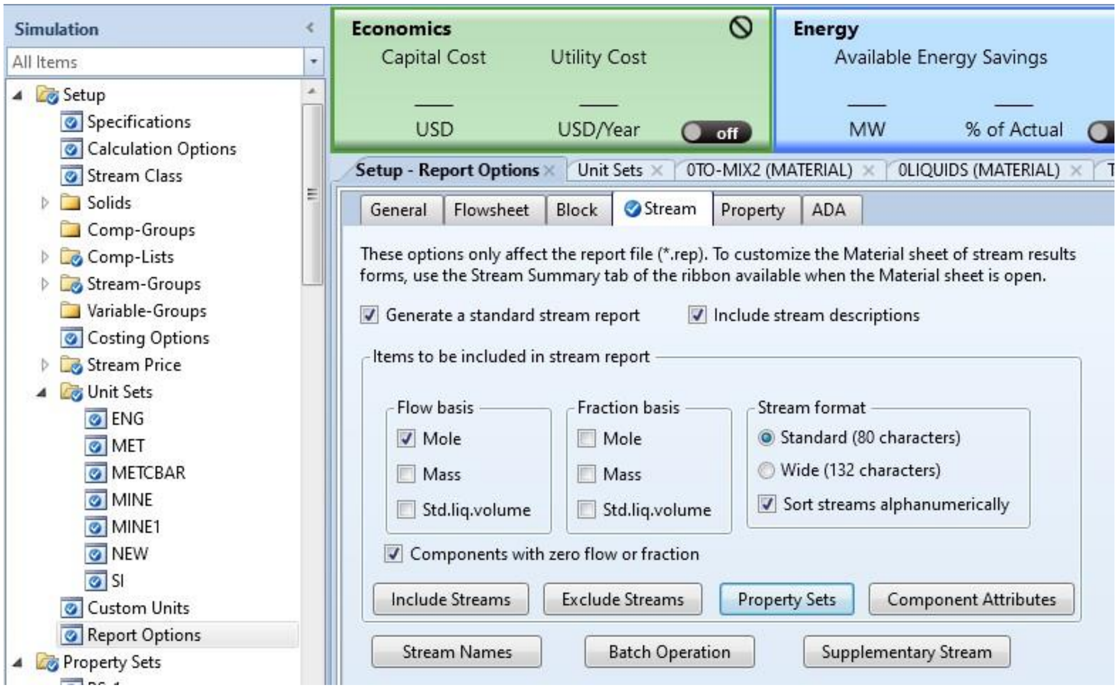


**Figure 3.8** Aspen Plus "report options" page.

- Move the wanted property sets from “Available property sets” to “Selected property sets”.

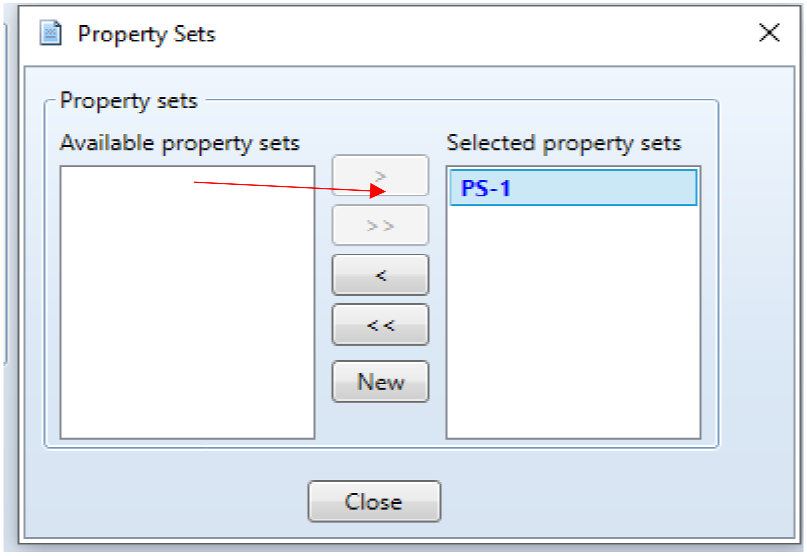


**Figure 3.9** Aspen Plus "Property sets" window.

- Then go to the stream results, scroll down then press “Add properties”.
- Add the wanted properties, then press “OK”.

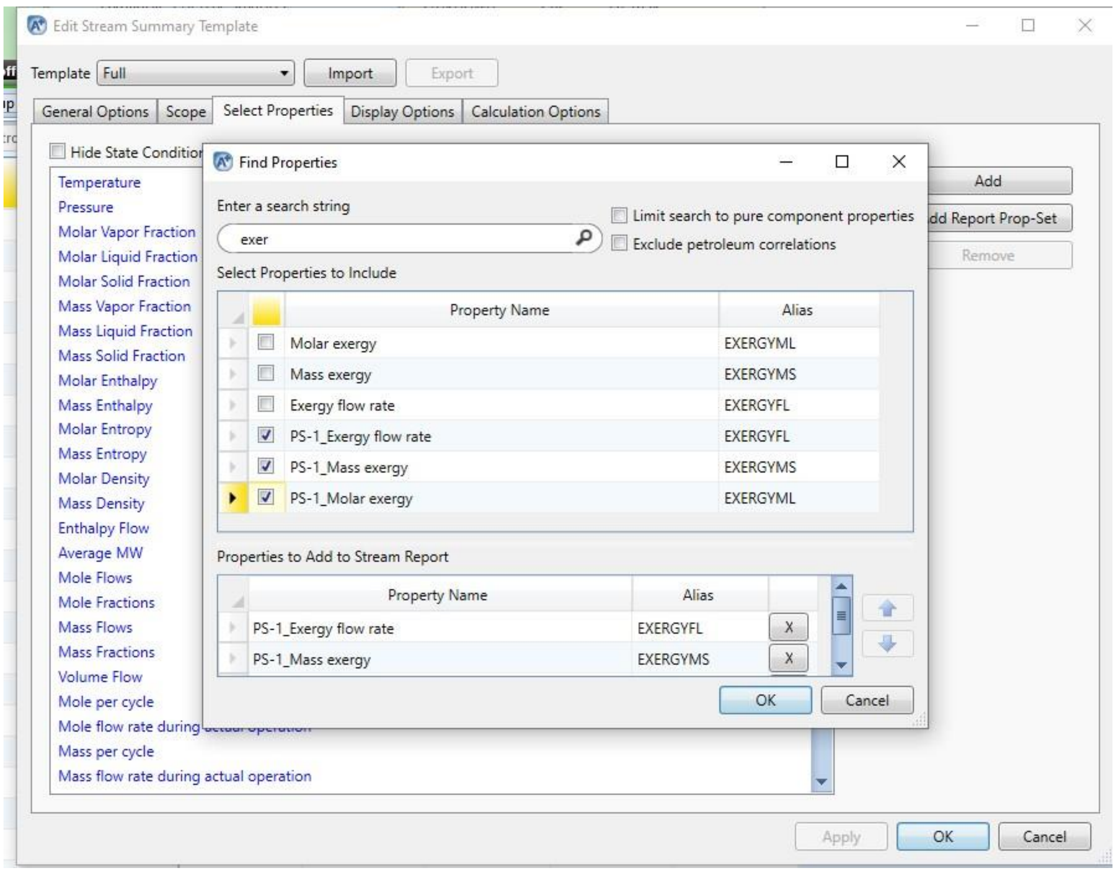


**Figure 3.10** Aspen Plus "Add Properties" window.

### *ii)* Aspen HYSYS V11

In this section, we provide steps on how the total exergy of each stream was calculated in Aspen HYSYS:

- Under “Properties” of any stream, there is a field named “Mass exergy”. See Figure (3.11).

