



**FACULTY OF APPLIED SCIENCES
MECHANICAL ENGINEERING DEPARTMENT**

FINAL YEAR PROJECT
presented for the requirements of the Master's Degree
Specialty: Mechanical Engineering
Option: Energetic

THEME

**Technical and Economic Feasibility of Flare Gas-to-Energy
Conversion at a Gas Refinery**

By:

BOUCHENAK Maroua
NADJI Younes

Presented on before a jury consisting of:

	Bouira university	President
Pr. Mahfoud Brahim	Bouira university	Supervisor
	Bouira university	Examiner
	Bouira university	Examiner



التصريح الشرفي الخاص بالالتزام بقواعد النزاهة العلمية لإنجاز بحث.

انا الممضي اسفله،

السيد(ة): بوشناق مريم الصفة: طالب جامعي
الحامل(ة) لبطاقة التعريف الوطنية: 1.1503340014875003 والصادرة بتاريخ: 2023.06.25
المسجل(ة) بكلية العلوم التطبيقية قسم: الهندسة الميكانيكية
والمكلف(ة) بإنجاز مذكرة ماستر فرع: الهندسة الميكانيكية، تخصص: طاقة / إنشاء ميكانيكي.
عنوانها: الجدوى الفنية والاقتصادية لتحويل الغاز
الحشيش إلى طاقة في منشآت الغاز
تحت إشراف الأستاذ(ة): براهيم صوفية
أصرح بشرفي اني ألتم بمراعاة المعايير العلمية والمنهجية الاخلاقيات المهنية والنزاهة الاكاديمية المطلوبة
في انجاز البحث المذكور أعلاه.

التاريخ: 2026/06/23

توقيع المعني(ة) [Signature]

رأي هيئة مراقبة السرقة العلمية:

النسبة: 07.4 %

الامضاء:





التصريح الشرفي الخاص بالالتزام بقواعد النزاهة العلمية لإنجاز بحث.

انا الممضي اسفله،

السيد(ة): حنان بن يوسف الصفة: طالب جامعي
الحامل(ة) لبطاقة التعريف الوطنية: 4000303290141300006 والصادرة بتاريخ: 2024 10 24
المسجل(ة) بكلية العلوم التطبيقية قسم: الهندسة الميكانيكية
والمكلف(ة) بإنجاز مذكرة ماستر فرع: الهندسة الميكانيكية، تخصص: طاقوية / إنشاء ميكانيكي.
عنوانها: الجدد الفني والاقتصادي لتحويل الغاز
المستعمل إلى طاقوية في مصفاة الغاز
تحت إشراف الأستاذ(ة): براهيم مرجعونا
أصرح بشرفي اني ألتم بمراعاة المعايير العلمية والمنهجية الاخلاقيات المهنية والنزاهة الاكاديمية المطلوبة
في انجاز البحث المذكور أعلاه.

التاريخ: 2026 / 06 / 23

توقيع المعني(ة)

رأي هيئة مراقبة السرقة العلمية:

% 07.4

النسبة:

الامضاء:



Acknowledgements

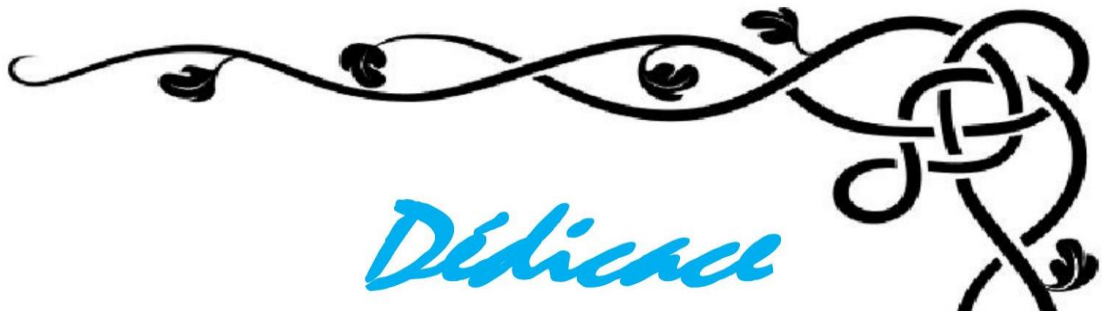
We thank **ALLAH** the Almighty for granting us the courage and the will to bring this work to completion.

We sincerely thank **Pr. Mahfoud Brahimi**

for agreeing to supervise us and for his invaluable guidance and support throughout the difficult moments of this work.

We also thank the members of the jury who kindly agreed to examine and evaluate this thesis.





Dedication

I dedicate this thesis

*To my dear parents, my mother and my father,
For their patience, their love, their support
and their encouragement.*

To my beloved brother.

To my beloved sisters.

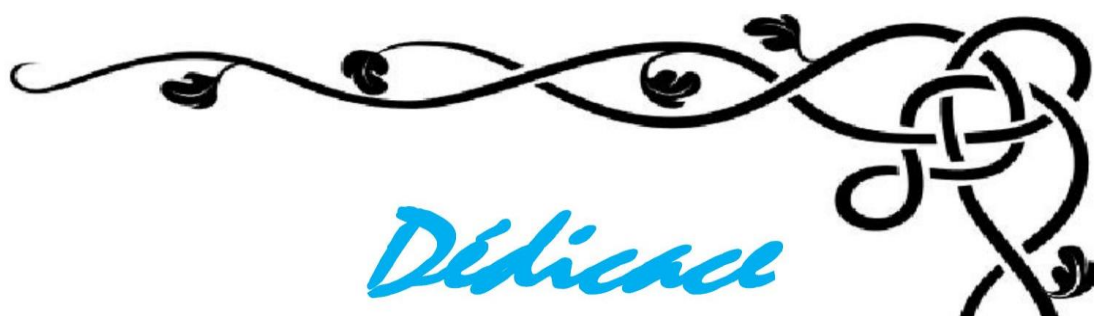
To my dear friend Amine.

To my friends and companions.

*And not forgetting all the teachers from primary school, middle school, high school and
higher education.*



MAROUA



Dédicace

Dedication

*I dedicate this thesis
To my dear parents, my mother and my father,
For their patience, their love, their support
and their encouragement.
To my beloved sisters.*

*To my friends and companions.
And not forgetting all the teachers from primary school, middle school, high school and
higher education.*



YOUNES

Summary

Acknowledgements	i
Dedication	ii
Résumé / Abstract / ملخص	iii
List of figures	v
List of table	vi
Nomenclature	vii
Abbreviations	viii
General introduction:.....	1
CHAPTRE I : LITERATURE REVIEW AND DEFINITIONS	
I.1 Introduction:.....	3
I.2 Definition of Flare Gas:	3
I.3 Properties and Composition of Flare Gas:	4
I.3.1 Main Characteristics of Flare Gas:	5
I.3.1.1 Physical Properties :.....	5
I.3.1.2 Chemical Properties :	6
I.3.1.3 Energy Properties:.....	6
I.4 Sonatrach has a permanent target to decrease flared gases:.....	6
I.4.1 Types of Keystones Flaring in the Oil and Gas Industry. Why is flaring required?.....	6
I.5 Sources of Flare Gas in Refineries:	8
I.6 Purpose and Function of Flare System:	11
I.7 Environmental and Health Impact of Gas Flaring:	12
I.8 Flare Gas Recovery Technologies :	12
I.8.1 Benefits of Flare Gas Recovery Technologies:	13
I.8.2 Challenges and Considerations:	13
I.9 Flare Gas Recovery Systems (FGRS):.....	14
I.9.1 Step-by-Step Operation of Flare Gas Recovery Systems (FGRS):	14
I.10 Feasibility Considerations for Flare Gas Recovery:	15
I.10.1 Technical Feasibility:.....	15
I.10.2 Economic Feasibility :	16
I.10.3 Environmental Feasibility :	17
I.10.4 Safety Feasibility :	17
I.10.5 Operational Feasibility :	17
Conclusion:.....	17

CHAPTRE II : THERMODYNAMIC MODELING WITH ASPEN HYSYS

II.1 Introduction:	18
II.2 Energy balance equations of cycles of Thermodynamic Cycles:	18
II.2.1. Equation of State and Physical Property Modeling:.....	19
II.2.2. Heat Exchanger Modeling (GNL-100, E-100):.....	20
II.2.3. Two-Phase Separator (V-100, V-101):.....	20
II.2.4. Gas Turbine Modeling (Brayton Cycle):.....	21
II.2.5. Combustion Reactions (CRV-100):.....	22
II.2.6. Ethane Recovery Optimization:.....	22
II.2.7. Turboexpander Modeling:	22
II.2.8. Global Mass and Energy Balances:	22
II.2.9. Équilibre de phases :.....	23
II.2.10. Bilans de matière et d'énergie :	23
II.3 Natural Gas Liquids (NGL) Recovery Technology:	23
II.4. Thermodynamic Properties of Flare Gas:.....	24
II.4.1. Introduction :	24
II.4.2. Heat Capacity (Cp):	24
II.4.2.1. Development of the Cp Correlation:	24
II.4.3. Enthalpy (H):	25
II.4.4. Entropy (S):	25
II.4.5. Application in Simulation:.....	26
II.5. Basic modeling of Organic Rankine Cycle (ORC) :	26
II.5.1 Description of the Rankine Cycle:.....	26
II.5.2 Energy Balance Equations:.....	27
II.5.3 Thermal Efficiency of the Cycle:	28

CHAPTRE III : DESCRIPTION OF PROCESS AND SIMULATION

III.1 Introduction:	29
III.2 Presentation of Aspen HYSYS:	29
III.3. Fundamental Concepts of the HYSYS Simulator:	30
III.4. Operational Workflow for Aspen HYSYS Simulation:	31
III.5. Operating Modes in HYSYS:.....	33
III.6. Approach to Combustion Simulation:.....	34

CHAPTER IV: OUTCOMES AND DISCUSSION

IV.1. Introduction:.....	47
IV.2. Process Description:.....	47

IV.3. Efficiency of Separation and Optimization:.....	48
IV.4. Performance of electricity generation:	50
IV.5 Feed gas composition:.....	55
IV.6 Economic evaluation:.....	56
IV.7 Environmental Impact and Risk Analysis:.....	59
IV.7.1. Emission Reduction Potential:	59
IV.7.2. Scenario Risk Assessment:	59
IV.8 Comparative Evaluation of Power Generation and Stream Profiles: Bid Boland (Iran) vs Skikda (Algeria):	60
IV.8.1 Thermodynamic Discussion and Chemical Profile Analysis:.....	60
IV.8.2 Industrial Philosophy & Strategic Destination:	61
IV.9 Conclusion:	63
General conclusion:	64
References:	64

List of tables

Table I.1: Flare gas composition (typical).....	4
Table I.2: Main characteristics of flare gas	5
Table II.1: Fitting curve coefficients (Cp polynomial).....	25
Table IV.1: Characteristics of compressors K-101, K-102 and K-103	52
Table IV.2: Characteristics of Turbines K-100, K-104, K-105 and K-107	53
Table IV.3: Material Streams	54
Table IV.4: Material Streams (continued).....	55
Table IV.5: Composition of streams of simulation.....	56
Table IV.6: Unit operation approximate cost.....	58
Table.IV.7: iranian (behbahan, khuzestan) natural gas composition.....	62
Table.IV.8: skikda natural gas composition.....	62

List of Figures

FIG. I.1: Complete combustion.....	7
FIG. I.2. incomplete combustion.....	8
FIG.I.3: step-by-step operation of flare gas recovery system (fgrs).....	15
FIG. II.1: t-s diagram of the basic orc system.....	27
FIG.III.1: representing the first HYSYS interface.....	30
FIG.III.2: Fundamental Concepts of the HYSYS Simulator.....	31
FIG.III.3: HYSYS Software Architecture.....	33
FIG.III.4: Identification and selection of components of gas.....	35
FIG.III.5: Choice of the Thermodynamic Fluid Package.....	36
FIG.III.6: the burning responses.....	36
FIG.III.7: Hydrocarbon combustion reactions.....	37
FIG.III.8: LNG-100 Connections.....	37
FIG.III.9: cooler E-100.....	38
Fig.III.10: parameters of the cooler E-100.....	38
FIG.III.11: cooler E-101.....	39
FIG.III.12: parameters of the cooler E-101.	39
FIG.III.13: fired Heater FH-100.....	40
FIG.III.14: parameters of the fired Heater FH-100.....	40
FIG.III.15: Conversion reactor CRV-100.....	41
FIG.III.16: Demethanizer (LPG Recovery).....	41
FIG.III.17: compressor k-101.....	42
FIG.III.18: parameters of the compressor K-101.....	42
FIG.III.19: compressor k-102.....	43
FIG.III.20: parameters of the compressor K-102.....	43
FIG.III.21: The gas turbine k-104.....	44
FIG.III.22: conditions of the gas turbine k-104.....	44
FIG.III.23: The gas turbine k-105.....	45
FIG.III.24: conditions of the gas turbine k-105.....	45
FIG.III.25: The gas turbine k-107.....	46
FIG.III.26: conditions of the gas turbine k-107.....	46
FIG.IV.1: Simulation mode.....	47
FIG.IV.2: Efficiency of Separation and Optimization schema.....	49

FIG.IV.3: reaction 1- methane combustion.....	50
FIG.IV.4: reaction 2- Ethane combustion.....	50
FIG.IV.5: Simulation of an Expender Natural Gaz unit.....	51
FIG.IV.6: Simulation of an Expender Natural Gaz unit (continued).....	51
FIG.IV.7: Simulation of Fired Heater unit and Power generation (continued).....	52
FIG. IV.8: A comparison between (a) total capital investments, and (b) annual profits.....	58
FIG.IV.9: A comparison between (a) rates of return for capacity increment, and (b) payback period.....	59
FIG.IV.10: Power output side by side.....	60

Nomenclature

Nomenclature

Symbol	Description	Unit	Symbol	Description	Unit
X_i, Y_i	Liquid and vapor mole fractions.	-	C_p	Specific heat	KJ/kg·K
K_i	Partition coefficient	-	T	Temperature	K
ΔT_{LMTD}	Log mean temperature difference	K	W	Work	KW
A	Heat transfer surface area	m ²	r_p	Pressure ratio	-
h	Enthalpy	KJ/kg	U	Overall heat transfer coefficient	W/m ² ·K
$\dot{m}$	Mass flow rate	Kg/s	α	Vaporized fraction	-
Q	Heat transfer	KW	s	Entropy	KJ/kg·K
ω	Acentric factor	-	A, B, C, D, E, F, G	Polynomial coefficients	-
κ	EOS adjustment factor	-	γ	Heat capacity ratio	-
P_c	Critical pressure	Bar	η	Efficiency	%
T_c	Critical temperature	K			
$a(T)$	Energy parameter	Pa·m ⁶ /mol ²			
P	Pressure	Bar			
v	Molar volume	m ³ /mol			
R	Universal gas constant	J/mol·K			
b	Covolume parameter	m ³ /mol			

Abbreviations

GTL – Gas- to-liquid

LNG – Liquefied natural gas

CNG – Compressed natural gas

NGL – Natural gas liquids

ORC – Organic Rankine Cycle

FGR – Flare Gas Recovery

CAPEX – Capital Expenditure

B.E.P. – Break -even point

ROR – Return on Investment

GHG – Greenhouse Gas

VLE – Vapor-liquid Equilibrium

LPG – Liquefied Petroleum Gas

FTS – Fischer-Tropsch Synthesis

PDF – Process Flow Diagram

PR – Peng-Robinson (equation of state)

LHV – Lower Heating value

tCO₂ - Tonnes of Carbon Dioxide

Bcm – Billion Cubic Metres

SI – International System of Units

CRV – Combustion reactor vessel

FH – Fired Heater

EOS – Equation of State

General introduction

General introduction

Global warming is evident in the increasing temperature of the Earth's surface, leading to widespread and extreme impacts on the global climate system including sea level rise, changes in precipitation regimes, and increased climate variability [38]. This environmental disaster is fueled by the growing release of greenhouse gases, including carbon dioxide and sulfur oxides, into the air. The biggest offenders are oil and gas companies when their routine flaring practices become less routine. Under the influence of the world population growth and the rising living standards especially in developing countries, the emission of greenhouse gasses has increased substantially in the past years. In the interest of meeting growing worldwide needs for oil and gas, large quantities of associated gas produced during co-extraction are routinely flared, resulting in a wasting of precious energy resources at an enormous scale and in substantial environmental harm. While flaring is a necessary safety practice to release pressure inside a facility, systemic reliance on it is devastating for the environment. The burning of gas in a controlled manner in oil production is an enormous waste of energy and a major source of pollution. According to information provided by the Global Gas Flaring Reduction Partnership, Algeria holds the position of the sixth largest gas flare in the world. The amounts of gas flared globally are mind-boggling and have been since before (2019–2023); this highlights both an intensifying climate emergency and the squandering of untold sums of money, and just nine countries—Russia, Iran, Iraq, the United States, Venezuela, Algeria, Libya, Nigeria, and Mexico—are responsible for 75% of global flaring, which highlights the need for focused mitigation options.

In this paper, advanced new technologies are investigated for the flare gas recovery with a case study on flaring emission reduction at Skikda refinery. The continuous flaring at this plant highlights fundamental structural problems in the industry, technical, financial, and regulatory barriers. The steady burning of gases in flares emits greenhouse gases and other harmful products of combustion, and this contributes to wasting a huge amount of energy. Therefore, various routes of conversion, including gas-to-liquids (GTL) route, power generation and other upgrading methods, will be analyzed on the basis of techno-economic feasibility.

Moreover, the study is concerned with environmental and financial consequences of using the FGRS. Efficient recovery can dramatically reduce the hydrocarbon footprint of the refinery and provide significant income from a waste previously not monetized. The final target is to identify, through a systematic assessment of the available alternatives considering

technical and operational constraints, how the Skikda refinery can be made a role model in sustainable energy practices within the Algerian refining industry by transforming flared gas to high value energy products. In order to do so, the thesis is organized as follows: the first chapter consists of a literature review and formal definitions; the thermodynamic modeling with Aspen HYSYS is presented in Chapter 2; the process description and the simulation scenarios are introduced in Chapter 3; the validation schemes, the engineering calculations, and results from the main case including technical discussions and sensitivity study are outlined in Chapter 4; finally, a general conclusion summarizing the major results and contributions of this research is included at the end of this thesis.

CHAPTRE I

LITERATURE REVIEW

AND DEFINITIONS

I.1 Introduction

Crude oil and natural gas production systematically generates associated gases, the management of which represents a major economic, environmental, and safety challenge. Liquefied Petroleum Gas (LPG), mainly composed of propane (C_3H_8) and butane (C_4H_{10}), is one of these associated gases and constitutes a high-value product widely used for heating, transportation, and industrial applications.

Refining processes inevitably produce excess gases whose immediate utilization is often hindered by production fluctuations, safety constraints, or unexpected shutdowns. These gases are subsequently directed to flaring systems, a practice that ensures operational safety by preventing overpressure in process units. However, flaring also results in significant energy losses and the emission of harmful pollutants.

This thesis aims to address the following research question: How can flared gas generated in gas refineries be efficiently recovered and valorized in order to mitigate its environmental impact and enhance energy production?

I.2 Definition of Flare Gas

Flare gas is the associated gas generated in the process of extracting crude oil that has to be separated and processed before refining [1] [3]. In normal oil and gas operations this gas is sometimes vented and burned in flare systems at production fields or refineries rather than captured and used. This process is often called gas flaring; it guarantees the operational safety and prevents overpressure but it results in a huge energy waste and environmental pollution. [2].

Growing concern for the environment led the World Bank to launch the “Zero Routine Flaring by 2030” initiative in 2015, aimed at ending routine gas flaring in production and refinery operations. [17]. To meet this target will require major changes in current production and processing practices.

Recovered flare gas can be used in a variety of ways, such as for the generation of electricity for local consumption or sale to the grid, as feedstock in industrial processes, re-injection into refinery pipelines or conversion into Liquefied Petroleum Gas (LPG). [2][3]. According to studies, economic viability of power generation [2].

Several flare gas management methods exist, but their optimal application may face financial and technical barriers [2]. The most popular techniques are:

Gas to liquid (GTL) production

Electrical generation – gas turbines

Compression and injection in refinery pipelines. [2][3].

I.3 Properties and Composition of Flare Gas

Flare gas is a mixture of hydrocarbons and non-hydrocarbon gases produced during oil and gas production. [4]. Its physical, chemical and energy properties and its chemical composition are of great importance for the design of flare gas recovery systems and energy conversion technologies. [5]. The composition and properties may be different depending on the operational conditions and if the gas is considered as sweet gas (low H₂S content) or sour gas (high H₂S content) [6].

Component	Chemical Formula	Approximate Percentage (%)
Methane	CH ₄	50 – 80
Ethane	C ₂ H ₆	5 – 15
Propane	C ₃ H ₈	1 – 5
Butane	C ₄ H ₁₀	0.5 – 2
Higher hydrocarbons	C ₅₊	0 – 2
Carbon dioxide	CO ₂	2 – 8
Nitrogen	N ₂	1 – 5
Hydrogen sulfide	H ₂ S	0 – 1

TABLE I.1: Flare gas composition (typical).