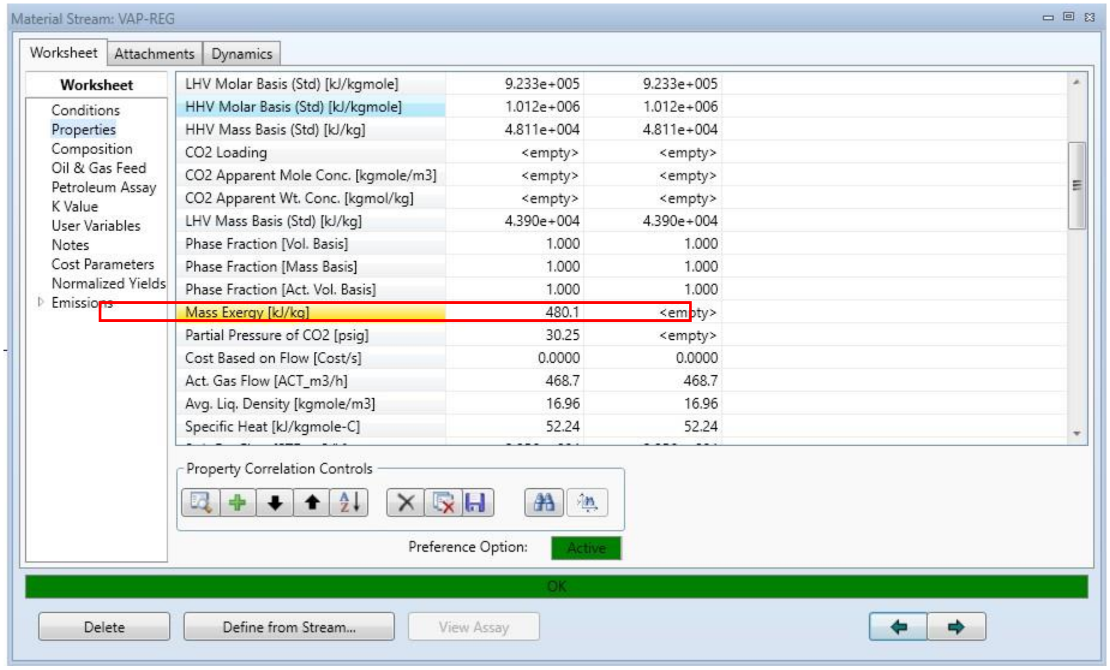


**Figure 3.11** Aspen HYSYS "mass exergy".

- To get the total exergy of a stream, Equation (3.7) was used:

$$Ex_{stream} = m \times ex_{mass} \tag{3.7}$$

Where

Ex: Exergy.

m: mass flow.

$ex_{mass}$: Specific mass exergy.

### 3.3.4.2. Physical exergy:

The physical exergy of each stream was calculated using visual basic code (VBA) in Aspen HYSYS. The entire code can be found in the appendix. An explanation of how to set the code, as well as the required steps can be found below.

- Right-click on the desired stream, then go to user variables.

- Add all the blue fields as shown in Figure (3.12). (Note that “Partial pres” means “Partial pressure”). The units are “kPa” and “C” for pressures and temperatures respectively.

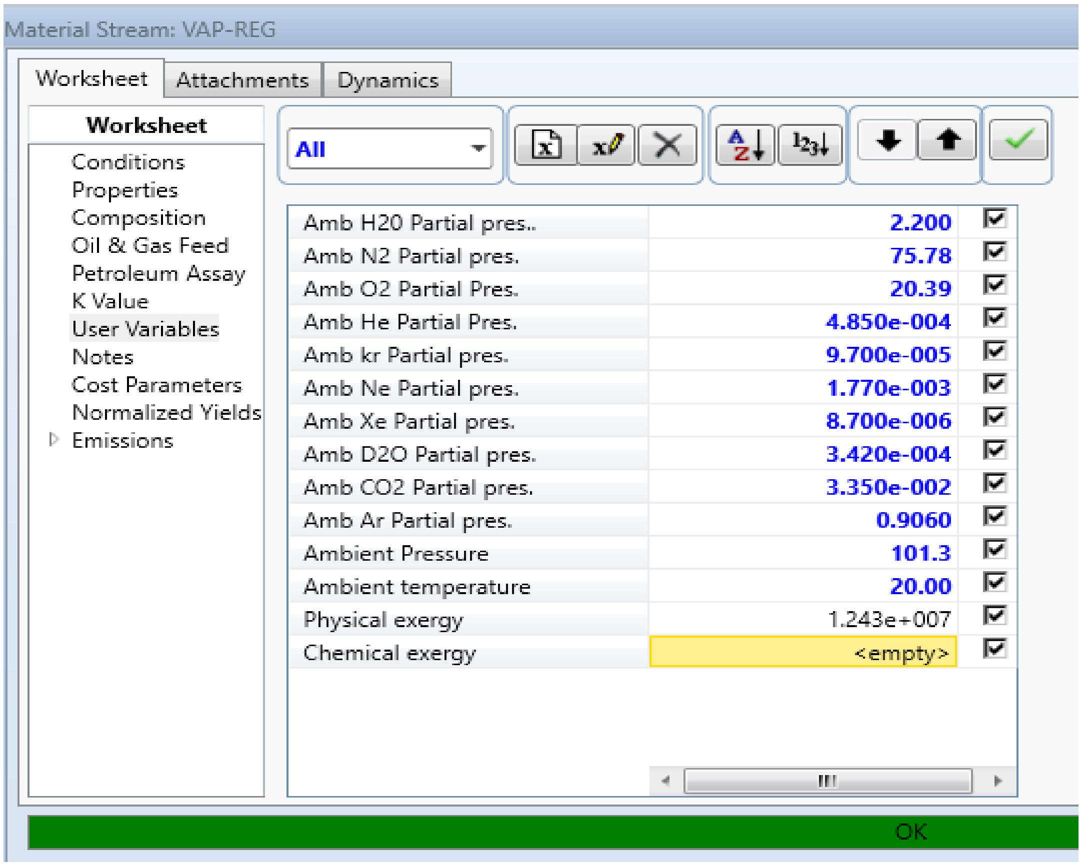


**Figure 3.12** Aspen HYSYS "user variable".

- Once the values of the blue fields are added, add a new user variable, then copy and paste the code provided in the appendix.

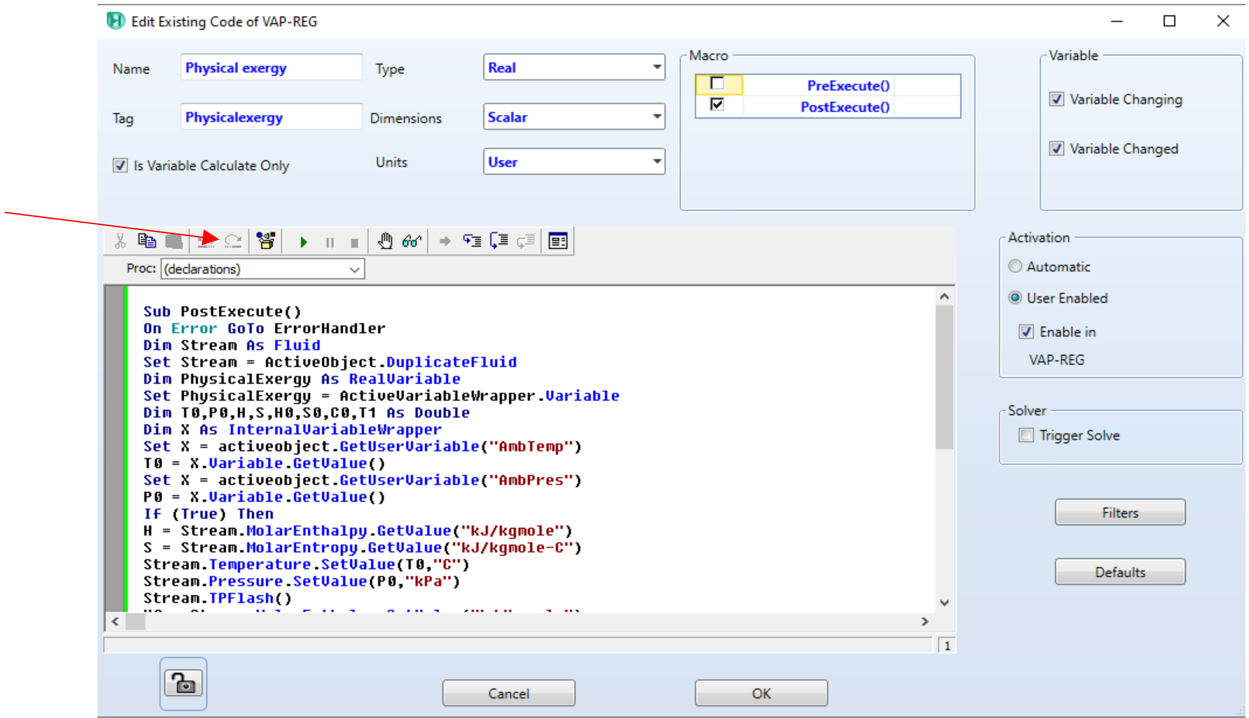


**Figure 3.13** Aspen HYSYS "Physical exergy"

- Click the "run" button, then ok. See Figure (3.13).