Note: Changes in composition directly affect heating value, environmental effects and choice of recovery technology.

I.3.1 Main Characteristics of Flare Gas

Property	Description	Typical Range / Value
Density	Mass of gas per unit volume; influences flow, combustion, and equipment design.	0.7 – 1.0 kg/m ³
Flow Rate	Volume or mass of gas released over time; crucial for energy recovery calculations. Highly variable depending on refinery operation.	Highly variable (site-dependent)
Molecular Weight	Average mass of gas molecules; indicates relative hydrocarbon content and energy potential.	18 – 30 g/mol
Temperature	Thermal state of flare gas at release; affects expansion, combustion efficiency, and material selection.	25 – 60 °C (typical)
Pressure	Force exerted by gas within pipes and systems; controls transport and safety.	1 – 5 bar (typical flare line)
Composition	Fraction of hydrocarbons and inert or toxic gases; determines energy content and environmental impact.	CH ₄ , C ₂ H ₆ , C ₃ H ₈ , CO ₂ , N ₂ , H ₂ S (trace)
Heating Value	Energy released during combustion; key for gas-to-energy conversion feasibility.	35 – 45 MJ/m ³
LEL (Lower Explosive Limit)	Minimum concentration in air at which the gas can ignite.	5% by volume
UEL (Upper Explosive Limit)	Maximum concentration in air at which the gas can ignite.	15% by volume

TABLE I.2: main characteristics of flare gas.

I.3.1.1 Physical Properties

- Density: 0.7 – 1.0 kg/m³ at standard conditions [7]
- Molecular weight : 18 – 30 g/mol [7]
- Flow rate: Highly variable depending on oil production [6]
- Boiling point range [7] :

Methane : -161°C

Propane : -42°C

Butane : -0.5°C

I.3.1.2 Chemical Properties

Mixture of light hydrocarbons and inert gases [6]

Presence of toxic and corrosive components such as H_2S in sour gas [8]

High reactivity and strong flammability [7]

I.3.1.3 Energy Properties

Calorific value: $35 - 45 \text{ MJ/m}^3$ [9]

Lower Explosive Limit (LEL): $\sim 5\%$ [8]

Upper Explosive Limit (UEL): $\sim 15\%$ [8]

I.4 Sonatrach has a permanent target to decrease flared gases

Sonatrach has been pursuing the goal of mitigating associated gas flaring since the 1970s. [10]. Today, after having been made official by 182 states, including Algeria, at the Rio de Janeiro 1992 summit, SONATRACH does not consider its economic growth without considering the sustainable development [11]. Considerable investment has been undertaken for the recovery of flared gases at production fields and at liquefaction plants and refineries [10][19].

I.4.1 Types of Keystones Flaring in the Oil and Gas Industry. Why is flaring required?

The burning off is generally considered to be a safe and effective method of disposing of the out-of-specification natural gas associated with LPG production [12].

This is the common method for evacuating unburnable flue gas, for depressurizing a equipment or a gas processing unit in the course of routine maintenance work, and after an emergency shutdown or start-up [13].

Flaring Products: In principle, the combustion of a pure hydrocarbon into the air is only a reaction of water, carbon dioxide, and nitrogen [14]. However, inefficient flares do not combust all of the gas, emitting unburned hydrocarbons and carbon monoxide in addition to carbon dioxide [15].

a - Complete combustion

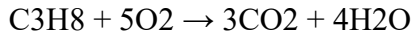
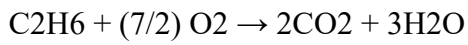
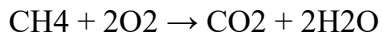


FIG. I.1: Complete combustion. [14]

b- Incomplete combustion

For example, torching during stops and starts or during triggers, the gas load will be important. Hence the combustion will be incomplete leading to products like carbon monoxide (CO) and water vapour (H₂O):

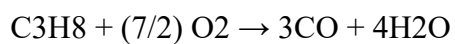
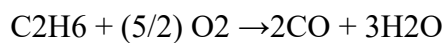
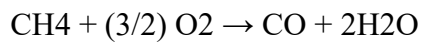




FIG. I.2. incomplete combustion. [15]

I.5 Sources of Flare Gas in Refineries

Flare gas is produced by several operational and safety processes in refineries.

Flaring is primarily a safety device to prevent overpressure and dangerous releases, but routine and non-routine activities also contribute to flare volumes [17], [18].

I.5.1 Startup and Shutdown Operations

During startup and shutdown:

- Units are depressurized.
- Off-specification gases are produced.
- Equipment is purged with inert gases (e.g., nitrogen).

Since these gases cannot be immediately processed or recycled, they are directed to the flare system [17], [19].

I.5.2 Pressure Relief Valve (PRV) Discharges:

Safety Relief Valves and Pressure Relief Valves (PRVs) are automatic valves that vent gas when the system pressure exceeds the design limits. These discharges are routed to the flare header to avoid the damage of the equipment or the risk of explosion [17], [16].

Reasons:

- Failure of equipment
- Clogged outlets
- Sudden rise in temperature Power Outage

PRV releases are directed to the flare header for safe combustion.

I.5.3 Process Upsets:

Process disturbances like:

- Compressor trips
- Instrumentation failure
- Sudden feedstock variation
- Power outages

can generate excess hydrocarbon gas that must be flared to maintain safe and stable refinery operation [18], [19].

I.5.4 Routine Continuous Venting:

Some refinery units generate small but continuous streams of excess gas due to:

- Separation inefficiencies
- Purge streams
- Stabilizer overhead gases

These streams may be routed to the flare if recovery systems are not available or not economical [18], [19].

I.5.5 Blowdown Operations:

Blowdown systems are used to rapidly depressurize equipment during:

- Maintenance
- Inspection
- Emergency isolation

The gas released during blowdown is directed to the flare stack for safe disposal [16].

I.5 6. Compressor Seal and Pump Seal Leaks:

Gas leakage from :

- Compressor seals
- Pump seals
- Valve packing
- is frequently collected in closed drain systems and routed to the flare header in accordance with refinery emission control practices [17], [18].

I.5 7. Tank Vapors and Storage Losses:

Hydrocarbon storage tanks generate vapors due to:

- Temperature changes
- Liquid movement (working losses)
- Breathing losses

If there are no vapour recovery units, these vapours may be directed to flare systems for controlled combustion [18], [19].

I.5 8. Off-Specification Gas:

Gas that does not meet process requirements (e.g. high H₂S concentration or incorrect calorific value) could be flared rather than recycled into the fuel system in order to guarantee operational safety and product quality [19]

I.5 9. Refinery Units That Commonly Contribute to Flaring:

The principal contributing units are

- Crude Distillation Unit (CDU)
- Fluid Catalytic Cracking Unit (FCCU)
- Hydrocrackers

- Reformers
- Hydrotreater

These units produce hydrocarbon-rich gases during both normal operation and abnormal process events [17], [18].

I.6 Purpose and Function of Flare System

- Flare systems are safety devices in oil and gas refineries. Primarily, they are constructed to safely burn off excess or hazardous gases instead of letting them out directly into the atmosphere, so as to prevent overpressure and environmental hazards. [16].
- The major purpose of a flare system is overpressure protection. If the process pressure exceeds safe limits, the gas is directed by relief devices to the flare stack to prevent mechanical failure or explosions [16].
- Flare systems also provide personnel and facility protection by safely burning off flammable gases and reducing fire and toxicity hazards [17].
- Flare systems have operational roles beyond emergencies. During start-up and shut-down, off-spec or unstable gases are routed to the flare to maintain stable refinery operations and protect downstream units [16][17].
- Flare combustion converts hydrocarbons into less harmful substances, such as carbon dioxide (CO₂) and water vapour (H₂O), reducing environmental impact [18].
- Key components of a flare system include the flare header, knock-out drum (for liquid removal), flare stack, flare tip, and ignition system. Together, these components ensure stable combustion under variable gas flows [16].
- The continuous flaring leads to energy loss and emission of greenhouse gases. In flare gas recovery projects, the aim is to use these gases to generate energy and keep the flare as a safety backup [17][19].
- Any scheme for recovery of flare gas shall ensure the safety function of the flare, reduce energy consumption and environmental impact [18][19].

1.7 Environmental and Health Impact of Gas Flaring

Gas flaring is a necessary safety and operational measure in refineries but has grave implications for the environment, human health and energy resources. Understanding these impacts is crucial for developing strategies to reduce emissions and improve gas management practices.

- **Environmental Impact:**

Flaring releases GHGs including carbon dioxide (CO₂) and methane (CH₄) along with nitrogen oxides (NO_x), sulphur oxides (SO_x) and unburned hydrocarbons. Such emissions contribute to climate change, global warming and local air pollution, with detrimental impacts for ecosystems and biodiversity [17][18]. Pollutants can also be deposited into soil and water, causing soil contamination, water pollution and damage to vegetation and wildlife [17].

- **Human Health Impact:**

Flaring also releases toxic compounds and particulate matter, especially during start-ups, shutdowns or process upsets, when combustion is incomplete, with direct risks to human health. Communities living near flare sites can be affected by respiratory diseases, cardiovascular problems and long-term health complications [18].

- **Impact on Resources and Energy:**

Flaring also wastes valuable hydrocarbon resources that could otherwise be captured and used to generate power or as chemical feedstock. The use of gas recovery and utilisation technologies reduces environmental and health impacts and increases operational efficiency and economic returns for refineries and production facilities [17].

1.8 Flare Gas Recovery Technologies

Flare gas recovery technologies aim to capture, process and use gases that would otherwise be burnt in flare systems, turning potential waste into valuable energy or chemical feedstock. These technologies reduce greenhouse gases, air pollution and environmental impact while improving operational efficiency and economic returns for refineries and gas processing facilities [19].

Depending upon gas volume, pressure, composition and facility infrastructure, several technologies are commonly utilised

- **Compression and Re-injection:**

Compressing flare gas and injecting it back into process streams, fuel networks or gas pipelines. This method is highly effective for continuous and steady gas streams, re-circulating the gas in refinery processes thus reducing fuel costs and emissions [20].

- Gas-to-Liquid (GTL) Conversion:

Hydrocarbon-rich flare gas can be converted into liquid fuels, methanol, or other petrochemical feedstock. This process reduces flaring volumes and unlocks economic value from previously wasted resources [19].

- Power Generation:

Captured flare gas can fuel gas turbines, engines, or combined heat and power (CHP) units, producing electricity or heat for onsite operations. This process turns waste gas into usable energy, reducing the facility's reliance on external power sources and decreasing the overall carbon footprint [20].

- Vapour Recovery Units (VRU):

VRUs are used to recover low pressure hydrocarbons from storage tanks, separators or other vent streams. This avoids emissions to the flare system and optimises resource recovery especially in tank farms or production sites [19].

- Cryogenic Recovery and LNG Integration:

More sophisticated flare gas recovery systems may use cryogenic separation for gases like methane or ethane, which could be liquefied as LNG. This is especially true for remote or offshore installations where it is not practical to transport gas by pipeline [20].

I.8.1 Benefits of Flare Gas Recovery Technologies

1. Environmental: Significant reduction in CO₂, CH₄ and VOC emissions, contributing to cleaner air & climate change mitigation [17].
2. Economic: Wasted gas converted to energy or feedstock, creating additional revenue [18].
3. Operational: Stabilises refinery operations through reduced flare dependency and pressure fluctuations [17].

I.8.2 Challenges and Considerations

- High capital and maintenance costs may limit feasibility in small or low-volume facilities [18].

- The different compositions of the gas can demand complex processing units [17].
- Strict management of safety and regulatory compliance during installation and operation [18].

When properly implemented, flare gas recovery technologies reduce flaring volumes, environmental and health impacts and help to make refinery and gas field operations more sustainable [17], [18].

I.9 Flare Gas Recovery Systems (FGRS)

Flare Gas Recovery Systems (FGRS) are key technologies in today's oil and gas operations. Their main function is to recover, process and re-utilise gases otherwise flared, reducing environmental emissions, saving valuable hydrocarbons and improving overall operational efficiency. FGRS offer a systematic methodology for transforming potentially wasteful and harmful gas streams into valuable energy or chemical feedstock, promoting economic and environmental sustainability in refineries and production facilities.

I.9.1 Step-by-Step Operation of Flare Gas Recovery Systems (FGRS)

- **Gas Collection:** Collect gas from flare headers, safety valves and vent streams in refineries or gas fields to avoid losing valuable resources [17].
- **Liquids and impurities are removed** by passing the gas through knockout drums or scrubbers to remove liquids, tar and solid impurities. This is to ensure the gas is clean for further processing [17].
- **Gas Compression:** Compress the treated gas using special compressors and increase the pressure for internal networks or re-injection in processing units [18].
- **Gas Conditioning:** Take out any remaining moisture or harmful compounds from the gas so that it can be used as a fuel or chemical feedstock [18].
- **Redirection and Utilisation** The conditioned gas is directed into fuel gas networks, pipelines or process units or is used for electricity and heat generation or chemical production [17].
- **Higher-End Applications:** Recovered gas can be used for power generation, GTL conversion, or LNG production, in particular for remote or offshore facilities [18].
- **Monitoring & Safety:** Sensors for pressure, temperature and chemical composition for safe, efficient operation and to prevent leaks and environmental hazards [17].

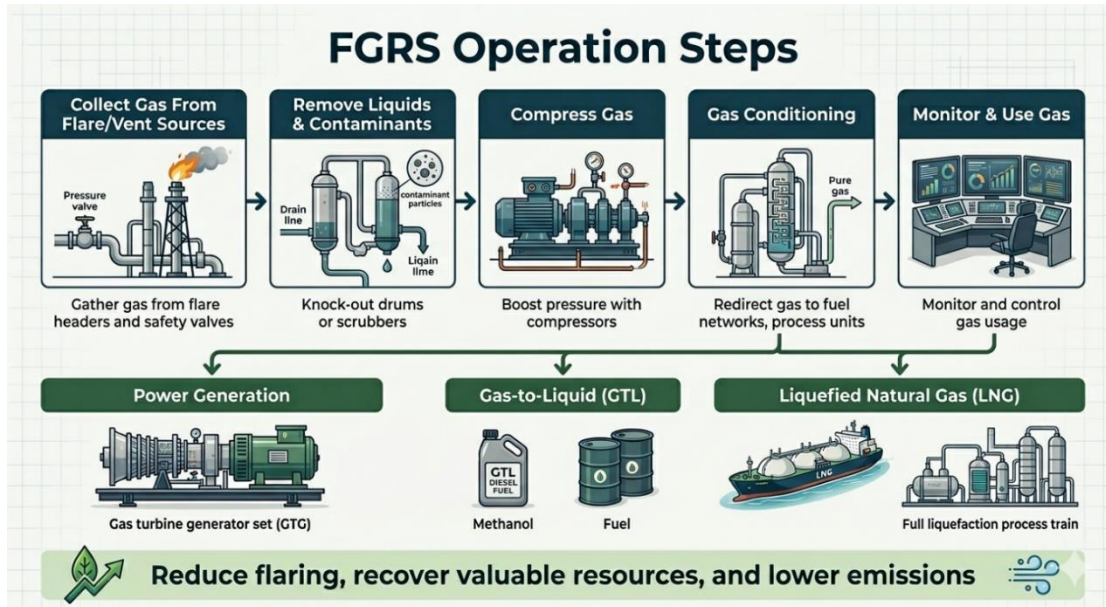


FIG.I.3: step-by-step operation of flare gas recovery system (fgrs). [17] [18]

Reduce harmful emissions, recover valuable hydrocarbons, cut flare volumes and improve operational efficiency in refineries and gas fields [17], [18]

I.10 Feasibility Considerations for Flare Gas Recovery

The feasibility study of a Flare Gas Recovery System (FGRS) implementation in a refinery is a comprehensive study that takes into consideration the technical feasibility, the economic feasibility, the environmental compliance and the operational safety [17][18]. This assessment analyses the technical feasibility and economics benefits of flare gas recovery as an alternative to continuous flaring without compromising refinery performance and safety integrity [17][18].

I.10.1 Technical Feasibility:

Technical feasibility considers the ability of the recovery system to operate efficiently under real refinery conditions [17].

Flare Gas Flow Rate and Variability:

Flare gas flow is normally intermittent and can have large fluctuations, especially during startup, shutdown or emergency depressurisation events [17]. This is why the recovery system has to be designed with enough flexibility and control capability to deal with the variable flow rates without impairing the primary safety function of the flare system.

- Gas Composition :

Flare Gas can consist of methane, ethane, propane, hydrogen, nitrogen and in some cases acid gases such as hydrogen sulphide (H₂S) and carbon dioxide (CO₂) [18]. The composition directly influences the sizing of the compressor, the choice of materials, the need for gas treatment and the ultimate utilisation path for the recovered gas.

- Pressure and Temperature Conditions :

Flare gas is usually available at low pressure and must be compressed before it can be re-injected into fuel gas systems or energy recovery units [17]. Equipment selection must consider thermodynamic properties, phase behaviour and process stability for reliable performance.

- Integration with Existing Units :

The recovery system has to be fully integrated with current refinery infrastructure like fuel gas networks, separation systems and control architecture [17]. If integrated properly, it works seamlessly, without interfering with the current processes at the refinery.

- Technology Selection :

Available recovery technologies include reciprocating compressors, screw compressors and liquid ring compressors, as well as gas conditioning and control systems [17]. The choice of the right technology is necessary to ensure efficiency, reliability and long-term operational stability.

I.10.2 Economic Feasibility

Economic feasibility is whether the project makes enough money to justify how much it costs to invest in and run [18][20].

- Capital Investment (CAPEX): Capital expenditures include purchase of compressors, piping systems, instrumentation, control systems, installation works and engineering studies [18].

- Operating Costs (OPEX): The main costs to run the plant are electricity consumption, maintenance operations, manpower requirements and replacement of spare parts.

- Revenue from Recovered Gas:

Recovered flare gas can be used as internal fuel gas, feedstock for process units or for power generation [18][20].

- Payback Period: The payback period is the period in which the initial investment is recovered by operational savings.

- Net Present Value (NPV) and Internal Rate of Return (IRR):

NPV and IRR are key financial indicators used to assess long-term profitability and project attractiveness [20].

I.10.3 Environmental Feasibility

Environmental feasibility is becoming increasingly important, thanks to the global climate policies and emission control regulations [17][18].

- Greenhouse Gas Emission Reduction [17][18].
- Environmental Regulations Compliance [18].
- Reduction of Air Pollutants [17].

I.10.4 Safety Feasibility

Safety is the primary goal of any flare system [17].

Automatic bypass devices should be installed for instantaneous diversion of excess gas to the flare during abnormal conditions [17].

I.10.5 Operational Feasibility

The ability to operate effectively depends on the availability of qualified personnel, adequate maintenance capabilities and the overall reliability of the system [17]. System redundancy, preventive maintenance planning and seamless integration with existing refinery operation are key [17][18].

Conclusion

This chapter provided a comprehensive review of flare gas, including its composition, physicochemical properties and environmental and economic impacts in refinery operations. The basic combustion properties of flare gas and related emissions were also studied to better understand their effect on process efficiency and environmental performance. A few technologies for flare gas recovery were also reviewed, such as gas-to-liquid (GTL) conversion, electricity generation systems, and gas compression and reinjection techniques. Their technical benefits, operational limitations and opportunities for energy valorisation were evaluated to emphasise their contribution to the improvement of resource efficiency and waste reduction. The analysis confirms that reduction of routine gas flaring is essential not only for minimising

greenhouse gas emissions and limiting the adverse environmental and health effects but also for improving energy recovery and improving the overall economic performance of refinery facilities. These results provide the theoretical basis for the next chapter, which will be dedicated to the thermodynamic modelling and technical feasibility analysis of the conversion of flare gas to energy using simulation tools.

CHAPTRE II

THERMODYNAMIC

MODELLING

II.1 Introduction

Thermodynamic modelling plays an important role in flare gas recovery (FGR) to understand and optimise the behaviour of complex hydrocarbon systems. A thermodynamic system is a defined amount of matter or a defined space used for engineering analysis. The main goal is to analyse and valorise gases that are generally sent to flaring rather than used as an energy resource [28].

It is separated physically from the surroundings by well-defined boundaries. It permits controlled exchange of mass and energy depending on the operating conditions. This is important for the analysis of industrial processes with energy recovery and gas processing systems.

In this study, the thermodynamic analysis is conducted for a toluene-based power generation cycle integrated with a flare gas waste heat recovery system. This configuration aims to recover wasted thermal energy from flare gases and convert it to useful electrical power thus contributing to energy efficiency and environmental sustainability [21].

The system is modelled and simulated in Aspen HYSYS, a popular process simulation tool, which is able to accurately model complex hydrocarbon mixtures under realistic operating conditions [22]. The model is developed under a set of simplifying assumptions to ensure numerical stability, reduce the computational complexity and maintain thermodynamic consistency during the analysis.

This chapter provides the theoretical basis for the development of energy balance equations, thermodynamic property models and process simulation of the flare gas recovery system used to evaluate the technical feasibility and performance of the.

II.2 Energy balance equations of cycles of Thermodynamic Cycles

The thermodynamic modelling is based on the fundamental laws of thermo-dynamics:

- First Law (Energy Conservation):

The first law states that the total energy of an isolated system is unchangeable. It is described in a process system by the general energy balance equation taking into account heat transfer, work, and enthalpy variations:

$$\Delta U = Q - W$$

ΔU : variation de l'énergie interne (J)

Q : chaleur échangée (J)

W : travail fourni par le système (J)

where Q is the heat exchanged, W is the work done by, or on, the system and H is the enthalpy of the system [27].

- Second Law (Entropy Principle):

The second law introduces irreversibility and specifies the natural direction of thermodynamic processes. We can formulate this in terms of entropy:

$$\Delta S \geq Q / T$$

ΔS : variation d'entropie (J/K)

Q : chaleur échangée (J)

T : température absolue (K)

(= for a reversible process; > for an irreversible process)

This principle is fundamental to establish the feasibility of a thermodynamic transformation and to determine the direction of spontaneous processes in energy systems [27].

- Third Law (Law of Absolute Entropy)

The third law of thermodynamics states that the entropy of a perfect crystalline substance tends to zero as the temperature approaches zero

$$\lim(T \rightarrow 0) S = 0$$

S : entropie (J/K)

$T \rightarrow 0 \text{ K}$: température tendant vers le zéro absolu ($-273,15 \text{ °C}$)

It is an absolute reference point of entropy and is important in the determination of absolute entropy values of substances. It is particularly important in low-temperature processes and in the accurate evaluation of thermodynamic properties in energy systems [23].

II.2.1. Equation of State and Physical Property Modeling

Equations of state describe the relationship between pressure, temperature, and volume.

The-Peng–Robinson-model

Peng-Robinson is the industry standard for hydrocarbon systems, providing the robust accuracy needed for high-pressure gas compression and phase equilibrium in refinery simulations. It is ideal for study because it reliably models the thermodynamic properties of complex gas mixtures while ensuring the computational stability required for accurate equipment sizing.

$$P = \frac{RT}{(v - b)} - \frac{a(T)}{[v(v + b) + b(v - b)]} \quad (\text{II.1})$$

Where:

$$a(T) = 0.45724 \frac{R^2 T_c^2}{P_c} \left(1 + \kappa \left(1 - \sqrt{\frac{T}{T_c}} \right) \right)^2$$

$$b = 0.07780 \frac{R T_c}{P_c}$$

$$K = 0.37464 + 1.54226\omega - 0.26992\omega^2 \text{ (acentric factor)}$$

The equation is used to model hydrocarbon properties (natural gas, NGL) and to calculate vapor-liquid equilibria (VLE), Ce modèle permet de:

- predict the properties of real gases
- Calculate the liquid-vapor equilibria

II.2.2. Heat Exchanger Modeling (GNL-100, E-100)

Energy Balance

$$Q = \dot{m} \cdot \Delta h = \dot{m} \cdot (h_{out} - h_{in}) \quad (II.2)$$

Q: Heat transfer. $\dot{m}$:

Mass flow rate.

Δh : Enthalpy change calculated via Peng-Robinson.

Over all Heat Transfer Coefficient

$$Q = U \cdot A \cdot \Delta T_{LMTD} \quad (II.3)$$

Where ΔT_{LMTD} is the logarithmic mean temperature difference.

II.2.3. Two-Phase Separator (V-100, V-101)

Vapor-Liquid Equilibrium (VLE)

$$Y_i = K_i \cdot X_i$$

K_i : Partition coefficient calculated via Peng-Robinson.

X_i, Y_i : Liquid and vapor mole fractions.

Adiabatic Flash (after expansion in VLV-100):

$$h_{in} = h_{liquid} \cdot (1 - \alpha) + h_{vapo} \cdot \alpha \quad (II.4)$$

α : Vaporized fraction.

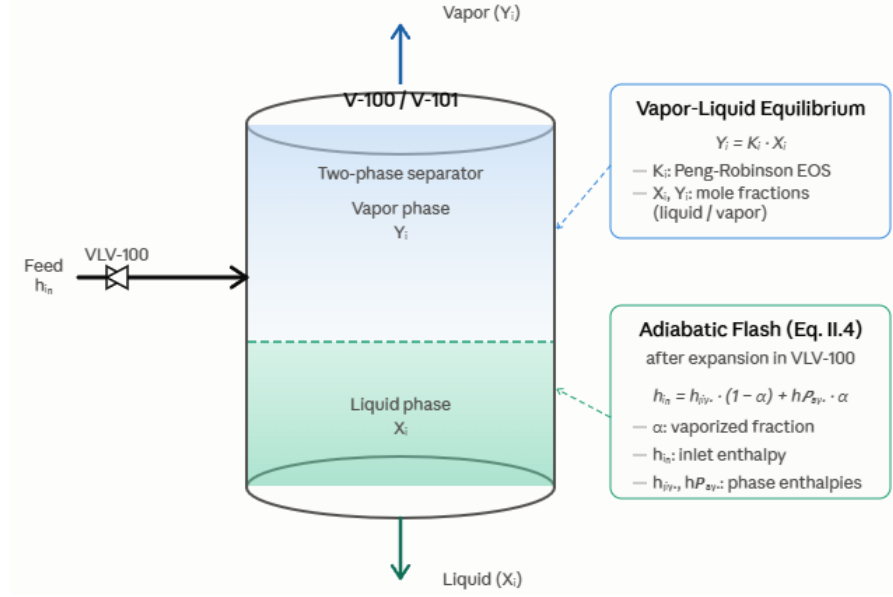


FIG. II.1: Two-Phase Separator (V-100, V-101) [29] [30]

II.2.4. Gas Turbine Modeling (Brayton Cycle)

Compressor Work (K-103)

$$W_{compressor} = \dot{m} \cdot C_p \cdot T_{in} \cdot \frac{\left(\left(\frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right)}{\eta_{comp}} \quad (II.5)$$

$\gamma = c_p / c_v$,

η_{comp} : Isentropic efficiency.

Turbine Work (K-104, K-105)

$$W_{turbine} = \dot{m} \cdot C_p \cdot T_{in} \cdot \left(1 - \left(\frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} \right) \cdot \eta_{turb} \quad (II. 6)$$

Brayton Cycle Thermal Efficiency

$$\eta_{th} = 1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}} \quad (II.7)$$

r_p : Pressure ratio.

II.2.5. Combustion Reactions (CRV-100)

Stoichiometry and Enthalpy



Adiabatic Energy Balance

$$\sum \dot{m}_{in} \cdot h_{in} = \sum \dot{m}_{out} \cdot h_{out} + Q_{combustion} \quad (\text{II.8})$$

$$Q_{combustion} = \sum \Delta H^\circ \cdot \eta_{reacted}$$

II.2.6. Ethane Recovery Optimization:

Design Variables

- Temperatures after heat exchange (LNG-100)
- Demethanizer pressure

Objective Function :

$$\text{maximize } \eta_{C_2} = \frac{\dot{m}_{C_2, \text{ recovered}}}{\dot{m}_{C_2, in}} \quad (\text{II.9})$$

Solved via sensitivity analysis in HYSYS.

II.2.7. Turboexpander Modeling

Isentropic Expansion

$$T_{out} = T_{in} \cdot \left(\frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} \quad (\text{II.10})$$

Work produced

$$W = \dot{m} \cdot C_p \cdot (T_{in} - T_{out}) \quad (\text{II.11})$$

II.2.8. Global Mass and Energy Balances

Mass Balance (per unit)

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (\text{II.12})$$

Energy Balance

$$\sum \dot{H}_{in} + Q + W = \sum \dot{H}_{out} \quad (\text{II.13})$$

II.2.9. Phase equilibrium

Thermodynamic equilibrium is reached when the chemical potentials are equal in all phases:

$$\mu_i^{\text{(vapeur)}} = \mu_i^{\text{(liquide)}} \quad (\text{II.14})$$

In practice, this leads to:

$$Y_i = K_i \cdot X_i \quad (\text{II.15})$$

Or K_i is the equilibrium coefficient [24].

II.2.10. Bilans de matière et d'énergie

The simulation is based on

Material balance

$$\sum \dot{m}_{in} \cdot h_{in} = \sum \dot{m}_{out} \cdot h_{out} + Q_{combustion} \quad (\text{II.16})$$

Energy balance

$$\sum H_{entrée} = \sum H_{sortie} \quad (\text{II.17})$$

In simulators such as Aspen HYSYS, these equations are solved simultaneously [29].

II.3 Natural Gas Liquids (NGL) Recovery Technology

The recovery of Natural Gas Liquids (NGL) is fundamentally governed by thermodynamic principles of phase equilibrium and energy transfer. The process uses a series of compression and cooling steps to encourage the heavier hydrocarbons in natural gas mixtures to condense. With rising pressure and falling temperature, the system moves toward vapor–liquid equilibrium conditions, enabling the selective separation of condensable components like ethane, propane, and heavier fractions.

Flare gas must be subjected to essential pre-treatment operations before recovery in order to ensure process integrity and avoid operational upsets. These include removing mercury to protect equipment, removing acid gases (H_2S and CO_2) to minimize corrosion and environmental impact, and dehydrating to avoid hydrate formation at low temperatures.

From a process engineering standpoint, NGL recovery technologies aim to maximize liquid yield and minimize energy use. Typical configurations include turbo-expander systems, Liquid Sub-Cooled (LSC) processes, and Gas Sub-Cooled (GSC) processes. Of these, the turbo-expander process is especially efficient because it can couple isentropic expansion with energy recovery. In the course of expansion, the gas experiences a notable decrease in temperature due to the Joule–Thomson effect and expansion work, which in turn promotes hydrocarbon condensation.

Depending on the equipment configuration, both isenthalpic and isentropic transformations may occur in practical systems. The low temperatures produced allow for phase separation in downstream units like demethanizers and fractionation columns, where the liquids recovered are further purified.

To accurately predict phase behavior in such systems, robust equations of state must be used. In this context, the Peng–Robinson equation of state is widely employed due to its capability to model vapor–liquid equilibrium of light hydrocarbon mixtures over a wide range of pressures and temperatures.

These thermodynamic models are incorporated into Aspen HYSYS to represent actual process conditions. The software enables the modeling of compression, heat exchange, expansion, and separation units, providing detailed insights into temperature profiles, phase distribution, and energy efficiency. This allows engineers to optimize operating conditions, evaluate different process configurations, and assess the feasibility of NGL recovery from flare gas streams.

In parallel, gas-to-power technologies provide an alternative solution for gas valorization, especially in remote locations. These systems use technologies like gas turbines, combined cycles, and solid oxide fuel cells (SOFC) to turn chemical energy into electricity, helping to cut down on flaring and boost overall energy efficiency.

II.4. Thermodynamic Properties of Flare Gas

II.4.1. Introduction

Accurate determination of thermodynamic properties is essential for the modelling and simulation of flare gas recovery systems. These properties play a crucial role in evaluating system performance, energy efficiency, and process feasibility. Flare gas, which is usually made up of light hydrocarbons like methane, ethane, and propane, shows different thermodynamic behavior based on its composition, temperature, and pressure conditions [28].

In this study, thermodynamic properties are assessed using correlations and simulation tools such as Aspen HYSYS which consists of reliable methods, written based on equations of state [29].

II.4.2. Heat Capacity (Cp)

The heat capacity at constant pressure is an important parameter for measuring the amount of heat needed to increase the temperature of the flare gas [30].

II.4.2.1. Development of the Cp Correlation

The resulting data set was tested in sensitivity analysis to enable a description of the variation of with temperature. The analysis showed a nonlinear relationship, which was modeled by a polynomial regression.

This polynomial expression gives a continuous and accurate description of the specific heat capacity as a function of temperature The correlation coefficients were obtained by curve fitting and are listed in Table II.2.

$$Cp_{fg}(T) = AT^6 + BT^5 + CT^4 + DT^3 + ET^2 + FT + G \quad (II.18)$$

Coefficient	Value
A	-4.30E-17
B	2.75E-13
C	-7.22E-10
D	9.96E-07
E	-7.61E-04
F	3.07E-01
G	-4.71E+01

TABLE II.1: Fitting curve coefficients.

By incorporating the specific heat expression obtained earlier, it becomes possible to precisely determine the enthalpy and entropy values at the inlet and outlet conditions of the system. The corresponding thermodynamic relations are used for this purpose.

For gas mixtures, the overall heat capacity is calculated as [33].

II.4.3. Enthalpy (H)

Enthalpy is an important thermodynamic property used in energy balance calculations [32]

$$H = \int Cp_P(T) dT \quad (II.19)$$

II.4.4. Entropy (S)

Entropy is used to evaluate the irreversibility of thermodynamic processes and is essential in exergy analysis [30]:

$$S = \int \frac{Cp_P(T)}{T} dT \quad (II.20)$$

II.4.5. Application in Simulation

In this work, thermodynamic properties of flare gas are estimated using Aspen HYSYS by selecting the Peng–Robinson equation of state, ensuring accurate prediction of real gas behavior [22].

II.5. Basic modeling of Organic Rankine Cycle (ORC)

The Rankine cycle is one of the most commonly used thermodynamic cycles for transforming thermal energy into mechanical and electrical energy. It is the basis for the functionality of steam power plants, and it serves as a reference point for even more complex energy conversion systems. Within the realm of energy recuperation and thermal system assessment, the elementary modeling of the Rankine cycle furnishes a straightforward but potent platform for gauging system efficacy and efficiency [29].

II.5.1 Description of the Rankine Cycle

Le cycle Rankine est un cycle thermodynamique à boucle fermée constitué de 4 étapes principales faisant intervenir le changement d'état du fluide utilisé de travail, généralement vapeur/d'eau. The cycle works by compressing, then adding heat, then expanding, and finally rejecting heat.

At the outset, the working fluid, which is a saturated liquid, enters the pump at a low pressure. It is then raised to a higher pressure before it enters the boiler. The boiler receives heat at constant pressure, converting the liquid into either saturated or superheated steam. The steam at high pressure passes through a turbine and does mechanical work. The steam is finally condensed at low pressure in the condenser, where it returns to the liquid state and the cycle is completed [29], [30].

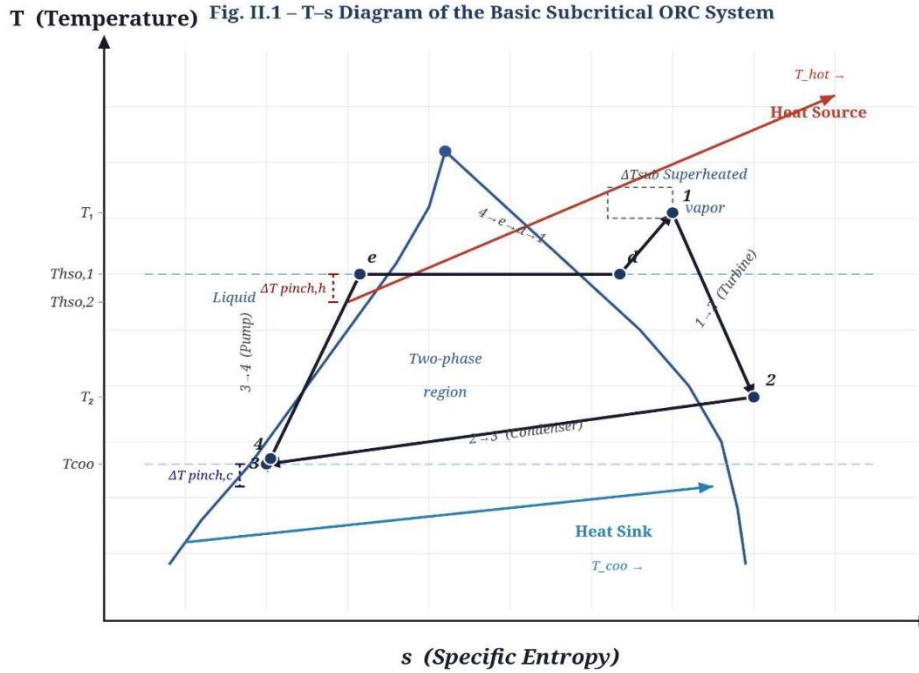


FIG. II.2: t-s diagram of the basic orc system [30]

3 → 4 (Pump): Isentropic/Adiabatic Compression. The working fluid enters the pump as a saturated liquid (point 3). The pump increases its pressure and slightly raises its temperature up to state 4. This step requires mechanical work input.

4 → e → d → 1: Heat Addition (Evaporator). The high-pressure fluid absorbs heat from the waste **Heat Source** (represented by the upper red line).

4 → e: Sensible heating of the liquid.

e → d: Phase change (boiling) inside the saturation dome at constant temperature and pressure.

d → 1: Vapor superheating (ΔT_{sub}) to reach point 1 as a superheated vapor.

1 → 2 (Turbine): Isentropic/Adiabatic Expansion. The high-pressure, high-temperature vapor expands through the turbine to generate mechanical power. Because organic fluids often have a positive or dry saturation curve slope, the fluid remains in the superheated vapor region (point 2) at the turbine exhaust, avoiding liquid droplet erosion on the turbine blades.

II.5.2 Energy Balance Equations

The performance of each component in the Rankine cycle can be evaluated using the first law of thermodynamics applied to steady-flow systems. The equations for energy balance are written in terms of specific enthalpy.

The work required of the pump is given by

$$\dot{W}_p = \dot{m}_{wf}(\mathbf{h}_c - \mathbf{h}_b) \quad (\text{II.20})$$

The work produced by the turbine is

$$/ \dot{W}_T / = \dot{m}_{wf}(\mathbf{h}_e - \mathbf{h}_f) \quad (\text{II.21})$$

The heat added in the boiler is expressed as

$$\dot{Q}_{hp} = \dot{Q}_{pre} + \dot{Q}_{ev} = \dot{m}_{wf}[(\mathbf{h}_d - \mathbf{h}_c) + (\mathbf{h}_e - \mathbf{h}_d)] = \dot{m}_{wf}(\mathbf{h}_e - \mathbf{h}_c) \quad (\text{II.22})$$

The heat rejected in the condenser is

$$/ \dot{W}_T / = \dot{m}_{wf}(\mathbf{h}_e - \mathbf{h}_f) \quad (\text{II.23})$$

These equations express the energy exchanges inside each element and are needed to assess the overall performance of the cycle [34].

II.5.3 Thermal Efficiency of the Cycle rankin

The thermal efficiency of the Rankine cycle is given by the ratio of the network produced to the heat supplied in the boile, it signifies how well the cycle transforms thermal energy into useful work.

$$\eta_{th} = \frac{/\dot{W}_T/-\dot{W}_p}{\dot{Q}_{hp}} \quad (\text{II.24})$$

The same expression may also be written in terms of enthalpy differences as follows:

$$\eta_{th} = \frac{/\dot{W}_T/-\dot{W}_p}{\dot{Q}_{hp}} \quad (\text{II.25})$$

To meet the specific goals of the present study, we introduce an additional ratio, called the evaporator heat ratio:

$$Q_{rat} = \frac{Q_{ev}}{Q_{pre}} = \frac{(h_e - h_d)}{(h_d - h_c)} \quad (\text{II.26})$$

The efficiency is mainly determined by the temperature and pressure levels of the cycle, and by the performance of its components. Increasing the work done by the turbine or reducing heat losses results in greater efficiency [31]

Thus, although the basic model is adequate for preliminary design and theoretical analysis, more sophisticated models that include real fluid properties and component efficiencies are necessary for accurate simulation and optimization.

CHAPTER III
PROCESS DESCRIPTION
AND SIMULATION WITH
ASPEN HYSYS

III.1 Introduction

Aspen HYSYS is the world's leading process simulation software, designed for the oil & gas, refining, and gas processing industries. [1]. It is a sophisticated mathematical engine that allows engineers to develop a “Digital Twin” of industrial plants for prediction, design and optimization of complex chemical processes. HYSYS uses a large selection of thermodynamic property packages including the Peng-Robinson (PR) equation of state which is based on the principle of corresponding states, to accurately model the behavior of the non-ideal hydrocarbon mixtures over a large temperature and pressure range. [2].

In the case of flare gas recovery, Aspen HYSYS is a vital tool for solving the complex mass and energy balances needed to convert a waste stream into a stable energy source. The software provides a flexible Process Flow Diagram (PFD) environment to characterize variable gas compositions, including “sour” components such as H₂S and CO₂, while simulating critical unit operations such as multi-stage compression, knock-out drums, and heat exchangers [1], [3].

In addition to basic steady-state modeling, HYSYS provides advanced Sensitivity Analysis and Case Study tools that allow engineers to stress-test the recovery system for varying flare flow rates and ambient conditions. Aspen HYSYS provides the exact data on the power needed by the compressors and the cooling loads to fill the gap between the theoretical thermodynamics and the practical engineering that is required to guarantee the technical safety and economic profitability of the conversion process [2].

III.2 Presentation of Aspen HYSYS

Aspen HYSYS is the industry leading process simulation tool used extensively in the oil and gas, petrochemical and refining industries. The software was initially developed by the Canadian company HYPROTECH. It is designed to solve diverse engineering problems, ranging from the preliminary design of chemical processes to the complex optimization of operating plants. It is necessary for finding the best design choices and checking how good the current equipment is working. This helps engineers improve how well things run.