- **Temperature- and pressure-based exergies**

The temperature- and pressure-based exergies were calculated using Equations (2.32) and (2.29), respectively.

### 3.3.4.3. Chemical exergy:

Equation (3.8) was used to calculate the "chemical exergy" of each stream.

$$Ex_{ch,k} = Ex_k - Ex_{phy,k} \tag{3.8}$$

Where

$Ex_{ch,k}$: Chemical exergy of the kth stream.

$Ex_k$: Total exergy of the kth stream.

$Ex_{phy,k}$: Physical exergy of the kth stream.

# 4. RESULTS AND DISCUSSION

The system boundary under consideration begins with the inflow streams "ALRAR" and "VAP-REG" and is confined by the outflow streams "FEEDGAS," "FUEL-GAS," "TO-PUMP," "WATER-1," "WATER-2," and "WATER-3."

## 4.1. Energy analysis

### 4.1.1. Energy balance

The energy balance around each device gave the results presented in Table (4.1).

**Table 4.1** Energy consumption.

| **Device** | **Q (kW)** |
|---|---|
| Separator V-101 | 0 |
| Mixer MIX-1 | 0 |
| Air cooler E-101 | -9,350.23 |
| Heat exchanger E-102 | -2,769.62 |
| Propane refrigerant E-103 | -4,599.37 |
| Separator V-102 | 0 |
| Mixer MIX-2 | 0 |
| Air cooler E-105 | -669 |
| Propane refrigerant E-104 | -504 |
| Separator V-103 | -19 |
| Total | **-17911.2** |

.

The energy analysis revealed that the air cooler (E-101), propane refrigerant (E-103), and heat exchanger (E-102) are the most energy consumers. No work might be done by the said devices; therefore, the cause of energy degradation is heat loss.

## 4.2. Exergy analysis

### 4.2.1. Exergy flow

The exergy flow rates of the streams are presented in Table (4.2). The total exergy entering the train from streams "ALRAR", and "VAP-REG" was found to be 33.759 MW, whereas 30.689 MW exited the train from streams "FEEDGAS", "FUEL-GAS", "TO-PUMP", "WATER-1", "WATER-2", and "WATER-3". Because the separated water is transferred to a treatment system, its exergy loss is not addressed in this study.

**Table 4.2** Streams' exergy flow rate

| **Device** | **Exergy flow rate (kW)** |
|---|---|
| ALRAR | 30,306.43601 |
| CLC-PRPN | 2,368.680711 |
| CLD-PRPN | 11,843.40355 |
| CLD-RG | 16,375.18179 |
| FEED-GAS | 29,917.02188 |
| FEED-LIQ | 368.5030373 |
| FEEDGAS | 29,990.28721 |
| FUEL-GAS | 277.3585199 |
| HOT-PRP | 2,380.761546 |
| HOT-PRPN | 12,027.3482 |
| HOT-RG | 16,529.25235 |
| LIQUIDS2 | 623.8651573 |

| | |
|---|---|
| T-V102 | 31,005.84683 |
| TO-E101 | 33,358.57194 |
| TO-E102 | 31,796.43736 |
| TO-E103 | 31,508.73945 |
| TO-E104 | 254.8994371 |
| TO-MIX2 | 181.8404244 |
| TO-PUMP | 414.4022143 |
| TO-V103 | 734.8677115 |
| VAP-REG | 3,452.255285 |
| WATER-1 | 0 |
| WATER-2 | 7.351898552 |
| WATER-3 | 0.038879452 |

It was found that 3 MW of exergy was destructed within the separation train. This was due to the irreversibilities that occurred within the train's equipment. Comparing the result presented in this section with literature reveals that the ALRAR separation train destructs a significant amount of exergy.

### 4.2.2. Exergy destruction

The amount of exergy destructed within each device is presented in Table (4.3). The total exergy destructed by all the devices is 17 MW. As mentioned in Section (4.2.1) 3 MW was destructed within the train, this amount is only the result of the difference between the exergy entering the train andthe exergy leaving the train – without including the work used by the air coolers, and the exergy decrease in the air streams entering the latter mentioned devices.

The air cooler (E-101) dissipated the most exergy, followed by the air cooler (E-105), and finally the separator (V-102), with 14,947 kW 1,071 kW, and 398.33 kW, respectively. The mixer (MIX-

1) dissipates the least exergy at 10.72 kW. The air stream and hot stream in the air cooler (E-101) dissipate 6,903 kW of exergy, and 1,563 kW of exergy respectively.

While the duty was set at 9,350 kW, the air pressures at the entrance and outflow were 16,736.31 psig and 16,211.27 psig, respectively. Air was required to chill the air cooler (E-101) at a rate of 6,732,200 kg/hr. To cool the heated stream, the air cooler (E-105) required 481,698 kg/hr of air. The air stream and the hot stream each dissipated 351.83 kW and 113.69 kW of exergy. The duty was determined to be 669.026 kW. The air pressures at the entrance and outflow were 16,736.31 psig and 16,211.27 psig, respectively. The exergy dissipated by the air coolers' (E-101) and (E-105) hot streams can be explained by the decrease in temperature.

**Table 4.3** Exergy destructed within each equipment.

| **Equipment** | **Exergy destructed (kW)** |
|---|---|
| Separator V-101 | 20.91109202 |
| Mixer MIX-1 | 10.71540846 |
| Air cooler E-101 | 14,947.2794 |
| Heat exchanger E-102 | 133.6271951 |
| Propane refrigerant E-103 | 318.948393 |
| Separator V-102 | 398.3382665 |
| Mixer MIX-2 | 70.63401361 |
| Air cooler E-105 | 1071.365116 |
| Propane refrigerant E-104 | 60.9781774 |
| Separator V-103 | 43.0644994 |
| **Total** | 17,075.86155 |

### 4.2.3. Physical exergy

The results of physical exergy, temperature-based exergy, and pressure-based exergy calculations for the streams are provided in Table (4.4).