The software is characterized by an object-oriented architecture, which guarantees that any change made to a particular unit or stream is immediately updated and reflected in the whole simulation model. HYSYS is an interactive, event-driven environment providing instant access to data. Calculations are automatically performed as new parameters are keyed in. The program employs modular operations and a non-sequential mathematical solver, thus ensuring

the dynamic propagation of information throughout the entire Flowsheet, enabling a complete and holistic analysis of the industrial process (**Fig.III.1**)

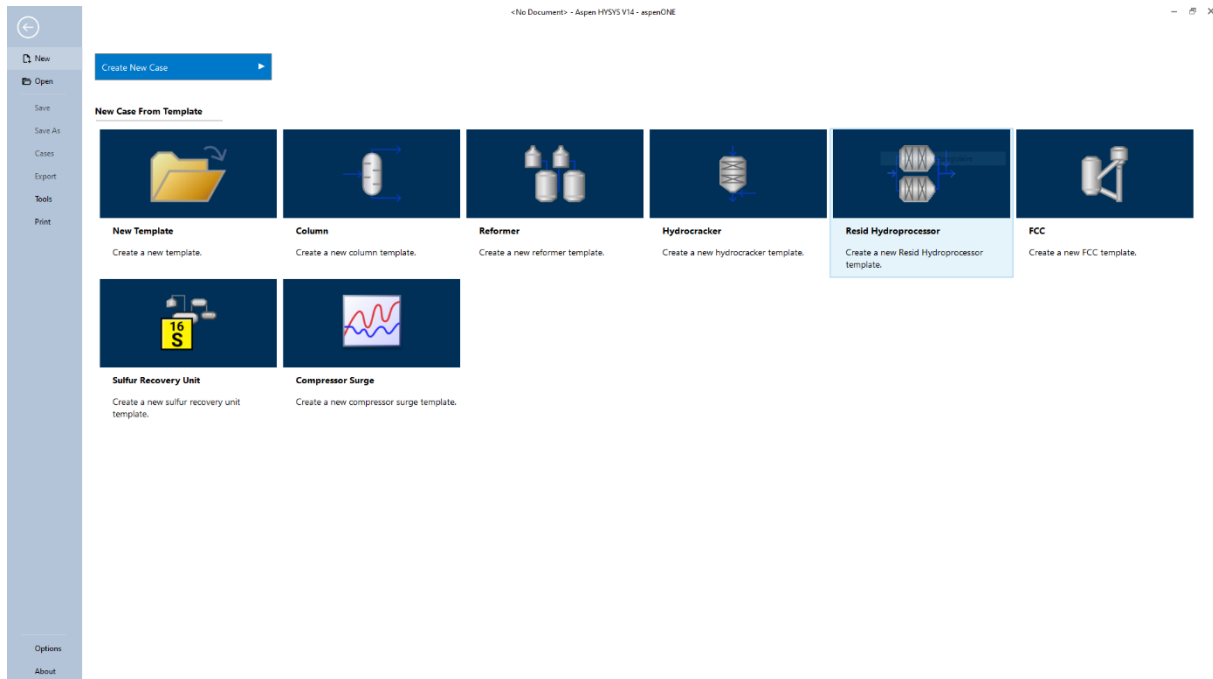


FIG.III.1: Representing the first HYSYS interface. [22]

III.3. Fundamental Concepts of the HYSYS Simulator

To create an efficient model in the HYSYS environment, it is important to know the basic terminology and the functional blocks that govern the simulation process. Following are the concepts that are the building blocks of any simulation case:

1. **Flowsheet** This is the main workspace, where the simulation is located. A Flowsheet is a structured set of elements that describe a particular process, including material streams, energy exchanges, and unit operations. HYSYS provides a multi-flowsheet architecture that allows users to break down complicated industrial processes into smaller, more manageable sub-flowsheets. The modularity facilitates the modeling of large refineries. The flowsheet is primarily maintained through two interfaces, the Process Flow Diagram (PFD) and the Workbook.
2. **Fluid Package** This is the thermodynamic foundation of the simulation. It identifies the chemical species involved in the process and accesses the physical and chemical data of these from a large pure substance database. The Fluid Package also defines the thermodynamic models (e.g., equations of state) used to calculate mixture properties. It defines the kinetics for any chemical reactions in the system.

3. **Process Flow Diagram (PFD)** The PFD is a graphical form of the simulation. It uses standard symbols to represent unit operations and streams, clearly showing the connectivity between different stages of the process. It also allows property tables to be placed for visual monitoring of stream data.
4. **Workbook** It is a tabular interface that presents all the numeric data in a compact view. It enables engineers to track and change the properties of material streams and unit operations in a structured spreadsheet format.
5. **Desktop** This is the main executive dashboard of the software, where all windows, diagrams and analysis tools are viewed and managed during the design phase.
6. **Property View** Every object in HYSYS, whether it is a stream or a piece of equipment, has a Property View dedicated to. This window shows all the specific parameters, specifications and computed results that define that specific object.
7. **Simulation Case** This is the full file that contains all of the parts of the model including the global Fluid Packages, all of the associated Flowsheets and each individual process element. It is the entire "Digital Twin" of the modeled process.

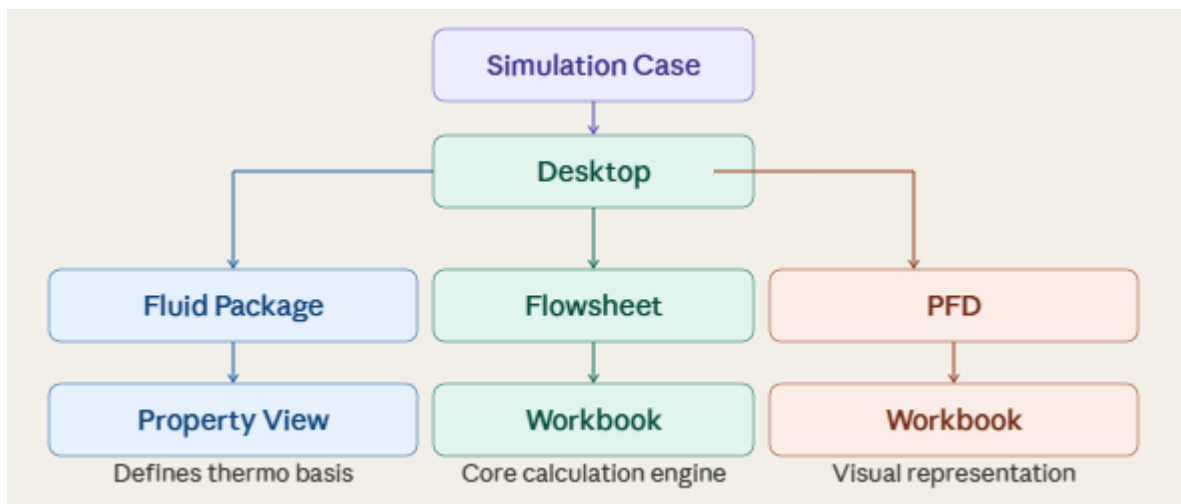


FIG.III.2: Fundamental Concepts of the HYSYS Simulator. [22]

III.4. Operational Workflow for Aspen HYSYS Simulation

A systematic approach is needed in order to have a successful simulation in HYSYS, starting from the specification of chemical properties to the final analysis of the behavior of the process. The workflow is typically divided into the following phases:

1. Project Initialization

- Create a new Simulation Case to contain all data for the project.
- Open Aspen HYSYS application.

2. Definition of the Basis (Properties Environment)

- **Selecting components:** Identify and add all chemical species (hydrocarbons, H₂O, H₂S, CO₂, etc.) in the flare gas stream from the internal database.
- **Thermodynamic Model Selection:** Use correct Fluid Package (e.g. Peng-Robinson) so that physical properties, phase behavior calculated correctly.

3. Simulation Environment (Flowsheet Construction)

- **PFD Montage:** Create the Process Flow Diagram by dragging unit operations (compressors, heat exchangers, separators) to the workspace.
- **Connectedness:** Define logical links between equipment, material and energy streams.

4. Parameter definition

- Identify the known boundary conditions for feed streams (temperature, pressure, flow rate, and composition).
- Specify the desired operating parameters for each unit operation (e.g., the efficiency of a compressor or the pressure drop of a vessel).

5. Execution and Convergence

- Run the simulation solver. HYSYS will automatically propagate calculations through the flowsheet until the mass and energy balances have converged. HYSYS will automatically propagate calculations through the flowsheet until mass and energy balances converge.

6. Analysis and interpretation of results

- Review data from the Workbook or the PFD property tables.
- Perform sensitivity analyses to assess the impact of variations in flare gas flow or composition on the energy recovery efficiency and economic profitability.

III.5. Operating Modes in HYSYS

The HYSYS simulator has two different computational modes for the analysis of industrial processes: Steady-State (Static) and Dynamic.

- **Steady State Mode** This mode is designed to solve static algebraic equations describing a process in equilibrium. It is mainly used for preliminary design, equipment sizing, and long-term heat and material balance calculations where variables do not change with time.
- **Dynamic-Modus** Dynamic simulation, on the other hand, determines the time variation of process variables. It allows engineers to model transient behaviors such as plant startups and shutdowns and the performance of control systems during process upsets. This is done by solving complex systems of differential equations.

The overall architecture and organizational logic of the HYSYS software environment is shown in (FIG. III.3)

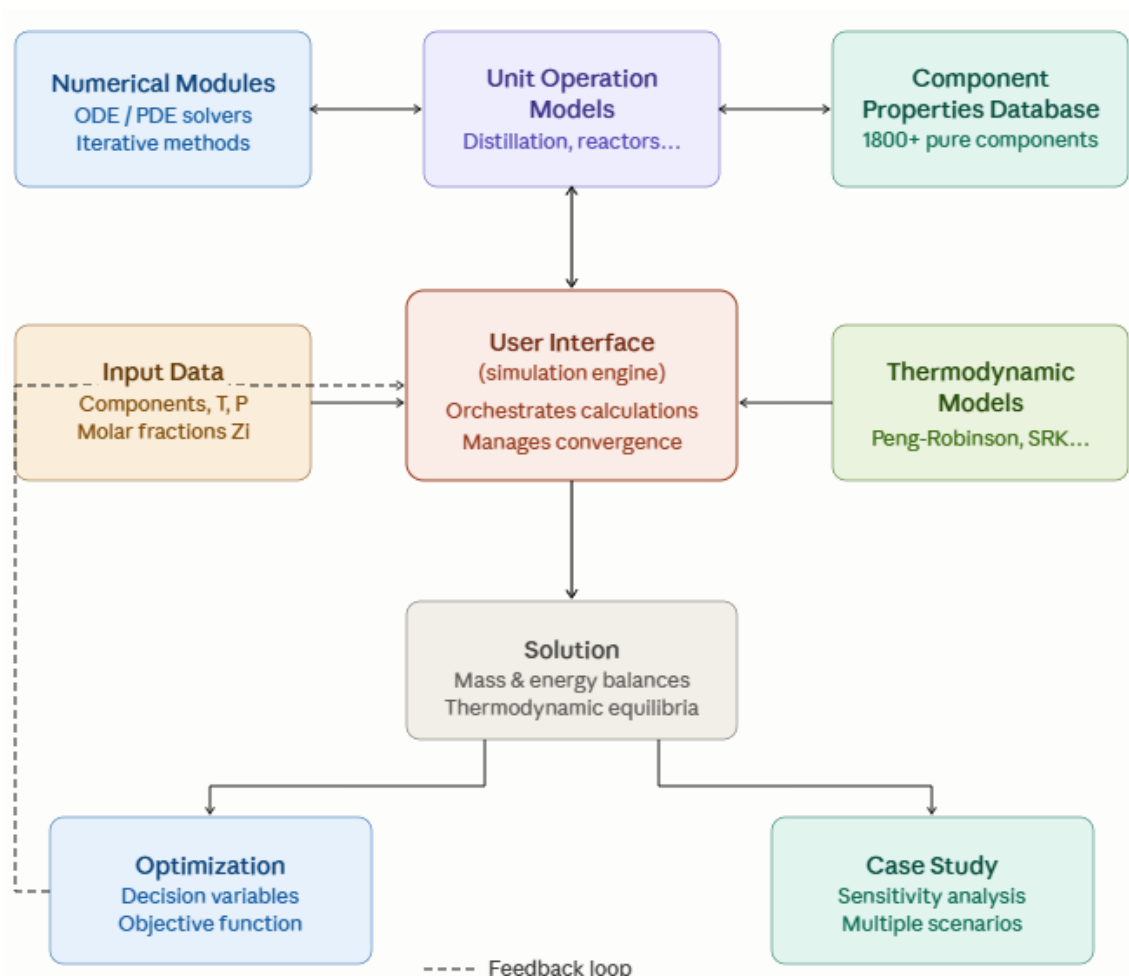


FIG.III.3: HYSYS Software Architecture. [22]

III.6. Approach to Combustion Simulation

The simulation of the combustion process is done by following a strict methodological sequence in Aspen HYSYS to ensure the accuracy of the model of energy conversion. This stage is important to determine the heat energy available for power generation.

1. Compositional Definition and Thermodynamic Selection

First, the chemical composition of the input streams has to be determined

- **Fuel Stream** Mainly methane (CH₄) and ethane (C₂H₆) with small amounts of heavier hydrocarbons (C₃+).
- **Oxidizer (Air)** Based on a standard molar ratio of 21 percent Oxygen (O₂) and 79 percent Nitrogen (N₂).

The Peng-Robinson (PR) equation of state is used for reactive fluid equilibria at high temperature and pressure. It is very accurate for hydrocarbon-gas mixture at operating conditions of more than 30 bar and 1000 K, with a fugacity coefficient error of less than 2.5%. It is very good for hydrocarbon-gas mixtures at operating conditions above 30 bar and 1000 K, with a fugacity coefficient accuracy within 2.5%. The reason for this precision is the temperature-dependent cohesion term $\alpha(T)$ in the PR equation:

$$P = \frac{RT}{(v - b)} - \frac{a(T)}{[v(v + b) + b(v - b)]} \quad (\text{III.1})$$

This equation is needed to consider phase non-idealities and solubility of H₂O and CO₂ in the flue gases produced.

2. Reactor Configuration

The combustion chamber is normally modelled using a Gibbs Reactor, which calculates the chemical equilibrium by minimising the Gibbs free energy of the system. The setup consists of:

- **Full Oxidation Path** For example, the methane reaction (CH₄ + 2O₂ → CO₂ + 2H₂O) with an enthalpy of $\Delta H = -802$ {kJ/mol}
- **Estimación de NO_x** Using Zeldovich kinetics with assumptions of chemical equilibrium to forecast thermal Nitrogen Oxide emissions.
- **Analysis of thermal** Calculation of the Adiabatic Flame Temperature (T_{ad}) (max. theoretical temperature reached without heat loss).

3. Simulation and Validation Outputs

The main results obtained from this simulation are

- **Flue Gases Analysis:** Final concentrations of CO₂, H₂O, and residual O₂.
- **Performance Indicators:** Combustion efficiency validation (> 99.5% usually).
- **Temperature Profiles:** Data of the exhaust gas of high temperature that feeds the downstream power turbines.

These results confirm the thermodynamic feasibility of the conversion process, demonstrating that the recoverable flare gas can be efficiently converted into stable energy.

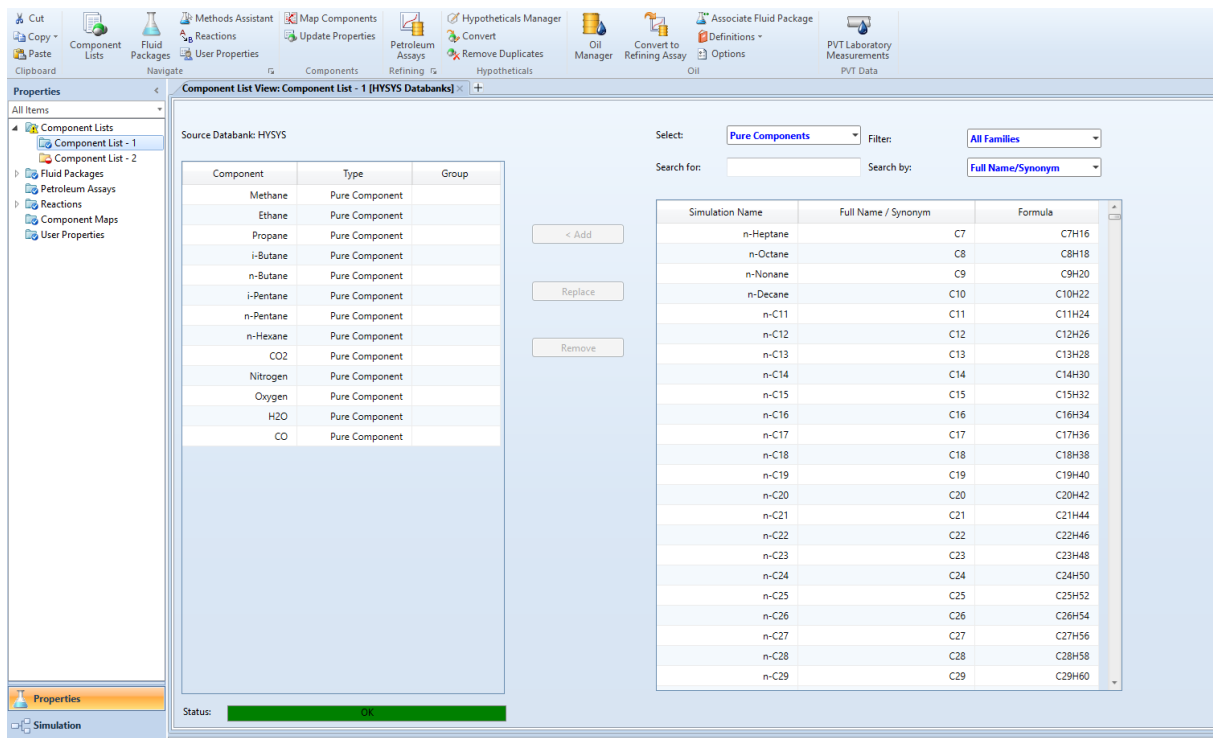


FIG.III.4: Identification and selection of components of gas. [22]

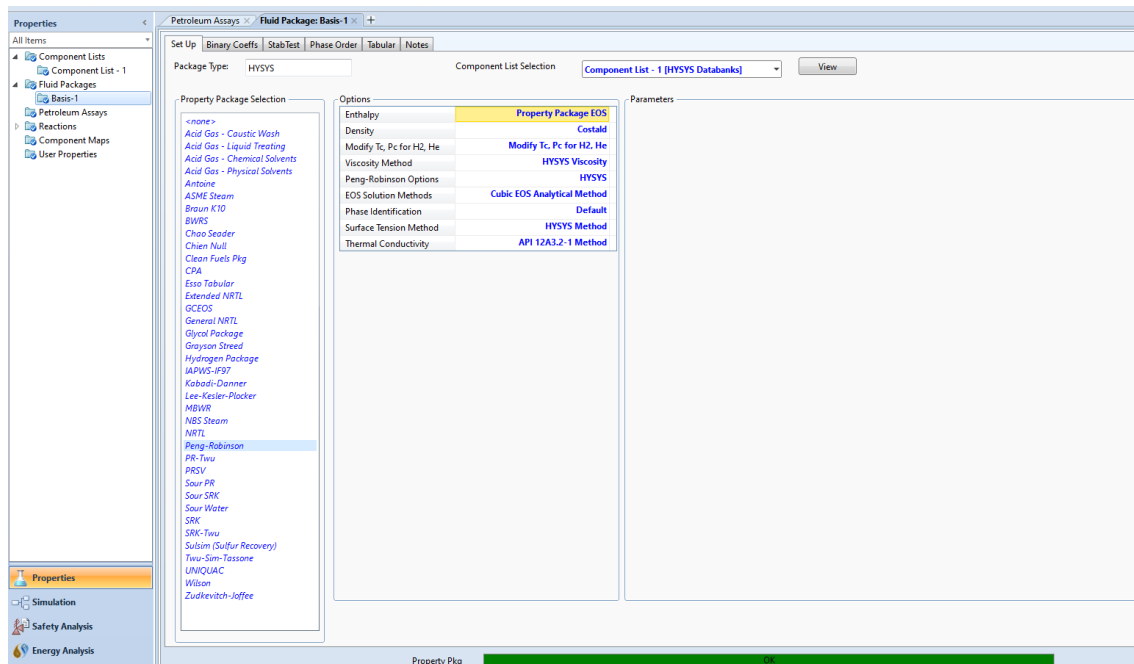


FIG.III.5: Choice of the Thermodynamic Fluid Package. [22]

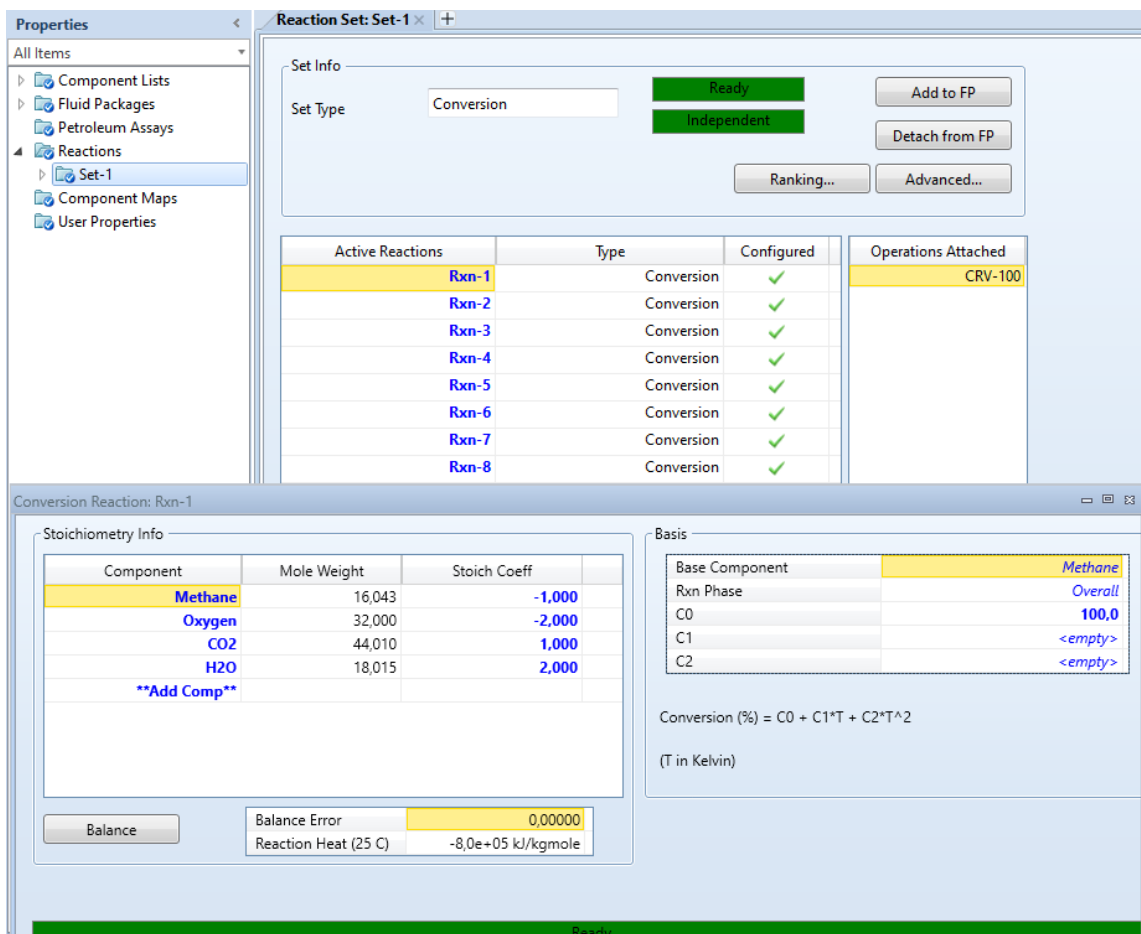


FIG.III.6: the burning responses. [22]

Fuel	+ Oxidant		Products	Eq.
CH_4	$+ 2 \text{O}_2$	$\longrightarrow$	$\text{CO}_2 + 2 \text{H}_2\text{O}$	(1)
C_2H_6	$+ 7/2 \text{O}_2$	$\longrightarrow$	$2 \text{CO}_2 + 3 \text{H}_2\text{O}$	(2)
C_3H_8	$+ 5 \text{O}_2$	$\longrightarrow$	$3 \text{CO}_2 + 4 \text{H}_2\text{O}$	(3)
C_4H_{10}	$+ 13/2 \text{O}_2$	$\longrightarrow$	$4 \text{CO}_2 + 5 \text{H}_2\text{O}$	(4)
C_5H_{12}	$+ 8 \text{O}_2$	$\longrightarrow$	$5 \text{CO}_2 + 6 \text{H}_2\text{O}$	(5)
Fuel (C_nH_k) + O_2		$\rightarrow n \text{CO}_2 + (n+1) \text{H}_2\text{O}$		General form

FIG.III.7: Hydrocarbon combustion reactions. [22]

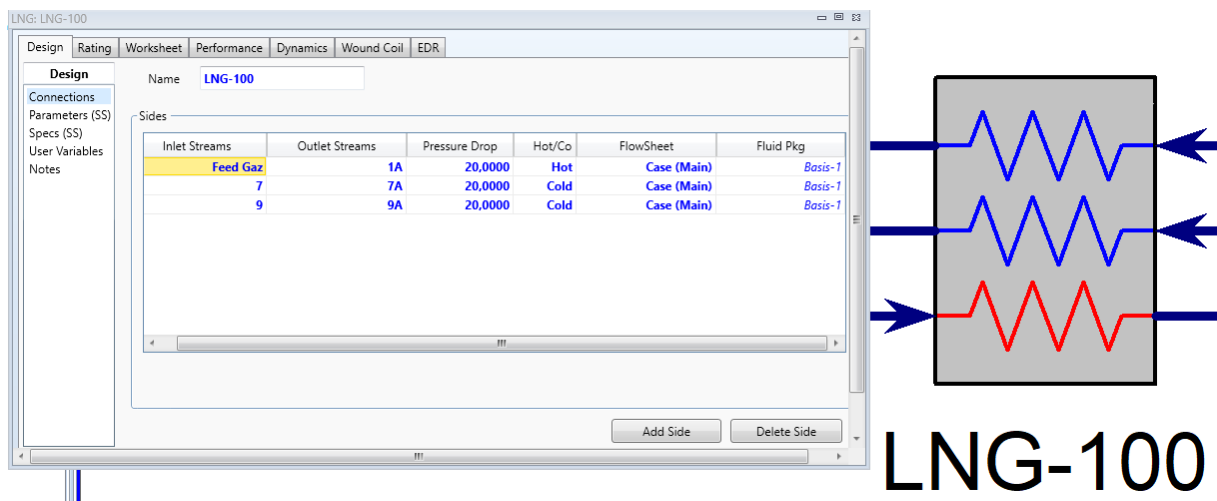


FIG.III.8: LNG-100 Connections. [22]

The cooler Aspen HYSYS. For a given pressure drop, heat (Duty) is removed from a stream to lower its temperature. To converge, outlet temperature or heat flow must be specified. It requires either the outlet temperature or the heat flow to be specified for convergence.

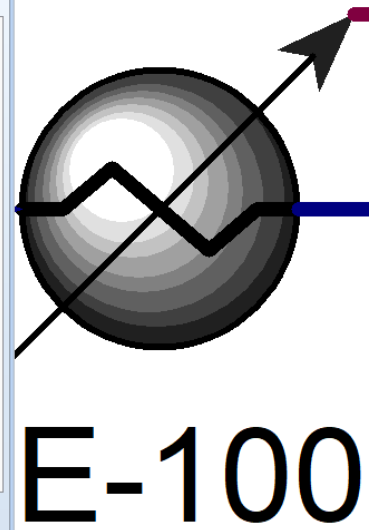
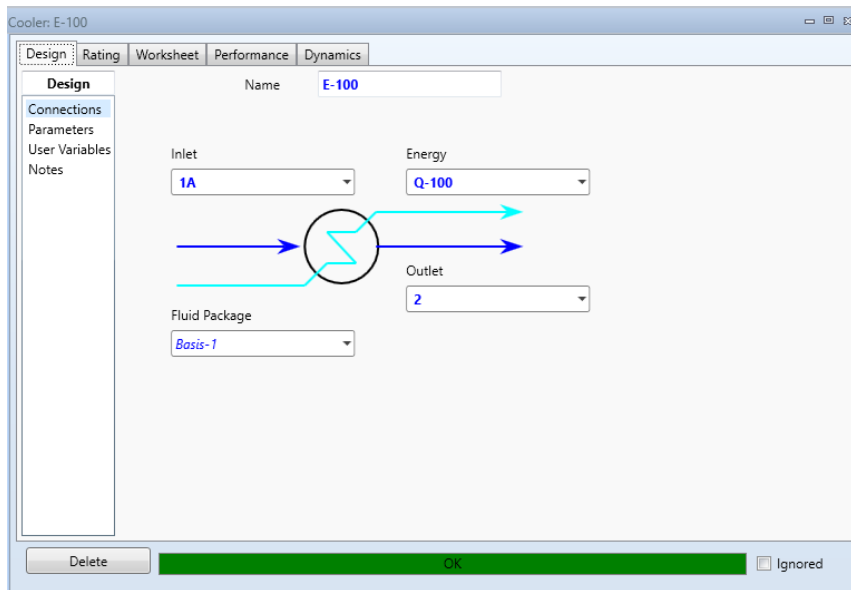


FIG.III.9: cooler E-100. [22]

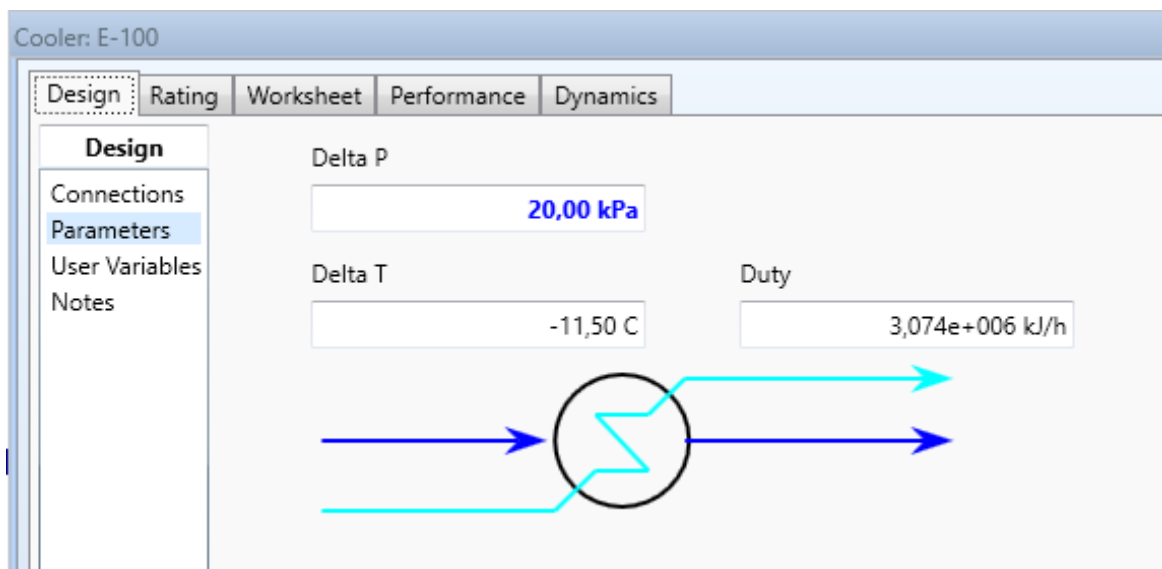


Fig.III.10: parameters of the cooler E-100. [22]

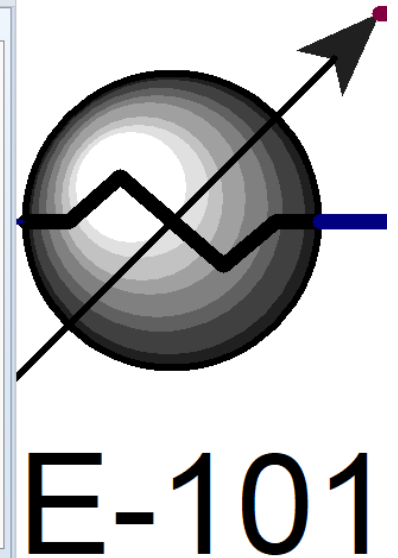
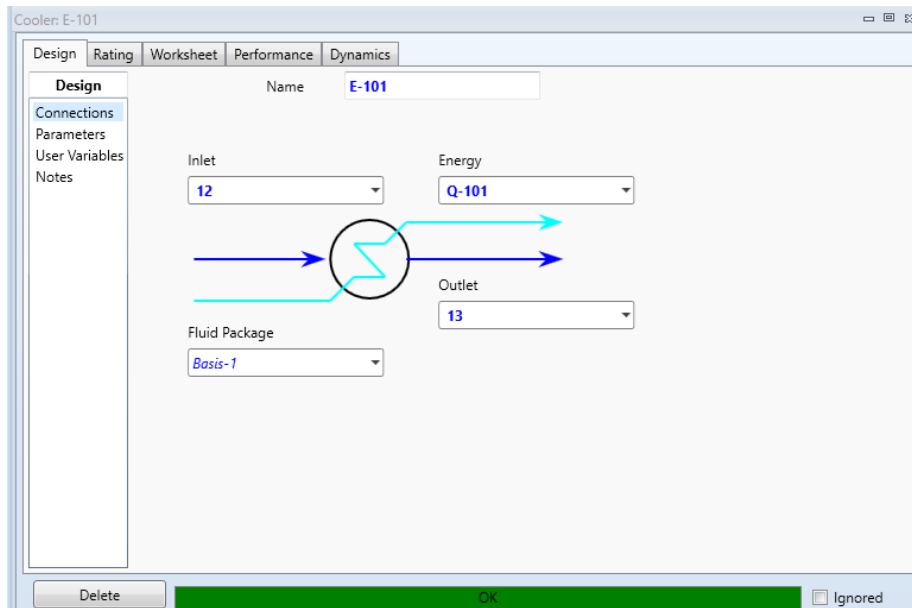


FIG.III.11: cooler E-101. [22]

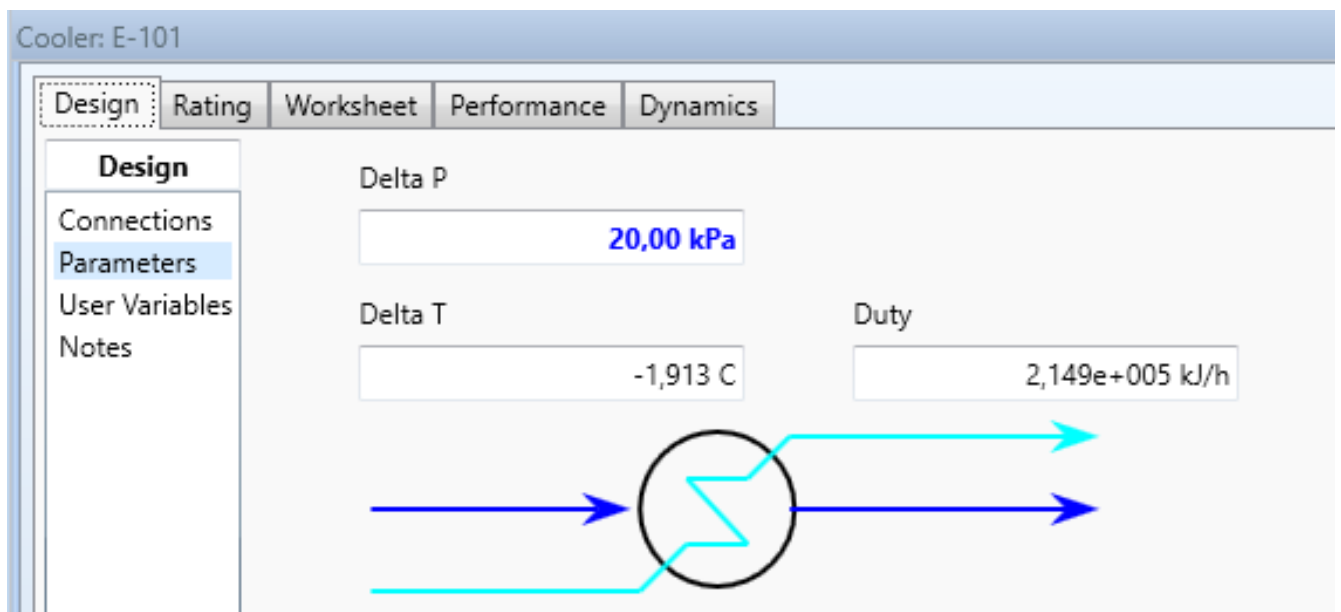


FIG.III.12: parameters of the cooler E-101. [22]

Fired Heater is a unit operation used to heat process streams to high temperatures by transfer of heat from direct combustion of fuel such as flare gas. In the simulation it calculates the required fuel flow and energy release to achieve a specified target temperature or vapor fraction of the process fluid.

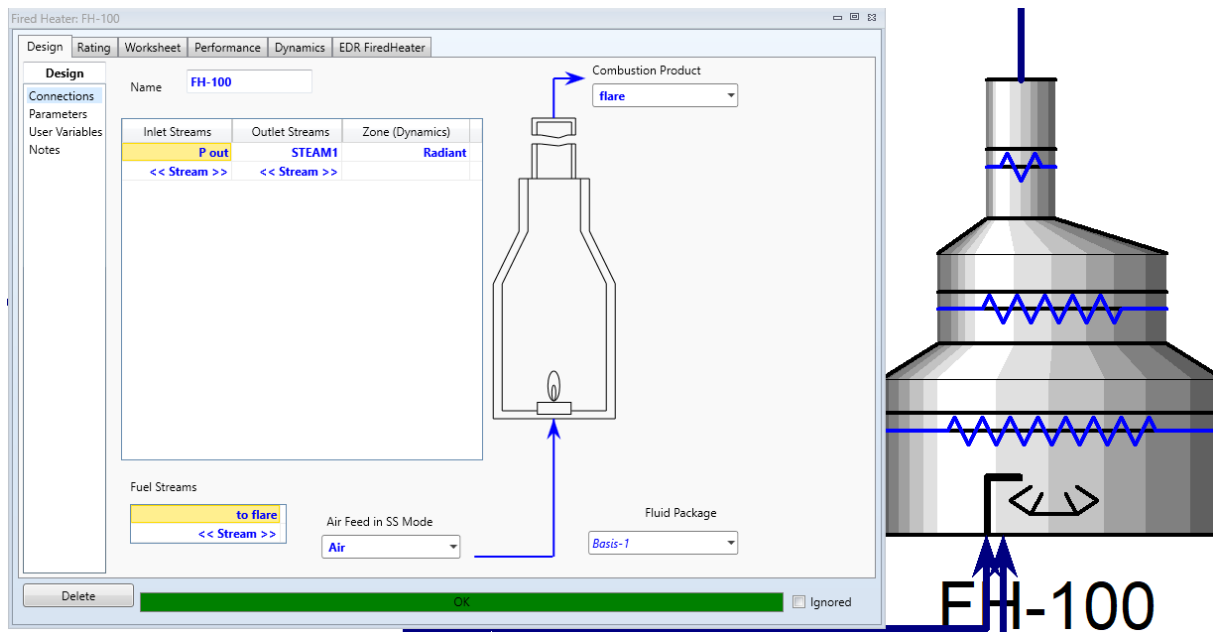


FIG.III.13: fired Heater FH-100. [22]

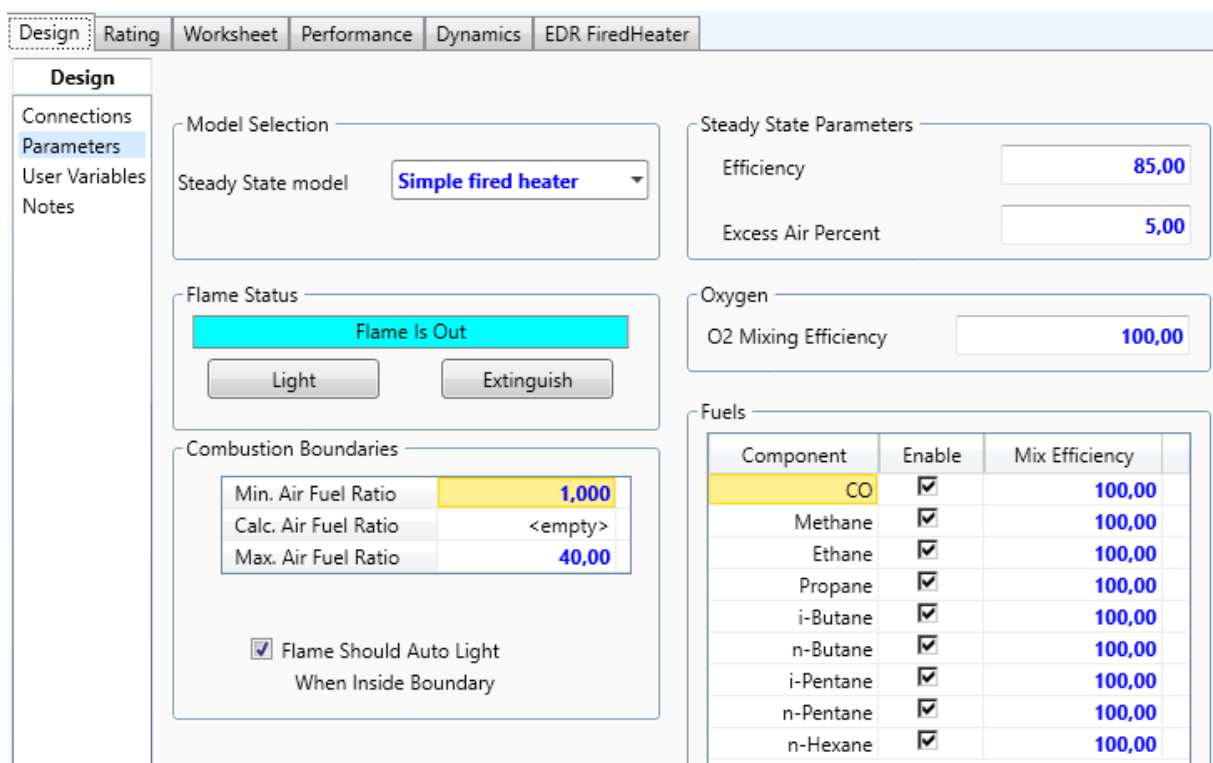


FIG.III.14: parameters of the fired Heater FH-100. [22]

Conversion reactor is a unit operation to model chemical reactions when the stoichiometry and the fixed percentage conversion of a limiting reactant are known. It does not enforce thermodynamic consistency (as equilibrium reactors do), it simply forces a certain fraction of reactants to become products according to user-specified conversion rates.