**Table 4.4**. Physical, temperature, and pressure-based exergy of the streams.

| Streams | Physical exergy (kW) | Temperature-based (kW) | Pressure-based (kW) |
|---|---|---|---|
| ALRAR | 30,306.43858 | 2,275.708932 | 28,030.72965 |
| FEED-GAS | 29,917.02422 | 2,070.646673 | 27,846.37754 |
| FEED-LIQ | 368.5030604 | 152.0160314 | 216.4870289 |
| VAP-REG | 3,452.255561 | 94.92905723 | 3,357.326504 |
| TO-E101 | 33,358.57454 | 2,140.230386 | 31,218.34415 |
| TO-E102 | 31,796.43984 | 578.0957091 | 31,218.34413 |
| TO-E103 | 31,508.7419 | 290.3977482 | 31,218.34415 |
| CLD-RG | 16,375.1831 | -167,324.1673 | 183,699.3504 |
| HOT-RG | 16,529.25367 | -149,926.8768 | 166,456.1304 |
| CLD-PRPN | 11,843.4045 | 0.341444773 | 11,843.06306 |
| HOT-PRPN | 69,949.30374 | 184.2861032 | 69,765.01764 |
| T-V102 | 31,005.84927 | 19.28729209 | 30,986.56198 |
| Water-2 | 7.344177703 | 0.339859134 | 7.004318569 |
| LIQUIDS2 | 622.9244262 | 1.562652358 | 621.3617738 |
| FEEDGAS | 86,202,487.17 | 86,172,517.65 | 29,969.52359 |
| TO-E104 | 254.899451 | 38.38350197 | 216.5159491 |
| TO-MIX2 | 181.8404326 | 1.243736174 | 180.5966964 |
| TO-V103 | 734.1306451 | -13.48284643 | 747.6134915 |

| | | | |
|---|---|---|---|
| FUEL-GAS | 276.7361925 | 0.045318467 | 276.690874 |
| TO-PUMP | 414.3534244 | 0.833925321 | 413.5194991 |

For all the streams, the pressure-based exergy is bigger than the temperature-based exergy. This can be explained by the significant difference between the streams' pressure and the environmental pressure – $P_0$ =- 1 atm -. While the streams' temperature is close to the environmental temperature – $T_0$ = 20 °C.

During the process, the physical-based exergy decreases (except in the cold streams of the heat exchangers (E-101) and (E-102)). More specifically, the temperature-based exergy had more share to the physical exergy decrease than the pressure-based exergy.

### 4.2.4. Chemical exergy

The results of the streams' chemical exergy are presented in Table (4.5).

**Table 4.5**. Streams' chemical exergy results.

| **Equipment** | **Chemical exergy (kW)** |
|---|---|
| ALRAR | -0.0001479 |
| FEED-GAS | 5.67559E-05 |
| FEED-LIQ | 6.40273E-06 |
| VAP-REG | -2.60253E-10 |
| TO-E101 | 7.05137E-05 |
| TO-E102 | 7.05146E-05 |
| TO-E103 | 7.02925E-05 |
| CLD-RG | -1.09689E-10 |
| HOT-RG | -8.48538E-11 |

| | |
|---|---|
| CLD-PRPN | 5.85096E-07 |
| HOT-PRPN | -57,921.95458 |
| T-V102 | 4.70641E-05 |
| Water-2 | -8.66485E-08 |
| LIQUIDS2 | -0.000401922 |
| FEEDGAS | -86,172,502.27 |
| TO-E104 | 6.40276E-06 |
| TO-MIX2 | 6.40273E-06 |
| TO-V103 | 0.001586184 |
| FUEL-GAS | -8.38491E-09 |
| TO-PUMP | 7.25031E-05 |

The chemical exergy for all streams is very small, if not negative. The exergy of mixing can account for this. It's worth noting that reaction exergy was not included in any of the streams. The variations in the chemical exergy of the streams are minor, as shown in Table (4.5). As a result, it is the physical-based exergy that had been destroyed the most.

#### 4.2.5. Exergy efficiency

As shown in Figure (4.1), the separator (V-101) and mixer (MIX-1) have nearly perfect efficiency - more than 99% -, with the separator (V-102) coming in second with 98.70% exergy efficiency. In descent order, the least inefficient devices inside the separation train in the matter are the propane refrigerant (E-103), mixer (MIX-2), and then the propane refrigerant (E-104), with 93.06%, 91.22%, and 87.89 %, respectively.

The temperature and pressure of the hot streams in the inlet of the propane refrigerant (E-104) and (E-103) were reduced by 33 °C, 81 psig, and 21 °C, 38 psig, respectively. The inlet pressures of the mixer (MIX-2) were 940 psig and 497 psig, while the exit stream pressure was 497 psig.

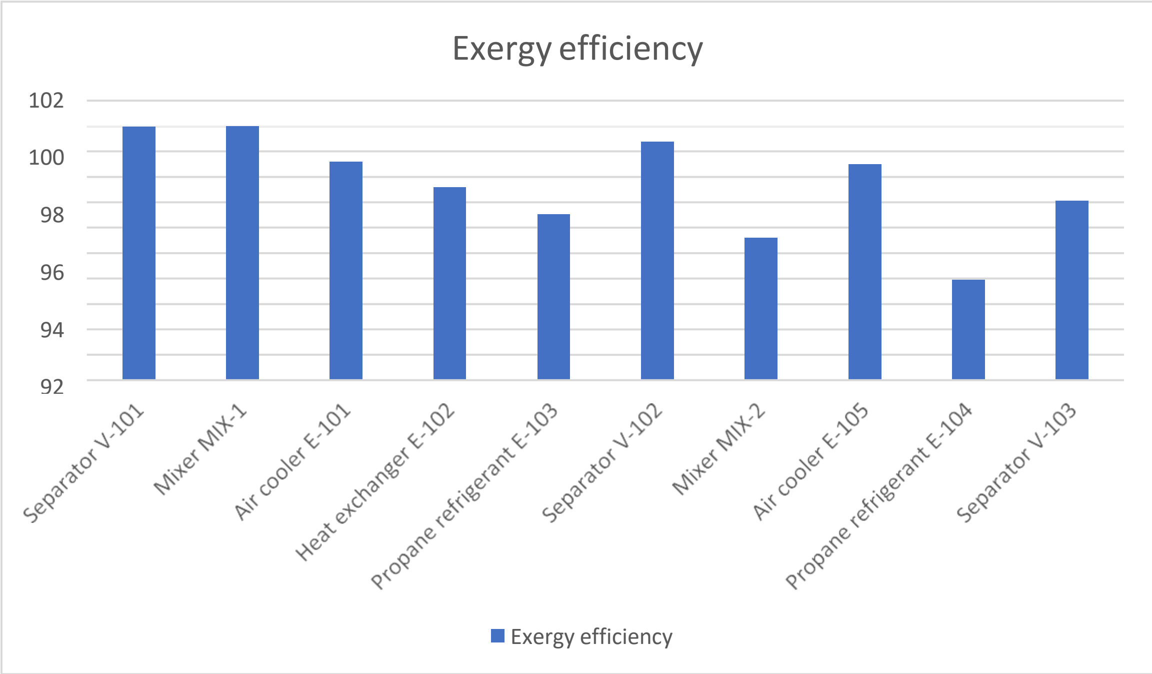


**Figure 4.1** Exergy efficiency.

### 4.2.6. Relative exergy destruction

The contribution of each device to the total exergy destruction within the separation train is shown in Table (4.6).

**Table 4.6** Exergy destruction ratio.

| Device | Exergy destructed ratio (%) |
|---|---|
| Separator V-101 | 0.122459953 |
| Mixer MIX-1 | 0.062751788 |
| Air cooler E-101 | 87.53455488 |
| Heat exchanger E-102 | 0.782550237 |
| Propane refrigerant E-103 | 1.867831922 |
| Separator V-102 | 2.332756478 |

| | |
|---|---|
| Mixer MIX-2 | 0.413648315 |
| Air cooler E-105 | 6.274149699 |
| Propane refrigerant E-104 | 0.357101615 |
| Separator V-103 | 0.252195178 |
| Total | 100% |

As shown in table (4.6), the air cooler (E-101) contributes the most to the overall exergy destructed within the train, accounting for 87% of the total exergy destructed. This can be explained by the enormous amount of work required, as well as the exergy destroyed by the hot stream. The air cooler (E-105) is the second-largest contributor, accounting for only 06% of the total. The main cause of the exergy destructed within this device, as well as the effort required, is the decrease in the hot stream's temperature.

### 4.3. Implications for Exergy destruction and Efficiency

The exergy destruction indicator shows that the air coolers (E-101) and (E-105) are the most exergy-inefficient components of the separation train. The substantial amount of exergy destroyed by the air chiller (E-101) can be explained using three considerations: i) the first consideration may be the significant temperature contrast between the air and hot streams. As mentioned in Section (4.2.3) temperature-based exergy was the main cause of the physical exergy destroyed in the hot stream; ii) the second point is the large amount of work required by the air cooler, as shown in Equation (3.2) the work value has a direct effect on the amount of exergy destroyed within the air cooler; iii) and finally, the third point is related to the pressure drop in the air stream. The exergy destructed by the air cooler could be viewed similarly (E-105).