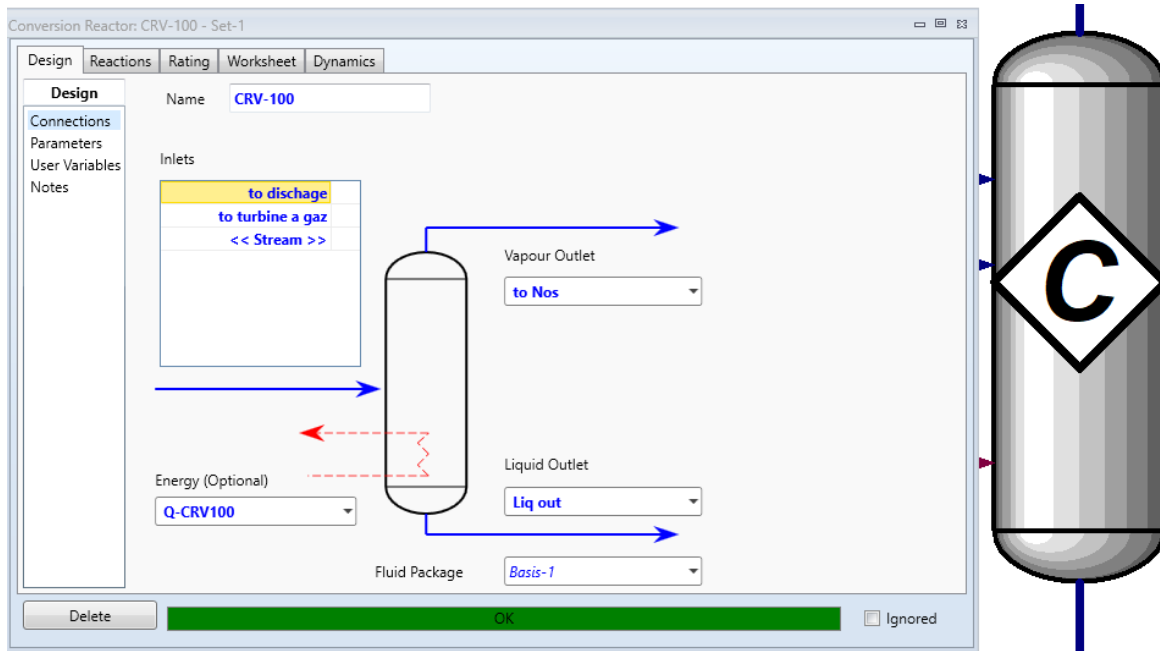


FIG.III.15: Conversion reactor CRV-100. [22]

Demethanizer (LPG Recovery) is a distillation unit intended for the separation of C3 and C4 hydrocarbons (propane and butane) from the gas stream. It uses fractional distillation to produce high-value Liquefied Petroleum Gas as a liquid product and discharges lighter components as overhead vapor.

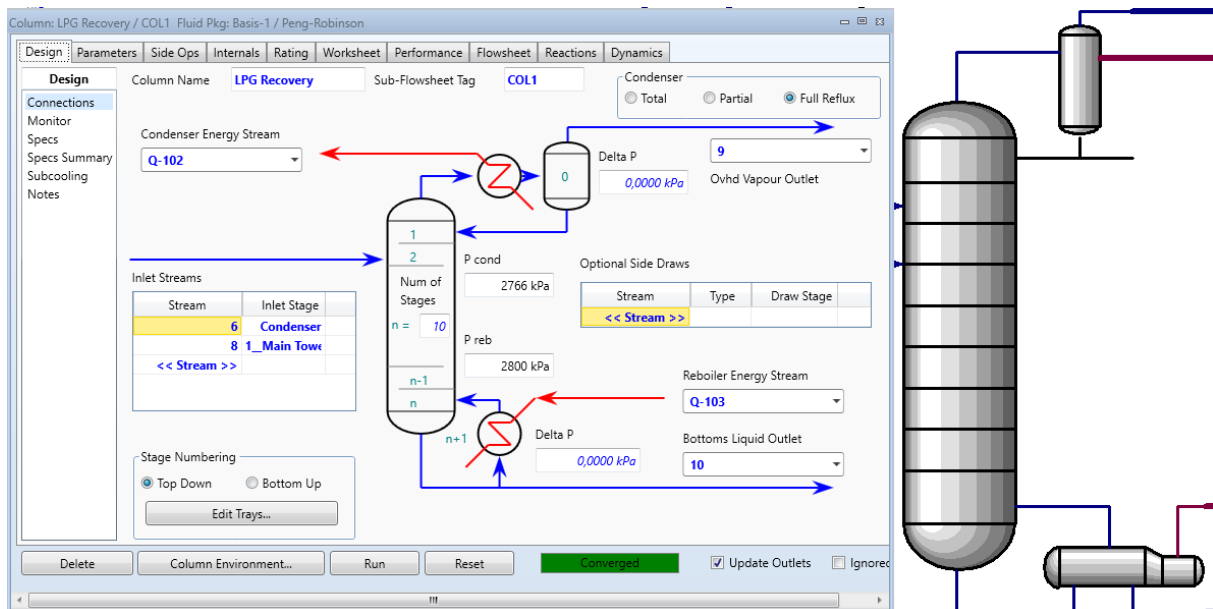


FIG.III.16: Demethanizer (LPG Recovery). [22]

Compressors: are unit operations which increase the pressure of vapor phase streams to suit process requirements or for export. The required work (Duty) and the temperature rise are calculated in Aspen HYSYS based on the specified outlet pressure and adiabatic or polytropic efficiency.

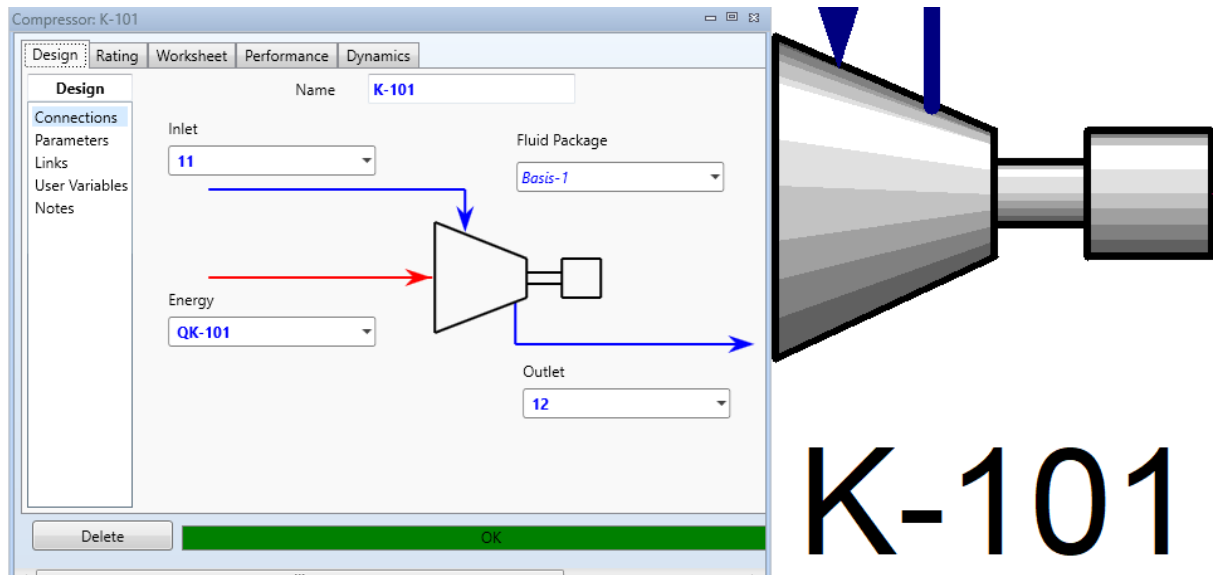


FIG.III.17: compressor k-101.[22]

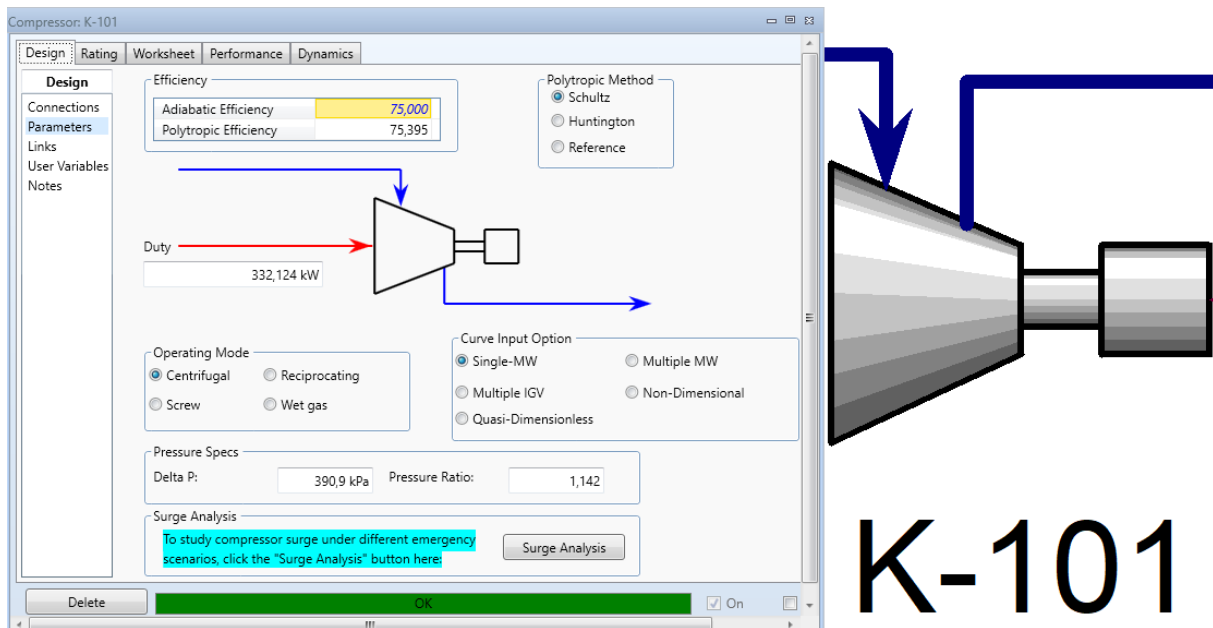


FIG.III.18: parameters of the compressor K-101. [22]

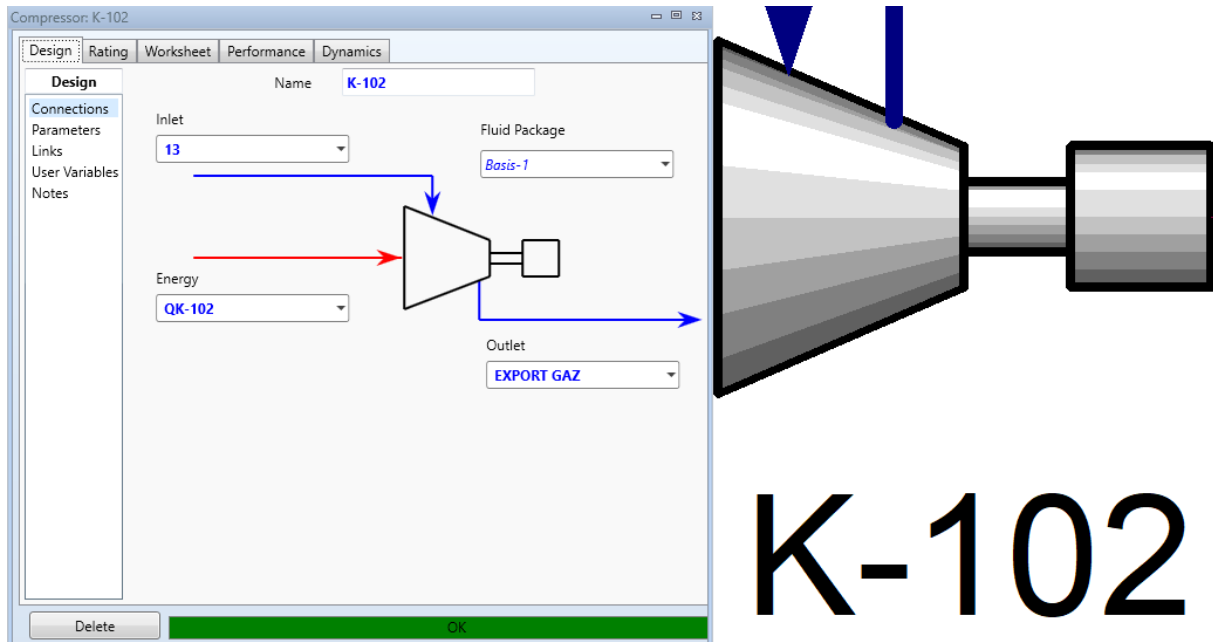


FIG.III.19: compressor k-102. [22]

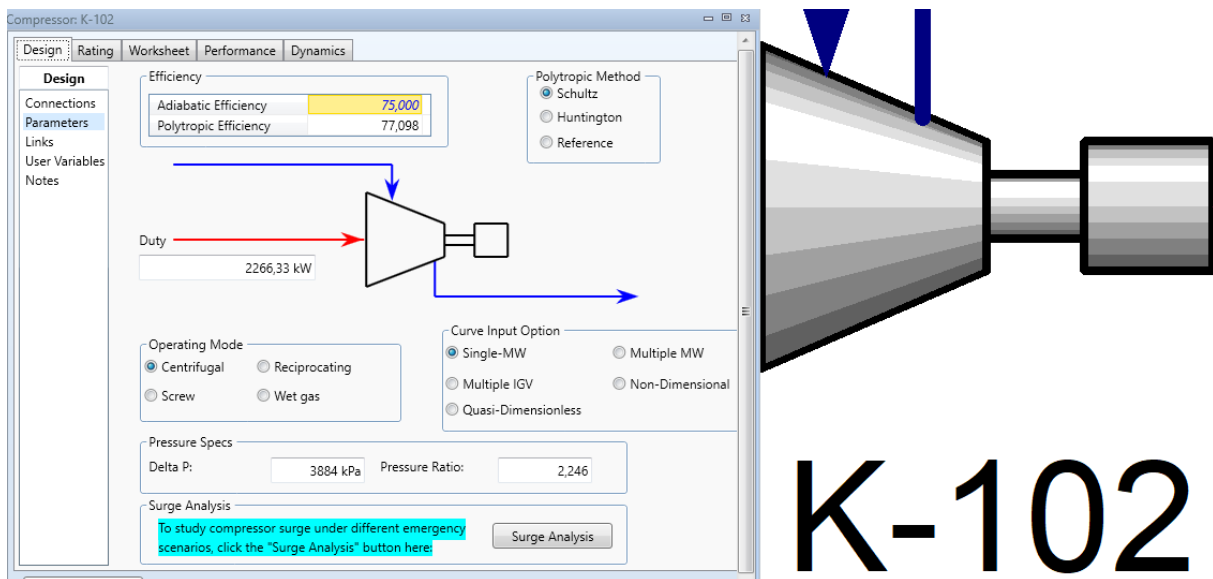


FIG.III.20: parameters of the compressor K-102. [22]

The turboexpander is a unit operation that reduces the pressure and temperature of a gas stream converting its internal energy into useful mechanical work (Duty). In Aspen HYSYS, it models the near-isentropic expansion of gases, thus making it indispensable for cryogenic cooling and energy recovery applications.

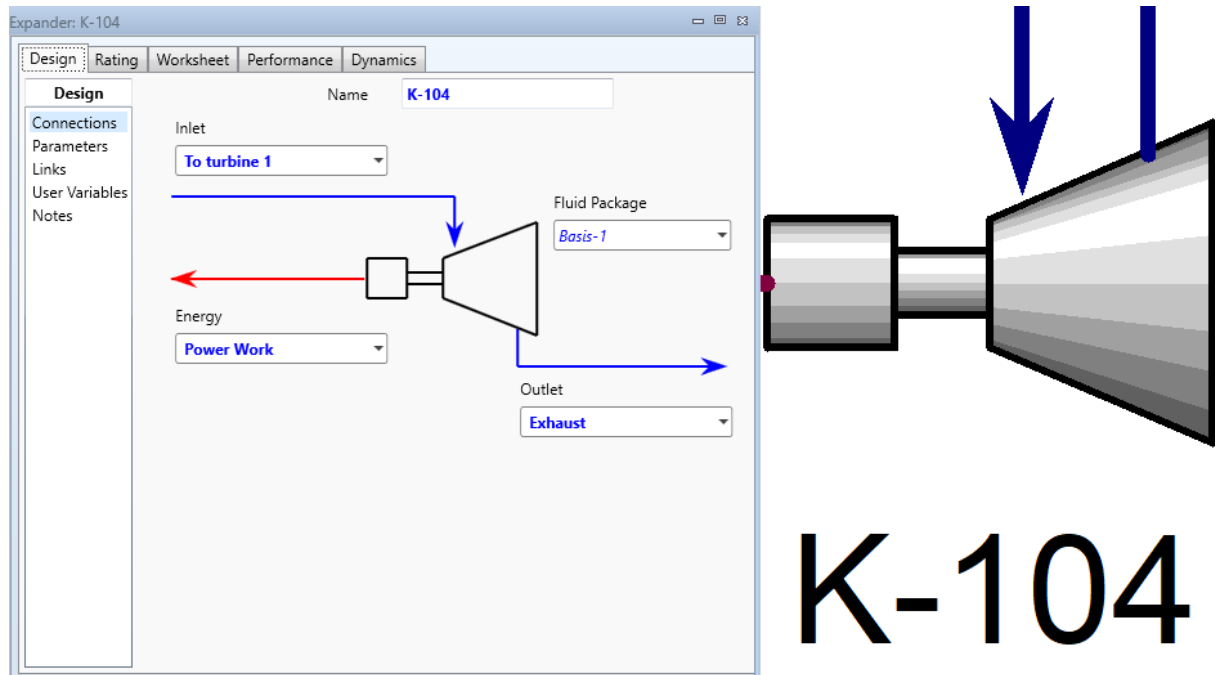


FIG.III.21: The gas turbine k-104. [22]

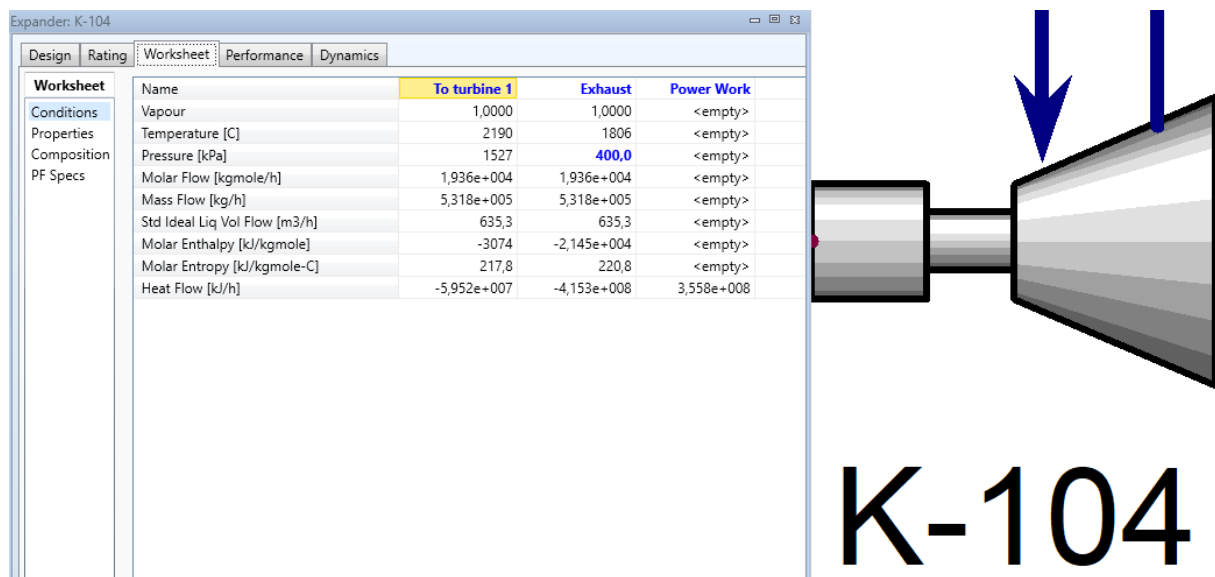
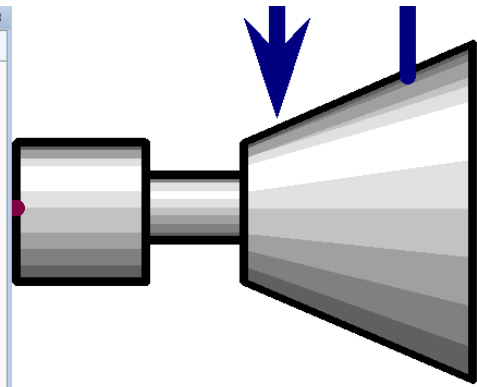
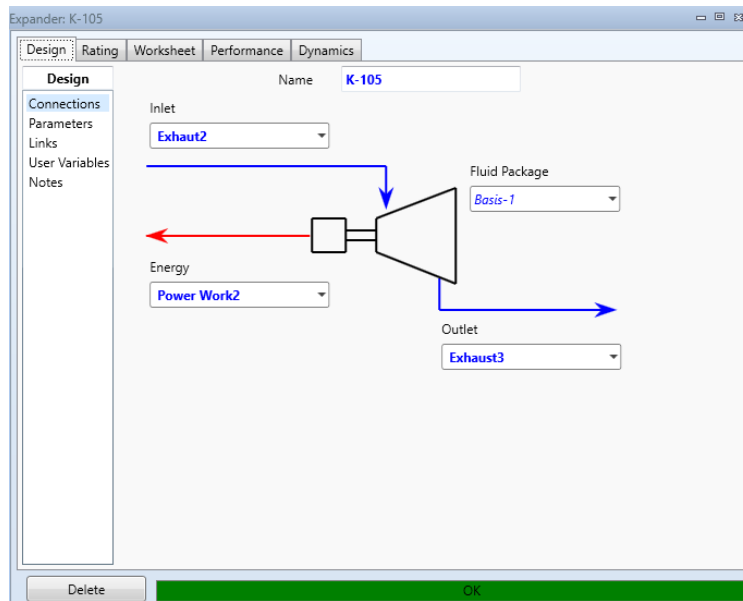