The significant difference in exergy destruction between the two air coolers (E-101) and (E-105) can be attributed directly to the hot stream flow rates. The latter affects two factors that directly affect exergy degradation within air coolers: the first is the amount of exergy (exergy dependent on temperature) in the hot streams. The second factor to consider is the difference in the amount of work that the two air coolers required as mentioned in Section (4.2.2). More precisely, the higher the flow rate of the hot streams, the more air is required, and the higher the flow rate of the hot streams, the more thermal exergy is destroyed. The same logic applies to air streams; the more air required; the more exergy based on pressure is lost.

The second metric in this study namely the exergy efficiency demonstrates that the propane refrigerant devices (E-104) and (E-103) were among the three least efficient devices (see Figure 4.1). The inefficiency of these two devices is a result of the significant quantity of physical exergy lost in the hot stream and not effectively recovered by the cold stream (propane), this can be explained by the negative effect of fouling and the film resistances. In addition to the pressure drop that had a place. The (E-103) heat exchanger is more efficient than (E-104). The difference in temperature between the hot and cold streams explains this, in addition to the lesser decrease in hot stream pressure as mentioned in Section (4.2.5).

The mixer (MIX-2) is the train's second inefficient equipment. Two factors contribute to this device's inefficiency. The first is the difference in the composition of the two input streams; the mix of the two inlet streams affects the chemical exergy, as well as an increase in the exergy of mixing. The second point is the pressure differential between the two input streams that caused the pressure drop, as cited in Section (4.2.5).

However, the findings of this study must be interpreted in light of the following constraint: the difficulty inherent in selecting the most appropriate equations for calculating the two exergy parameters - exergy destruction and exergy efficiency. According to numerous investigations, the two exergy parameters were estimated without considering the type of equipment employed. This may be unreasonable, and the results of estimating exergy destructionwithin an air cooler may be incorrect unless work is included in the formula. To put it another way, calculating exergy destruction within any device using Equation (2.3) will provide inconsistent results.

One of this dissertation's accomplishments has been the ability to integrate exergy analysis with Aspen Plus and Aspen HYSYS, in addition, it shows how to compute physical exergy with Aspen HYSYS.

# 5 CONCLUSION AND RECOMMENDATIONS

Petrochemical and chemical industries are among the most energy-intensive sectors of the economy, accounting for more than a third of all industrial energy consumption. Exergy analysis can be a beneficial tool for identifying energy waste in this case. Exergy analysis can also be used to visualize process change and environmental constraints at a high level. This study examined the separation trains at Algeria's ALRAR gas separation facility and potential solutions for reducing exergy losses. Specifically, it addressed the following research questions: which sections of the separation train experience significant exergy losses, and what are the potential solutions for increasing the separation train's exergy efficiency, using a combination of Aspen Plus and Aspen HYSYS simulations.

The results indicate that the ALRAR gas plant's air coolers (E-101) and (E-105) suffer considerable exergy losses, and the heat exchangers (E-104) and (E-103) have low exergy efficiency. Additionally, the exergy study led to the formulation of the actionable following recommendations for increasing the exergy efficiency of the separation train:

*(1) Reduce the propane refrigerants' significant temperature gap. This can be accomplished by using the propane stream to cool another stream - in another train - that has a higher temperature before using it in the separation train.*

*(2) Close the heat capacity gap between the two streams exchanging heat in the heat exchangers (E-104) and (E-103).*

*(3) Avoid direct mixing of streams (LIQUIDS2) and (TO-MIX2) to avoid the destruction of pressure- and chemical-based exergies while gaining some energy. Connecting the stream (LIQUIDS2) to a turbo expander does this.*

*(4) Place the air coolers in a cooler location: because the amount of required air is less, the driving force of the fan is reduced.*

This is not easy to achieve because there are constraints to consider such as industrial limitations and the specification of the refrigeration cycle which can sometimes be complex. Thus, a feasibility study is required.

In addition to the recommendations above, this study has demonstrated how to compute physical exergy with Aspen HYSYS, which is a significant contribution, and we believe it is a valuable tool that can provide accurate results in a matter of seconds.

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## APPENDICES

Streams information for Figure 3.4

***Table E1*** *ASPEN PLUS streams information*

| | ALRAR | FEED-GAS | FEED-LIQ | VAP-REG | TO-E101 |
|---|---|---|---|---|---|
| **Temperature** (C) | 100 | 100 | 100 | 77 | 97.74211455 |
| **Pressure** (psig) | 977.6 | 977.6 | 977.6 | 977.6 | 977.6 |
| **Mole Flows** (kmol/hr) | 10919.4 | 10656.50201 | 262.897986 | 1250 | 11906.50201 |
| **Mole Fractions** | | | | | |
| NITROGEN | 0.003143934 | 0.003210432 | 0.000448447 | 0.003383664 | 0.003228618 |
| C1 | 0.740786022 | 0.754461277 | 0.186463051 | 0.790574157 | 0.758252575 |
| C2 | 0.090674963 | 0.091512546 | 0.056723739 | 0.091755992 | 0.091538104 |
| $CO_2$ | 0.043126746 | 0.043682594 | 0.020595582 | 0.045280797 | 0.043850381 |
| C3 | 0.041752133 | 0.041514406 | 0.051388365 | 0.038215089 | 0.041168028 |
| IC4 | 0.007957366 | 0.007761102 | 0.015912896 | 0.006369141 | 0.007614967 |
| NC4 | 0.014244318 | 0.013758527 | 0.033935706 | 0.010548938 | 0.01342157 |
| IC5 | 0.005698093 | 0.005301412 | 0.021777466 | 0.00378169 | 0.005141865 |
| NC5 | 0.004992013 | 0.004580452 | 0.021674557 | 0.002587451 | 0.004371217 |
| C6 | 0.007466499 | 0.006273904 | 0.055808027 | 0.002089858 | 0.005834643 |
| C7 | 0.005501197 | 0.00402255 | 0.065437766 | 0.000696646 | 0.003673381 |
| C8 | 0.005010329 | 0.002970517 | 0.0876936 | 0.00029854 | 0.00269 |
| C9 | 0.003732791 | 0.001667612 | 0.087444311 | 9.94866E-05 | 0.001502983 |
| C10 | 0.002751056 | 0.000863626 | 0.079257574 | 1.59946E-05 | 0.000774637 |
| C11 | 0.001768405 | 0.000363506 | 0.058715645 | 0 | 0.000325343 |
| C12 | 0.004125669 | 0.000558625 | 0.148714872 | 0 | 0.000499978 |
| WATER | 0.017268465 | 0.017496913 | 0.008008395 | 0.004302555 | 0.016111707 |
| AIR | 0 | 0 | 0 | 0 | 0 |
| **Exergy flow rate (kW)** | 30306.43601 | 29917.02188 | 368.5030373 | 3452.255285 | 33358.57194 |

Stream information for Figure 3.4

***Table E2*** *ASPEN PLUS streams information.*

| | **TO-E102** | **TO-E103** | **CLD-RG** | **HOT-RG** | **CLD-PRPN** |
|---|---|---|---|---|---|
| **Temperature** (C) | 60 | 48 | 21 | 54.04147957 | 21 |
| **Pressure** (psig) | 978 | 978 | 394 | 394 | 99.88386403 |
| **Mole Flows** (kmol/hr) | 11906.50201 | 11906.50201 | 7435 | 7435 | 9071.010592 |
| **Mole Fractions** | | | | | |
| NITROGEN | 0.003228618 | 0.003228618 | 0.0043 | 0.0043 | 0 |
| C1 | 0.758252575 | 0.758252575 | 0.8938 | 0.8938 | 0 |
| C2 | 0.091538104 | 0.091538104 | 0.0548 | 0.0548 | 0 |
| $CO_2$ | 0.043850381 | 0.043850381 | 0.0409 | 0.0409 | 0 |
| C3 | 0.041168028 | 0.041168028 | 0.0058 | 0.0058 | 1 |
| IC4 | 0.007614967 | 0.007614967 | 0.0002 | 0.0002 | 0 |
| NC4 | 0.01342157 | 0.01342157 | 0.0002 | 0.0002 | 0 |
| IC5 | 0.005141865 | 0.005141865 | 0 | 0 | 0 |
| NC5 | 0.004371217 | 0.004371217 | 0 | 0 | 0 |
| C6 | 0.005834643 | 0.005834643 | 0 | 0 | 0 |
| C7 | 0.003673381 | 0.003673381 | 0 | 0 | 0 |
| C8 | 0.00269 | 0.00269 | 0 | 0 | 0 |
| C9 | 0.001502983 | 0.001502983 | 0 | 0 | 0 |
| C10 | 0.000774637 | 0.000774637 | 0 | 0 | 0 |
| C11 | 0.000325343 | 0.000325343 | 0 | 0 | 0 |
| C12 | 0.000499978 | 0.000499978 | 0 | 0 | 0 |
| WATER | 0.016111707 | 0.016111707 | 0 | 0 | 0 |
| AIR | 0 | 0 | 0 | 0 | 0 |
| **Exergy flow rate (kW)** | 31796.43736 | 31508.73945 | 16375.18179 | 16529.25235 | 11843.40355 |

Streams information for Figure 3.4

***Table E3*** *ASPEN PLUS streams information.*

| | **HOT-PRPN** | **T-V102** | **LIQUIDS2** | **FEEDGAS** | **TO-MIX2** |
|---|---|---|---|---|---|
| **Temperature** (C) | 43.58546426 | 27 | 27 | 27 | 27 |
| **Pressure** (psig) | 99.88386403 | 940 | 940 | 940 | 497 |
| **Mole Flows** (kmol/hr) | 9071.010592 | 11906.50201 | 493.8712285 | 11229.14155 | 262.897986 |
| **Mole Fractions** | | | | | |
| NITROGEN | 0 | 0.003228618 | 0.000484748 | 0.00340201 | 0.000448447 |
| C1 | 0 | 0.758252575 | 0.259882788 | 0.792561727 | 0.186463051 |
| C2 | 0 | 0.091538104 | 0.105681347 | 0.092411843 | 0.056723739 |
| $CO_2$ | 0 | 0.043850381 | 0.031136991 | 0.045110536 | 0.020595582 |
| C3 | 1 | 0.041168028 | 0.111017972 | 0.038768643 | 0.051388365 |
| IC4 | 0 | 0.007614967 | 0.03562099 | 0.006507659 | 0.015912896 |
| NC4 | 0 | 0.01342157 | 0.077017857 | 0.010843838 | 0.033935706 |
| IC5 | 0 | 0.005141865 | 0.046198757 | 0.00342015 | 0.021777466 |
| NC5 | 0 | 0.004371217 | 0.044722829 | 0.002667929 | 0.021674557 |
| C6 | 0 | 0.005834643 | 0.088178079 | 0.002308414 | 0.055808027 |
| C7 | 0 | 0.003673381 | 0.069708796 | 0.000829083 | 0.065437766 |
| C8 | 0 | 0.00269 | 0.057709733 | 0.000314118 | 0.0876936 |
| C9 | 0 | 0.001502983 | 0.034239569 | 8.77452E-05 | 0.087444311 |
| C10 | 0 | 0.000774637 | 0.018149868 | 2.31104E-05 | 0.079257574 |
| C11 | 0 | 0.000325343 | 0.007738086 | 4.63772E-06 | 0.058715645 |
| C12 | 0 | 0.000499978 | 0.011965351 | 3.886E-06 | 0.148714872 |
| WATER | 0 | 0.016111707 | 0.000546239 | 0.000734671 | 0.008008395 |
| AIR | 0 | 0 | 0 | 0 | 0 |
| **Exergy flow rate** (kW) | 12027.3482 | 31005.84683 | 622.9239744 | 29984.90301 | 181.8404244 |

.

Streams information for Figure 3.4

***Table E4*** *ASPEN PLUS streams information.*

| | TO-V103 | FUEL-GAS | TO-PUMP | WATER-1 | WATER-2 | WATER-3 |
|---|---|---|---|---|---|---|
| **Temperature** (C) | 23.78285941 | 24 | 24 | | 27 | 24 |
| **Pressure** (psig) | 497 | 474.6 | 474.6 | 977.6 | 940 | 474.6 |
| **Mole Flows** (kmol/hr) | 756.7692145 | 120.7247059 | 634.0863088 | 0 | 183.489237 | 1.958199788 |
| **Mole Fractions** | | | | | | |
| NITROGEN | 0.000472137 | 0.002191803 | 0.000146181 | | 2.74685E-06 | 9.40219E-07 |
| C1 | 0.234377125 | 0.774030756 | 0.132355141 | | 2.61516E-07 | 1.19544E-07 |
| C2 | 0.088673709 | 0.109156778 | 0.085047739 | | 4.3045E-10 | 2.6942E-10 |
| $CO_2$ | 0.027474956 | 0.049433578 | 0.023376955 | | 0.000950525 | 0.000680618 |
| C3 | 0.090302933 | 0.041380372 | 0.099896278 | | 9.20563E-13 | 5.59403E-13 |
| IC4 | 0.028774493 | 0.006098534 | 0.033180679 | | 2.70374E-16 | 1.47478E-16 |
| NC4 | 0.062051325 | 0.009729239 | 0.072204665 | | 7.20304E-16 | 3.91095E-16 |
| IC5 | 0.037714918 | 0.002673001 | 0.044503094 | | 2.84404E-19 | 1.36899E-19 |
| NC5 | 0.03671597 | 0.002008578 | 0.043437371 | | 2.45958E-19 | 1.17552E-19 |
| C6 | 0.076932878 | 0.001509704 | 0.091530441 | | 8.81782E-22 | 9.15306E-22 |
| C7 | 0.068225061 | 0.000496987 | 0.081330646 | | 6.97089E-22 | 8.13308E-22 |
| C8 | 0.068125984 | 0.000185048 | 0.08127179 | | 5.77098E-22 | 8.12719E-22 |
| C9 | 0.052722641 | 5.54005E-05 | 0.062912887 | | 3.42396E-22 | 6.2913E-22 |
| C10 | 0.039378391 | 1.67818E-05 | 0.04699414 | | 1.81499E-22 | 4.69942E-22 |
| C11 | 0.025447445 | 4.17697E-06 | 0.030370229 | | 7.7381E-23 | 3.03703E-22 |
| C12 | 0.059471477 | 4.40781E-06 | 0.070977199 | | 1.19654E-22 | 7.09773E-22 |
| WATER | 0.003138556 | 0.001024856 | 0.000464563 | | 0.999046467 | 0.999318322 |
| AIR | 0 | 0 | 0 | | 0 | 0 |
| **Exergy flow rate** (kW) | 734.1303852 | 276.7361703 | 414.3534638 | | 7.344177029 | 0.038881909 |