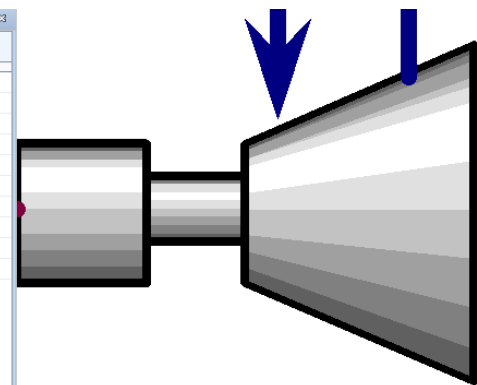
FIG.III.22: conditions of the gas turbine k-104. [22]



K-105

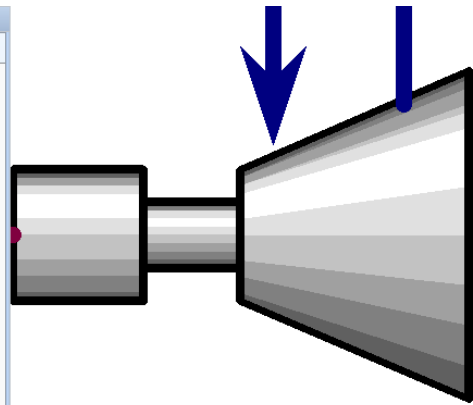
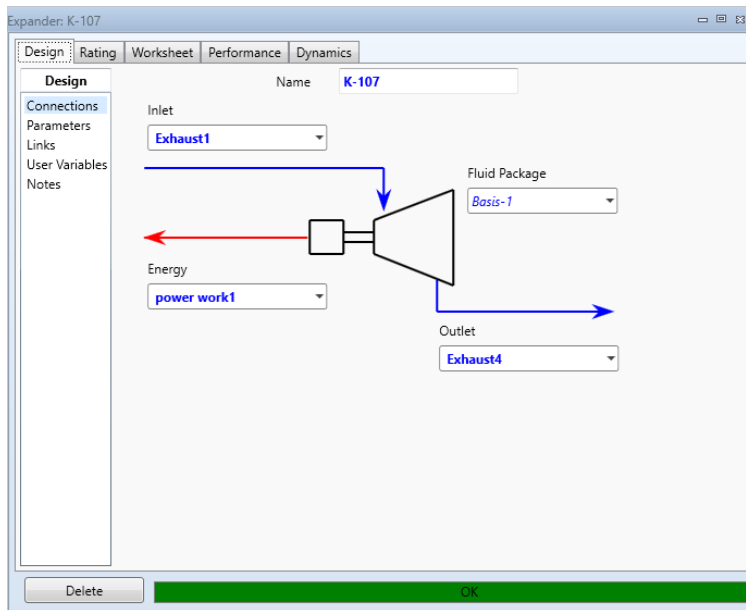
FIG.III.23: The gas turbine k-105. [22]

Name	Exhaust2	Exhaust3	Power Work2
Conditions			
Vapour	1,0000	1,0000	<empty>
Properties			
Temperature [C]	1806	1276	<empty>
Composition			
Pressure [kPa]	400,0	50,00	<empty>
PF Specs			
Molar Flow [kgmole/h]	9680	9680	<empty>
Mass Flow [kg/h]	2,659e+005	2,659e+005	<empty>
Std Ideal Liq Vol Flow [m3/h]	317,6	317,6	<empty>
Molar Enthalpy [kJ/kgmole]	-2,145e+004	-4,353e+004	<empty>
Molar Entropy [kJ/kgmole-C]	220,8	225,9	<empty>
Heat Flow [kJ/h]	-2,077e+008	-4,214e+008	2,137e+008



K-105

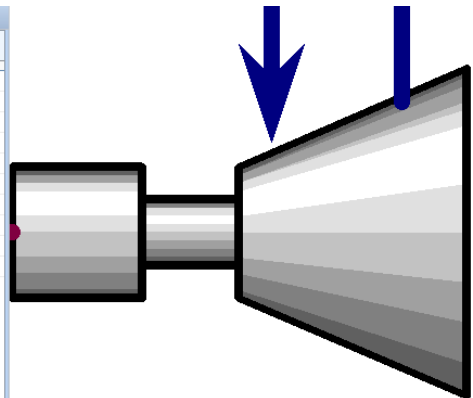
FIG.III.24: conditions of the gas turbine k-105. [22]



K-107

FIG.III.25: The gas turbine k-107. [22]

Name	Exhaust1	Exhaust4	power work1
Vapour	1,0000	1,0000	<empty>
Temperature [C]	1806	1276	<empty>
Pressure [kPa]	400,0	50,00	<empty>
Molar Flow [kgmole/h]	9679	9679	<empty>
Mass Flow [kg/h]	2,659e+005	2,659e+005	<empty>
Std Ideal Liq Vol Flow [m3/h]	317,6	317,6	<empty>
Molar Enthalpy [kJ/kgmole]	-2,145e+004	-4,353e+004	<empty>
Molar Entropy [kJ/kgmole-C]	220,8	225,9	<empty>
Heat Flow [kJ/h]	-2,077e+008	-4,213e+008	2,137e+008



K-107

FIG.III.26: conditions of the gas turbine k-107. [22]

Conclusion

In summary, the simulations carried out in Aspen HYSYS show that optimizing recovery systems turns the waste of energy into a valuable resource. The identified performance improvements confirm the feasibility of the project and pave the way for a concrete industrial implementation, aiming at minimizing the environmental impact, while maximizing the overall energy yield of the refinery.

CHAPTER IV

OUTCOMES AND

DISCUSSION

IV.1. Introduction

This part of the book looks at flare gas recovery systems, at the Skikda LNG processing unit. It does this by looking at how the process works what effect it has on the environment how much it. What risks are involved in different situations. The goal is to get a picture of flare gas recovery systems at the Skikda LNG processing unit. We are looking at two ways to get the most value from something. The first way is to get natural gas liquids, which is done by using a machine called a turboexpander. The second way is to make electricity in a location using a system that has two turbines and is called a Brayton cycle system. The main goal of this approach is to find the way to set things up so we can stop flaring all the time. We want to lower the stuff we send into the air, like greenhouse gases and make the industrial site use energy in a better way. This is what we are trying to do with this approach to make the industrial site use energy in a way and lower greenhouse gas emissions. The idea is to make the industrial site more energy efficient and reduce flaring.

IV.2. Process Description

A simulation model was created using Aspen HYSYS to show how different parts of a refinery make flare gas. The study looks at the NGL recovery unit to see how much gas is flowing through it and what the gas is made of. This is done to see if the unit is working well and to understand the economics of the process. To make sure the predictions are accurate the Peng-Robinson equation was used. This equation is very good for understanding how the hydrocarbon mixtures behave and how they affect the cycles and recovery turbines. The model was. It was found to be very reliable with an error of less than 1.5% when calculating the vapor-liquid equilibrium. The Aspen HYSYS model is a tool, for designing and evaluating the NGL recovery unit and the associated equipment. The study uses the Peng-Robinson equation to get an understanding of the flare gas generation and the NGL recovery unit.

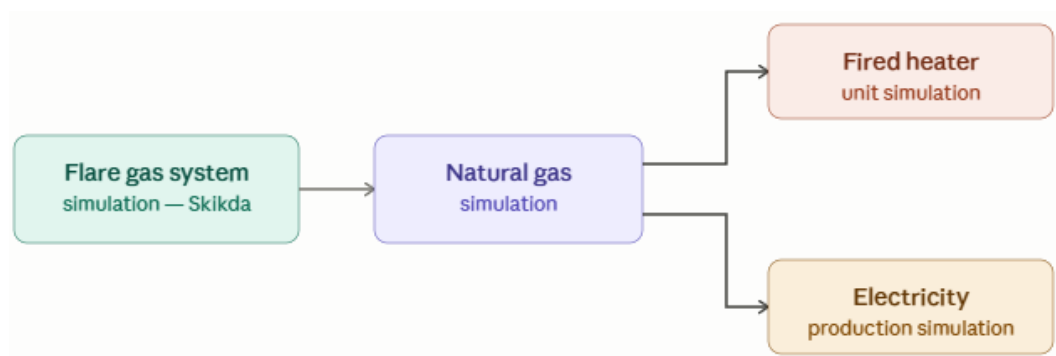


FIG.IV.1 : Simulation mode. [34]

IV.3. Efficiency of Separation and Optimization

This integrated scheme is a complex liquefied natural gas (LNG) production process associated with the flare gas recovery and value enhancement. The operation starts with a precooling of the feed gas (2,988 kmol/h, 30°C, 50 bar) by means of two heat exchangers down to -62°C, a temperature that permits initial two-phase separation in separator V-100. The liquid phase is then expanded to the demethanizer, while the vapor phase is expanded in a turboexpander to 28 bar to produce mechanical power and to drive partially compressor K-101 for recompression. After recompression to 70 bar by K-101 and K-102, the stream is split at a T-junction where 60% of the flow goes to gas turbines to generate power, and 40% to the flare. The vapor (Vap3 93.4% CH₄ and Vap9 79.7% CH₄) is the ideal fuel source and the liquid phase contain a lot of valuable heavy hydrocarbons like propane (53.5%) and butane (19.3%) liquid phases are rich in useful heavy hydrocarbon such as propane and butane. The flare stream (67.5% nitrogen, 10.7% CO₂, and 20.8% water vapor) enables good segregation from the contaminants and protects the quality of the product, while allowing an efficient waste-to-energy use of waste. The two-stage Brayton cycle system uses the flare gas (40% stream) as a fuel via controlled combustion (CRV-100) at 15 bar compression, turning gas that would be vented into a useful form of electrical power. The design ensures efficient heat integration in residual gas recycling loops, reduces the need for external refrigeration, enhances recovery of ethane, and provides for stable operation and environmental protection by controlled utilization of flare gas and power generation. The expanded combustion products flow through the three gas turbines (K-104, K-105, and K-107) to generate electricity. The feed gas, which is mostly methane (95%) and ethane (4%), is fully oxidized with oxygen to form carbon dioxide and water vapor in an exothermic reaction. Simulation results as presented in Tables 3 to 4 show that the output power of the turbine K-104 is 98.833 MW and 59.361 MW for both K-105 and K-107, respectively, as presented in

(FIGURE 5), The design parameters of the K-104 turbine are presented in (TABLE 2).

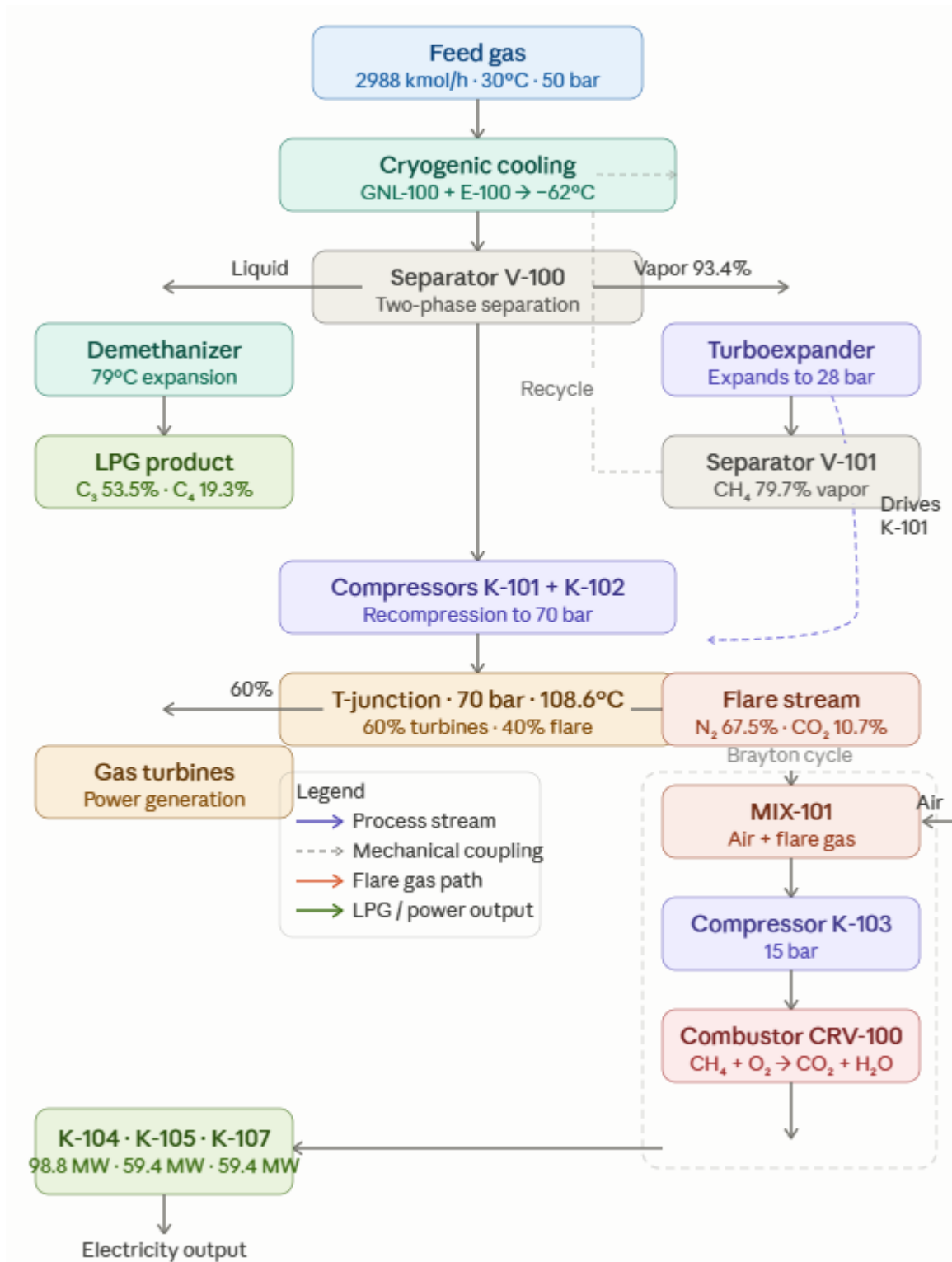


FIG.IV.2: Efficiency of Separation and Optimization schema. [34]

IV.4. Performance of electricity generation

The second path of valorisation is a two-stage turbine Brayton cycle. The flare gas (93.4% the of methane) is blended with air, compressed to 15 bar, burnt, and expanded in turbines. The following reactions dominate combustion are:

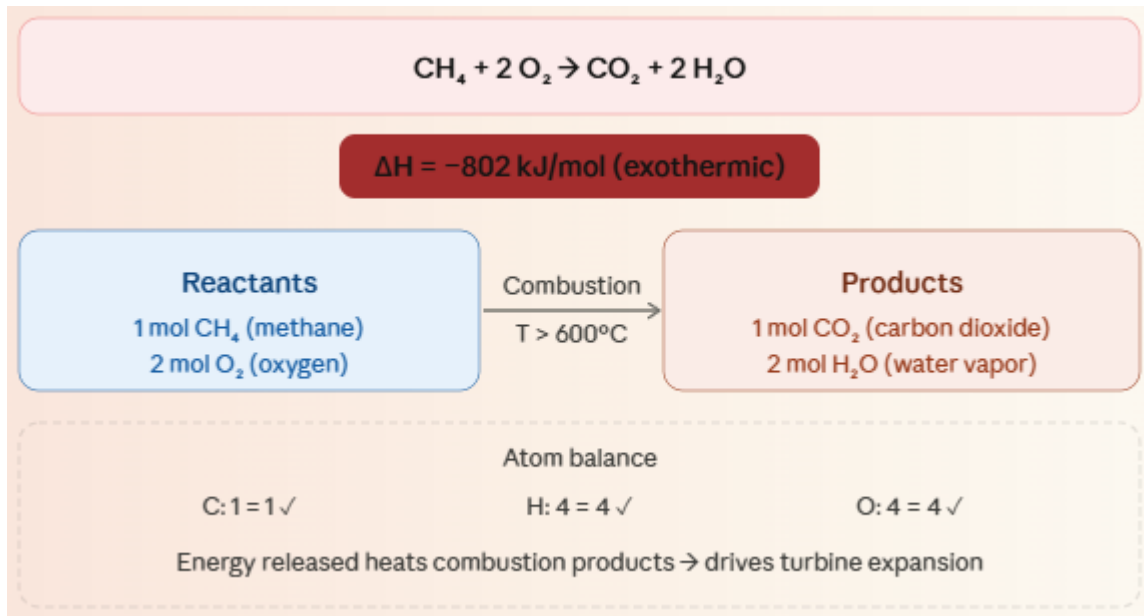


FIG.IV.3: reaction 1- methane combustion [34]

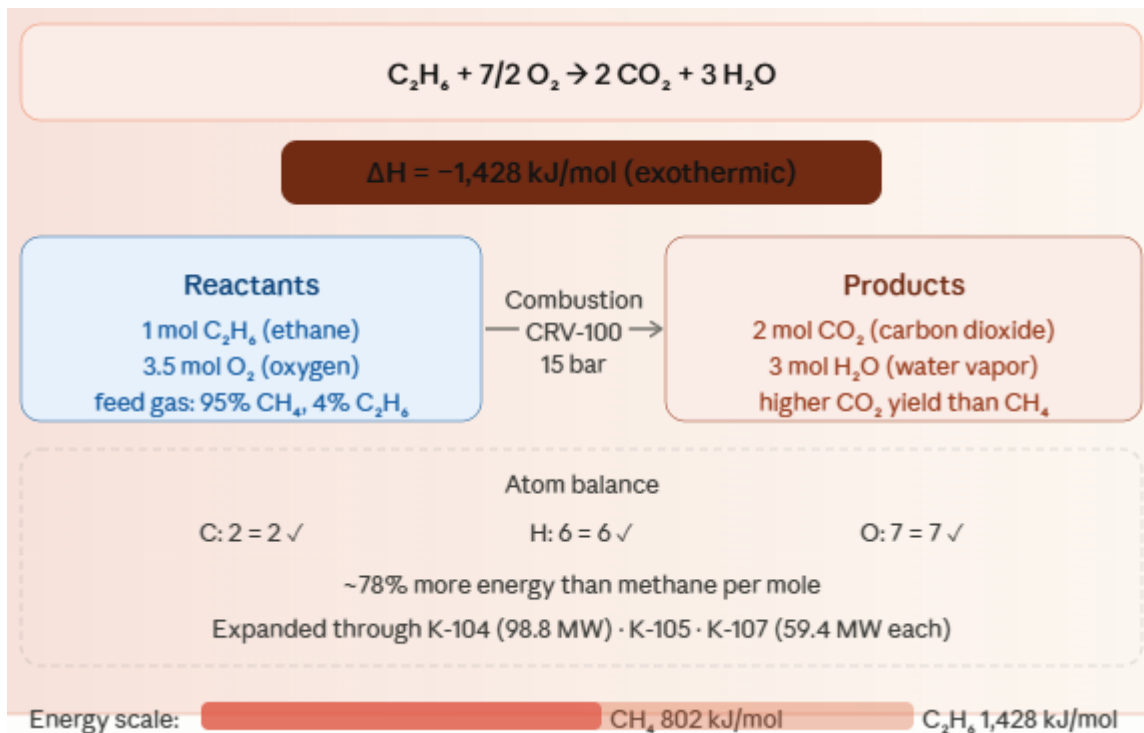


FIG.IV.4: reaction 2- Ethane combustion [34]