Streams information for Figure 3.5

***Table E5.*** *Aspen HYSYS streams information.*

| | TO-E-101 | FEED-GAS | FEED-LIQ | WATER-1 | TO-E-102 | CLD-RG |
|---|---|---|---|---|---|---|
| **Temperature (C)** | 97.73959 | 100 | 100 | 100 | 60 | 21 |
| **Pressure (kPa)** | 6841.641 | 6841.641 | 6841.641 | 6841.641 | 6841.641 | 2817.86 |
| **Mole Flows (kmol/hr)** | 11906.81 | 10656.81 | 262.6285 | 0 | 11906.81 | 7434.77 |
| **Mole Fractions** | | | | | | |
| **Methane** | 0.758257 | 0.754436 | 0.186922 | 9.82E-06 | 0.758257 | 0.893849 |
| **Ethane** | 9.15E-02 | 9.15E-02 | 5.70E-02 | 7.96E-08 | 9.15E-02 | 5.48E-02 |
| **Propane** | 4.12E-02 | 4.15E-02 | 5.16E-02 | 1.21E-09 | 4.12E-02 | 5.75E-03 |
| **i-Butane** | 7.61E-03 | 7.76E-03 | 1.60E-02 | 3.60E-12 | 7.61E-03 | 2.14E-04 |
| **n-Butane** | 1.34E-02 | 1.38E-02 | 3.41E-02 | 8.87E-12 | 1.34E-02 | 1.80E-04 |
| **i-Pentane** | 5.14E-03 | 5.30E-03 | 2.19E-02 | 4.43E-14 | 5.14E-03 | 9.42E-06 |
| **n-Pentane** | 4.37E-03 | 4.58E-03 | 2.18E-02 | 4.04E-14 | 4.37E-03 | 4.04E-06 |
| **n-Hexane** | 5.83E-03 | 6.27E-03 | 5.60E-02 | 5.70E-16 | 5.83E-03 | 0 |
| **n-Heptane** | 3.67E-03 | 4.02E-03 | 6.56E-02 | 2.69E-18 | 3.67E-03 | 0 |
| **n-Octane** | 2.69E-03 | 2.97E-03 | 8.79E-02 | 1.30E-20 | 2.69E-03 | 0 |
| **n-Nonane** | 1.50E-03 | 1.66E-03 | 8.77E-02 | 4.27E-23 | 1.50E-03 | 0 |
| **$CO_2$** | 4.39E-02 | 4.38E-02 | 1.78E-02 | 4.25E-04 | 4.39E-02 | 4.09E-02 |
| **n-C12** | 4.97E-04 | 5.56E-04 | 0.148991 | 4.13E-31 | 4.97E-04 | 0 |
| **Nitrogen** | 3.23E-03 | 3.21E-03 | 4.48E-04 | 1.86E-06 | 3.23E-03 | 4.28E-03 |
| **n-C11** | 3.24E-04 | 3.62E-04 | 5.88E-02 | 1.19E-28 | 3.24E-04 | 0 |
| **$H_2O$** | 1.61E-02 | 1.75E-02 | 7.99E-03 | 0.999563607 | 1.61E-02 | 0 |
| **n-Decane** | 7.72E-04 | 8.63E-04 | 7.94E-02 | 5.94E-26 | 7.72E-04 | 0 |

Streams information for Figure 3.5

***Table E6*** *Aspen HYSYS streams information.*

| | HOT-RG | TO-E-103 | T-V-102 | FEEDGAS | LIQUIDS2 | WATER-2 |
|---|---|---|---|---|---|---|
| **Temperature (C)** | 54 | 47.97644 | 26.99978 | 26.99978 | 26.99978 | 26.99978 |
| **Pressure (kPa)** | 2817.86 | 6840.952 | 6582.399 | 6582.399 | 6582.399 | 6582.399 |
| **Mole Flows (kmol/hr)** | 7434.77 | 11906.81 | 11906.81 | 11231.37 | 492.348 | 183.0983 |
| **Mole Fractions** | | | | | | |
| **Methane** | 0.893849 | 0.758257 | 0.758257 | 0.792455 | 0.260134 | 2.62E-07 |
| **Ethane** | 5.48E-02 | 9.15E-02 | 9.15E-02 | 9.24E-02 | 0.106024 | 4.30E-10 |
| **Propane** | 5.75E-03 | 4.12E-02 | 4.12E-02 | 3.88E-02 | 0.111214 | 9.21E-13 |
| **i-Butane** | 2.14E-04 | 7.61E-03 | 7.61E-03 | 6.51E-03 | 3.57E-02 | 2.70E-16 |
| **n-Butane** | 1.80E-04 | 1.34E-02 | 1.34E-02 | 1.08E-02 | 7.72E-02 | 7.20E-16 |
| **i-Pentane** | 9.42E-06 | 5.14E-03 | 5.14E-03 | 3.42E-03 | 4.63E-02 | 2.84E-19 |
| **n-Pentane** | 4.04E-06 | 4.37E-03 | 4.37E-03 | 2.67E-03 | 4.48E-02 | 2.46E-19 |
| **n-Hexane** | 0 | 5.83E-03 | 5.83E-03 | 2.31E-03 | 8.84E-02 | 1.92E-22 |
| **n-Heptane** | 0 | 3.67E-03 | 3.67E-03 | 8.29E-04 | 6.99E-02 | 3.83E-26 |
| **n-Octane** | 0 | 2.69E-03 | 2.69E-03 | 3.14E-04 | 5.78E-02 | 6.86E-30 |
| **n-Nonane** | 0 | 1.50E-03 | 1.50E-03 | 8.83E-05 | 3.43E-02 | 7.65E-34 |
| **CO2** | 4.09E-02 | 4.39E-02 | 4.39E-02 | 4.52E-02 | 2.95E-02 | 9.53E-04 |
| **n-C12** | 0 | 4.97E-04 | 4.97E-04 | 3.84E-06 | 1.19E-02 | 1.14E-46 |
| **Nitrogen** | 4.28E-03 | 3.23E-03 | 3.23E-03 | 3.40E-03 | 4.84E-04 | 2.75E-06 |
| **n-C11** | 0 | 3.24E-04 | 3.24E-04 | 4.64E-06 | 7.74E-03 | 1.47E-42 |
| **H2O** | 0 | 1.61E-02 | 1.61E-02 | 7.35E-04 | 5.44E-04 | 0.999044 |
| **n-Decane** | 0 | 7.72E-04 | 7.72E-04 | 2.29E-05 | 1.81E-02 | 2.44E-38 |

Streams information for Figure 3.5

***Table E7*** *Aspen HYSYS streams information.*

| | TO-MIX2 | TO-V103 | FUEL-GAS | TO-PUMP | WATER-3 |
|---|---|---|---|---|---|
| **Temperature (C)** | 27 | 23.78693 | 23.49499 | 23.49499 | 23.49499 |
| **Pressure (kPa)** | 3525.262 | 3525.262 | 3373.578 | 3373.578 | 3373.578 |
| **Mole Flows (kmol/hr)** | 262.6285 | 754.9765 | 119.9343 | 633.0798 | 1.962353 |
| **Mole Fractions** | | | | | |
| **Methane** | 0.186922 | 0.234666 | 0.774515 | 0.133122 | 1.16E-07 |
| **Ethane** | 5.70E-02 | 8.90E-02 | 0.108412 | 8.56E-02 | 2.56E-10 |
| **Propane** | 5.16E-02 | 9.05E-02 | 4.09E-02 | 0.100153 | 5.21E-13 |
| **i-Butane** | 1.60E-02 | 2.89E-02 | 6.01E-03 | 3.33E-02 | 1.34E-16 |
| **n-Butane** | 3.41E-02 | 6.22E-02 | 9.58E-03 | 7.23E-02 | 3.56E-16 |
| **i-Pentane** | 2.19E-02 | 3.78E-02 | 2.63E-03 | 4.46E-02 | 1.22E-19 |
| **n-Pentane** | 2.18E-02 | 3.68E-02 | 1.97E-03 | 4.35E-02 | 1.05E-19 |
| **n-Hexane** | 5.60E-02 | 7.71E-02 | 1.48E-03 | 9.17E-02 | 7.21E-23 |
| **n-Heptane** | 6.56E-02 | 6.84E-02 | 4.85E-04 | 8.15E-02 | 1.32E-26 |
| **n-Octane** | 8.79E-02 | 6.83E-02 | 1.80E-04 | 8.14E-02 | 2.34E-30 |
| **n-Nonane** | 8.77E-02 | 5.28E-02 | 5.42E-05 | 6.30E-02 | 2.78E-34 |
| **$CO_2$** | 1.78E-02 | 2.54E-02 | 5.06E-02 | 2.07E-02 | 7.04E-04 |
| **n-C12** | 0.148991 | 5.96E-02 | 4.23E-06 | 7.11E-02 | 6.98E-47 |
| **Nitrogen** | 4.48E-04 | 4.72E-04 | 2.20E-03 | 1.46E-04 | 9.50E-07 |
| **n-C11** | 5.88E-02 | 2.55E-02 | 4.05E-06 | 3.04E-02 | 7.41E-43 |
| **$H_2O$** | 7.99E-03 | 3.13E-03 | 9.95E-04 | 4.51E-04 | 0.999295 |
| **n-Decane** | 7.94E-02 | 3.94E-02 | 1.62E-05 | 4.70E-02 | 9.96E-39 |

Streams information for Figure 3.5

***Table E8*** *Aspen HYSYS streams information.*

| | VAP-REG | TO-E-104 | ALRAR |
|---|---|---|---|
| **Temperature (C)** | 77 | 60 | 100 |
| **Pressure (kPa)** | 6842 | 6841.641 | 6841.641 |
| **Mole Flows (kmol/hr)** | 1250 | 262.6285 | 10919.44 |
| **Mole Fractions** | | | |
| **Methane** | 0.79084 | 0.186922 | 0.740786 |
| **Ethane** | 9.18E-02 | 5.70E-02 | 9.07E-02 |
| **Propane** | 3.82E-02 | 5.16E-02 | 4.18E-02 |
| **i-Butane** | 6.37E-03 | 1.60E-02 | 7.96E-03 |
| **n-Butane** | 1.06E-02 | 3.41E-02 | 1.42E-02 |
| **i-Pentane** | 3.78E-03 | 2.19E-02 | 5.70E-03 |
| **n-Pentane** | 2.59E-03 | 2.18E-02 | 4.99E-03 |
| **n-Hexane** | 2.09E-03 | 5.60E-02 | 7.47E-03 |
| **n-Heptane** | 6.97E-04 | 6.56E-02 | 5.50E-03 |
| **n-Octane** | 2.99E-04 | 8.79E-02 | 5.01E-03 |
| **n-Nonane** | 9.96E-05 | 8.77E-02 | 3.73E-03 |
| **$CO_2$** | 4.53E-02 | 1.78E-02 | 4.31E-02 |
| **n-C12** | 0 | 0.148991 | 4.13E-03 |
| **Nitrogen** | 3.38E-03 | 4.48E-04 | 3.14E-03 |
| **n-C11** | 0 | 5.88E-02 | 1.77E-03 |
| **$H_2O$** | 3.98E-03 | 7.99E-03 | 1.73E-02 |
| **n-Decane** | 0 | 7.94E-02 | 2.75E-03 |

Streams compositions and conditions as provided by the oil company “SONATRACH”.

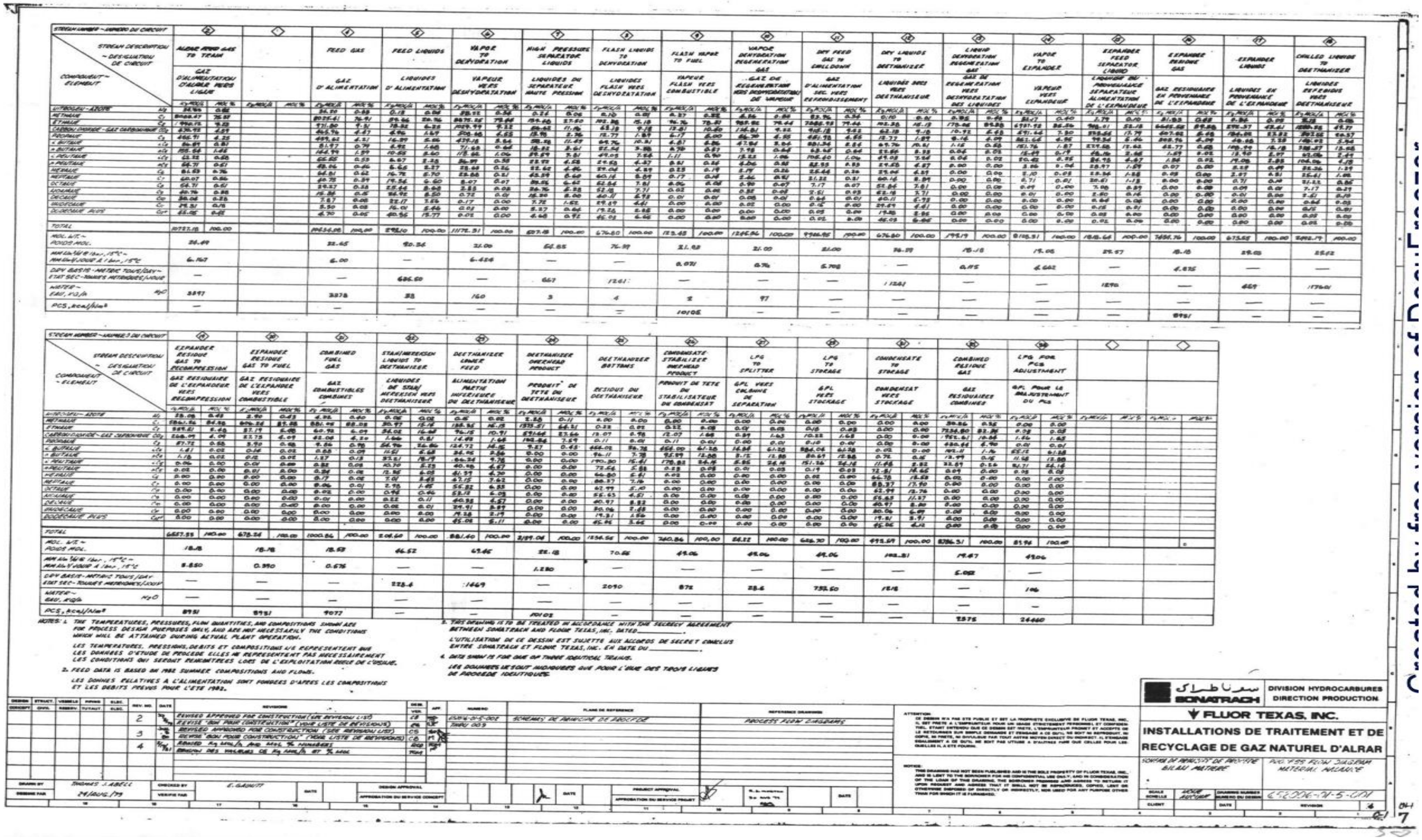


*Figure E1 Compositions and conditions of streams. This document was received from the oil firm “SONATRACH”.*

**Aspen HYSYS “Physical exergy code”:**

```
Sub PostExecute()
On Error GoTo ErrorHandler
Dim Stream As Fluid
Set Stream = ActiveObject.DuplicateFluid
Dim PhysicalExergy As RealVariable
Set PhysicalExergy = ActiveVariableWrapper.Variable
Dim T0,P0,H,S,H0,S0,C0,T1 As Double
Dim X As InternalVariableWrapper
Set X = activeobject.GetUserVariable("AmbTemp")
T0 = X.Variable.GetValue()
Set X = activeobject.GetUserVariable("AmbPres")
P0 = X.Variable.GetValue()
If (True) Then
H = Stream.MolarEnthalpy.GetValue("kJ/kgmole")
S = Stream.MolarEntropy.GetValue("kJ/kgmole-C")
Stream.Temperature.SetValue(T0,"C")
Stream.Pressure.SetValue(P0,"kPa")
Stream.TPFlash()
H0 = Stream.MolarEnthalpy.GetValue("kJ/kgmole")
S0 = Stream.MolarEntropy.GetValue("kJ/kgmole-C")
C0 = Stream.MolarFlow.GetValue("kgmole/h")
PhysicalExergy.SetValue(((H-H0)-T0*(S-S0)))*C0
MsgBox(((H-H0)-T0*(S-S0)))*C0
Else
PhysicalExergy.Erase()
End If
ErrorHandler:
End Sub
```