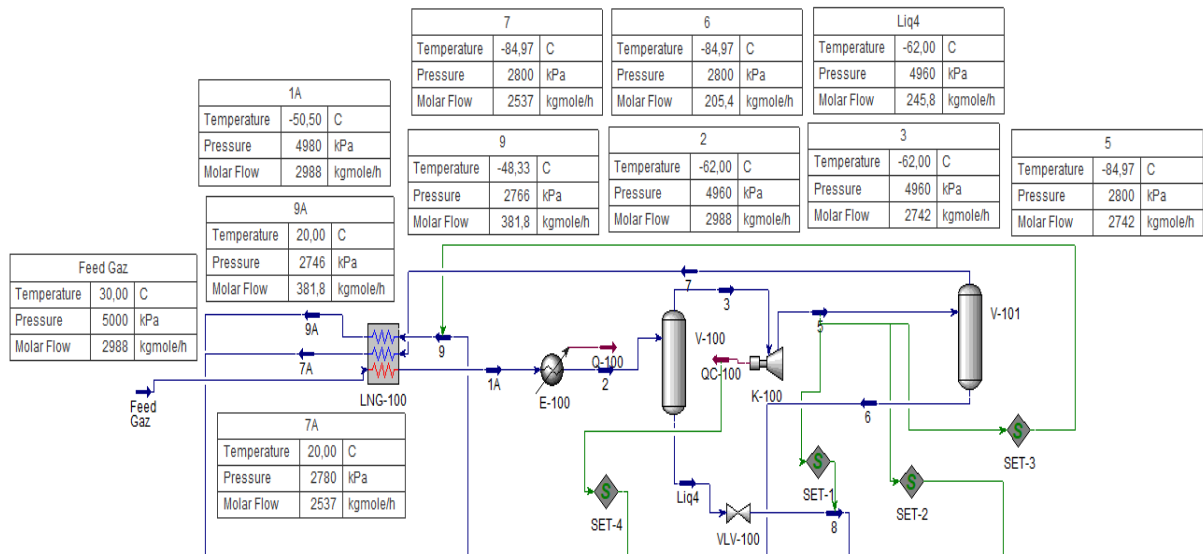


FIG.IV.5: Simulation of an Expander Natural Gas unit. [22]

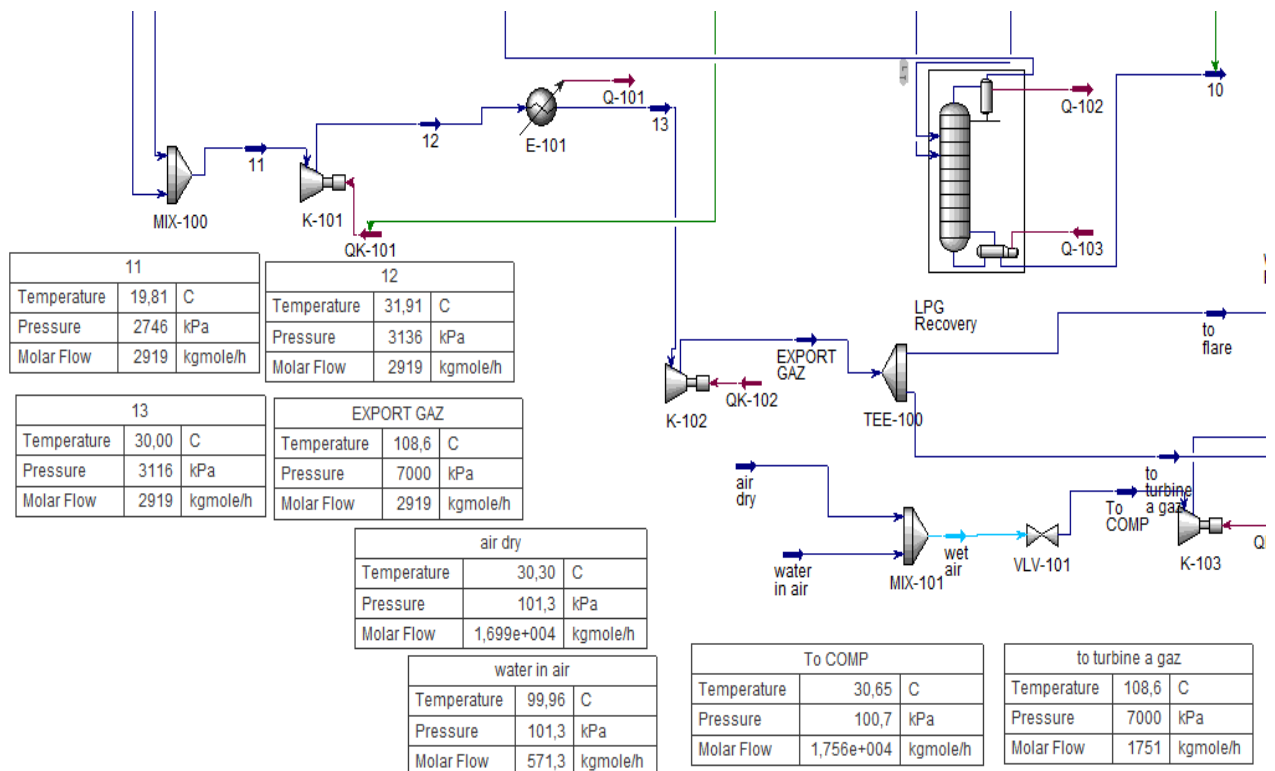


FIG.IV.6: Simulation of an Expander Natural Gas unit (continued). [22]

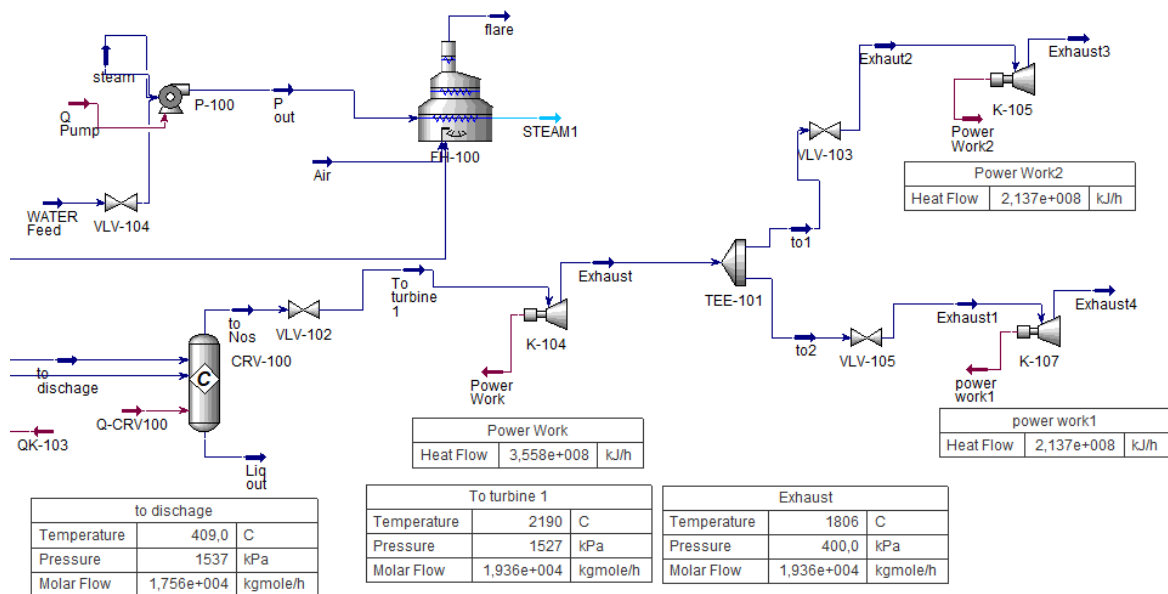


FIG.IV.7: Simulation of Fired Heater unit and Power generation (continued). [22]

PARAMETER	UNIT	K-101	K-102	K-103
Power	kW	332.1	2266	5.638e+4
Capacity (act feed vol flow)	ACT m³/h	2416	2202	4.401e+5
Feed Pressure	kPa	2746	3116	100.7
Product Pressure	kPa	3136	7000 *	1537
Product Temperature	°C	31.91	108.6	409.0
Adiabatic Head	m	1843	1.257e+4	3.676e+4
Polytropic Head	m	1852	1.292e+4	3.802e+4
Adiabatic Fluid Head	kJ/kg	18.07	123.3	360.5
Polytropic Fluid Head	kJ/kg	18.16	126.7	372.8
Adiabatic Efficiency	%	75	75	89 *
Polytropic Efficiency	%	75	77	92
Polytropic Head Factor	—	1.000	0.9993	1.003
Polytropic Exponent	—	1.454	1.435	1.426

TABLE.IV.1: parameter of compressor (K-101 · K-102 · K-103). [22]

PARAMETER	UNIT	K-100	K-104	K-105	K-107
Power	kW	332.1	9.883e+4	5.936e+4	5.936e+4
Capacity (act feed vol flow)	ACT m ³ /h	574.6	2.600e+5	4.184e+5	4.184e+5
Feed Pressure	kPa	4960	1527	400.0	400.0
Product Pressure	kPa	2800 *	400.0 *	50.00 *	50.00 *
Product Temperature	°C	-84.97	1806	1276	1276
Adiabatic Head	m	3465	9.096e+4	1.093e+5	1.093e+5
Polytropic Head	m	3513	9.410e+4	1.161e+5	1.161e+5
Adiabatic Fluid Head	kJ/kg	33.98	892.0	1071	1071
Polytropic Fluid Head	kJ/kg	34.45	922.8	1139	1139
Isentropic Efficiency	%	75	75	75	75
Polytropic Efficiency	%	74	72	71	71
Friction Loss	kW	0.0000	0.0000	0.0000	0.0000
Rotational Inertia	kg·m ²	6.000	6.000	6.000	6.000
Fluid Power	kW	332.1	9.883e+4	5.936e+4	5.936e+4
Polytropic Head Factor	—	0.9951	1.004	1.005	1.005
Polytropic Exponent	—	1.012	1.146	1.165	1.165
Isentropic Exponent	—	1.064	1.219	1.256	1.256

TABLE.IV.2: parameter of Expander (K-100 · K-104 · K-105 · K-107). [22]

STREAM	VAP. ...	TEMP (°C)	PRESS (...)	MOLAR FL...	MASS FLO...	LIQ. VOL (...)
Feed Gaz	 ...	30.00*	5000*	2988	5.287e+4	166.4
1A	 ...	-50.50	4980	2988	5.287e+4	166.4
7A	 ...	20.00	2780	2537	4.234e+4	137.3
9	 ...	-48.33	2766	381.8	7284	22.73
7	 ...	-84.97	2800	2537	4.234e+4	137.3
9A	 ...	20.00	2746	381.8	7284	22.73
2	 ...	-62.00*	4960	2988	5.287e+4	166.4
3	 ...	-62.00	4960	2742	4.691e+4	150.4
Liq4	 ...	-62.00	4960	245.8	5956	16.01
5	 ...	-84.97	2800	2742	4.691e+4	150.4
6	 ...	-84.97	2800	205.4	4565	13.10
8	 ...	-79.32	2800	245.8	5956	16.01
10	 ...	69.92	2800	69.44	3237	6.382
11	 ...	19.81	2746	2919	4.963e+4	160.0
12	 ...	31.91	3136	2919	4.963e+4	160.0
13	 ...	30.00*	3116	2919	4.963e+4	160.0
EXPORT GAZ	 ...	108.6	7000	2919	4.963e+4	160.0
air dry	 ...	30.30*	101.3*	1.699e+4	4.918e+5	564.1
water in air	 ...	99.96	101.3*	571.3*	1.029e+4	10.31
wet air	—	—	101.3	1.756e+4	5.021e+5	574.4
to flare	 ...	108.6	7000	1167	1.985e+4	63.99
to turbine a gaz	 ...	108.6	7000	1751	2.978e+4	95.99
To COMP	 ...	30.65	100.7	1.756e+4	5.021e+5	574.4
to discharge	 ...	409.0	1537	1.756e+4	5.021e+5	574.4
to Nos	 ...	2190	1527	1.936e+4	5.318e+5	635.3
Liq out	 ...	2190	1527	0.0000	0.0000	0.0000
To turbine 1	 ...	2190	1527	1.936e+4	5.318e+5	635.3
Exhaust	 ...	1806	400.0*	1.936e+4	2.659e+5	635.3

TABLE.IV.3: Material Stream. [22]

STREAM	VAP. ...	TEMP (°C)	PRESS (...)	MOLAR FL...	MASS FLO...	LIQ. VOL (...)
Exhaust2	 ...	1806	400.0	9680	2.659e+5	317.6
Exhaust3	 ...	1276	50.00*	9680	2.659e+5	317.6
Exhaust4	 ...	1276	50.00*	9679	2.659e+5	317.6
Air	 ...	25.00*	101.3*	1.013e+4	2.938e+5	335.4
flar	—	—	—	—	—	—
WATER Feed	 ...	25.00*	101.3*	27.75	500.0	0.5010
steam	 ...	25.00	91.32	27.75	500.0	0.5010
P out	 ...	25.07	831.3*	27.75	500.0	0.5010
flare	 ...	462.3	101.3	1.133e+4	3.136e+5	375.9
STEAM1	—	—	831.3	27.75	500.0	0.5010
to1	 ...	1806	400.0	9680*	2.659e+5	317.6
to2	 ...	1806	400.0	9679	2.659e+5	317.6
Exhaust1	 ...	1806	400.0*	9679	2.659e+5	317.6

TABLE.IV.4: Material Stream (continued) [22]

IV.5 Feed gas composition

Table 5 shows the detailed part composition for various streams of the simulation from the feed gas which is mainly composed of methane (91.22%), with small amounts of ethane (4.96%) and propane (1.48%), in addition to traces of heavier hydrocarbons, CO₂ (0.2%), and N₂ (1.49%). In V-100, phase separation is already occurring, and the vapor phase (Vap3) is rich in methane (93.4%) whereas heavier hydrocarbons are in the liquid phase (Liq4), showing the anticipated pattern, with lighter components in the vapor phase and heavier components condensed in the liquid. V-101 is experiencing a similar trend, with the vapor stream (Vap7) having a higher methane content (95.4%) and the liquid stream (Liq6) with more ethane and propane, as expected, since they are less volatile. The effectiveness of the LPG removal is confirmed in the liquid line (Liq10) that has the largest amounts of propane (53.5%) and butanes (19.3%), the main components of LPG, and the vapor line (Vap9) holds a lot of methane (79.7%) and ethane (18.4%). Streams that go to different units, like CRV-100 and FH-100, have different compositions; the turbine inlet is 93.4% methane, mainly while the Nos stream moves to higher amounts of CO₂ and H₂O. In the same way, the flare stream has a significant content of CO₂ (10.7%), nitrogen (67.5%) and H₂O (20.8%), indicative of good emissions control. In general, methane is still the predominant component in most of the streams, which shows that it is the main feed and product in vapor phases. Ethane, propane and heavier hydrocarbons can be separated with high efficiency into liquid streams, indicating that the process can recover valuable LPG components. The distributions of N₂, CO₂ and H₂O, on the other hand, show

that the method has been successfully applied to separate non-hydrocarbon species, at least in waste and flare gas.

Name	CH4 (Methane)	C2H6 (Ethane)	C3H8 (Propane)	i-C4 (i-Butane)	n-C4 (n-Butane)	i-C5 (i-Pentane)	n-C5 (n-Pentane)	n-C6 (n-Hexane)	CO2	N2 (Nitrogen)	O2 (Oxygen)	H2O	CO
Feed Gaz	0,9122	0,0496	0,0148	0,0026	0,0020	0,0010	0,0006	0,0003	0,0020	0,0149	0,0000	0,0000	0,0000
1A	0,9122	0,0496	0,0148	0,0026	0,0020	0,0010	0,0006	0,0003	0,0020	0,0149	0,0000	0,0000	0,0000
7A	0,9544	0,0255	0,0015	0,0000	0,0000	0,0000	0,0000	0,0000	0,0016	0,0169	0,0000	0,0000	0,0000
9	0,7974	0,1844	0,0087	0,0003	0,0001	0,0000	0,0000	0,0000	0,0049	0,0041	0,0000	0,0000	0,0000
7	0,9544	0,0255	0,0015	0,0000	0,0000	0,0000	0,0000	0,0000	0,0016	0,0169	0,0000	0,0000	0,0000
9A	0,7974	0,1844	0,0087	0,0003	0,0001	0,0000	0,0000	0,0000	0,0049	0,0041	0,0000	0,0000	0,0000
2	0,9122	0,0496	0,0148	0,0026	0,0020	0,0010	0,0006	0,0003	0,0020	0,0149	0,0000	0,0000	0,0000
3	0,9338	0,0399	0,0073	0,0007	0,0004	0,0001	0,0000	0,0000	0,0019	0,0159	0,0000	0,0000	0,0000
Liq4	0,6717	0,1575	0,0989	0,0235	0,0196	0,0110	0,0068	0,0036	0,0035	0,0040	0,0000	0,0000	0,0000
5	0,9338	0,0399	0,0073	0,0007	0,0004	0,0001	0,0000	0,0000	0,0019	0,0159	0,0000	0,0000	0,0000
6	0,6782	0,2186	0,0788	0,0091	0,0055	0,0014	0,0006	0,0001	0,0049	0,0028	0,0000	0,0000	0,0000
8	0,6717	0,1575	0,0989	0,0235	0,0196	0,0110	0,0068	0,0036	0,0035	0,0040	0,0000	0,0000	0,0000
10	0,0000	0,1901	0,5353	0,1083	0,0847	0,0429	0,0258	0,0129	0,0000	0,0000	0,0000	0,0000	0,0000
11	0,9339	0,0463	0,0024	0,0001	0,0000	0,0000	0,0000	0,0000	0,0020	0,0153	0,0000	0,0000	0,0000
12	0,9339	0,0463	0,0024	0,0001	0,0000	0,0000	0,0000	0,0000	0,0020	0,0153	0,0000	0,0000	0,0000
13	0,9339	0,0463	0,0024	0,0001	0,0000	0,0000	0,0000	0,0000	0,0020	0,0153	0,0000	0,0000	0,0000
EXPORT GAZ	0,9339	0,0463	0,0024	0,0001	0,0000	0,0000	0,0000	0,0000	0,0020	0,0153	0,0000	0,0000	0,0000
air dry	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,7671	0,2329	0,0000	0,0000
water in air	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,0000
wet air	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,7421	0,2253	0,0325	0,0000
to flare	0,9339	0,0463	0,0024	0,0001	0,0000	0,0000	0,0000	0,0000	0,0020	0,0153	0,0000	0,0000	0,0000
to turbine a gaz	0,9339	0,0463	0,0024	0,0001	0,0000	0,0000	0,0000	0,0000	0,0020	0,0153	0,0000	0,0000	0,0000
To COMP	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,7421	0,2253	0,0325	0,0000
to discharge	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,7421	0,2253	0,0325	0,0000
to Nos	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000
Liq out	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000
To turbine 1	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000
Exhaust	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000
Exhaust2	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000
Exhaust3	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000
Air	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,7528	0,2472	0,0000	0,0000
WATER Feed	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,0000
steam	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,0000
P out	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,0000
flare	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,1068	0,6748	0,0105	0,2079	0,0000
STEAM1	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,0000
to1	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000
to2	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000
Exhaust1	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0937	0,6747	0,0197	0,2119	0,0000

TABLE.IV.5: Composition of streams of simulation [22]

IV.6 Economic evaluation

An economic analysis for both routes was carried out with a break-even point (B.E.P.) analysis including capital expenditure (CAPEX), operation costs, fixed charges, and net profits. The rate of return on investment (ROR) was estimated as follows:

$$ROR = \left(\frac{\text{Annual Profit}}{\text{Capital Investment}} \right) \times 100$$

Key Findings

- **Payback Period:** 2.83 years (NGL) vs. 2.33 years (Power)
- **Annual Net Profit :** \$1.24 million (NGL) vs. \$14.06 millions (Power)
- **Major Equipment Cost:** \$5.2 million (NGL) vs. \$102.18 million (Power)
- **Utility Cost:** \$12.4/hour (NGL) vs. \$10,161.60/hour (Power)

Although the investment in major equipment is 19.6 times higher, the power generation route obtains a 11.4 times higher net profit, which confirms its economic superiority.

Details of economics and breakdown of units

These calculations indicate that, with an annual net profit of \$1,235,510, the breakeven point for the investment in the compression NGL recovery unit is approximately 2 years and 10 months (2.8 years).

In the case of the power production alternative, the two-stage Brayton cycle system is driven by the controlled combustion of the 40% waste flare gas stream. This design includes three gas turbines (K-104, K-105, and K-107) for a total power of 217.56 MW. Specifically, the simulation result of turbine K-104 shows an output power of 98.833 MW, while that of K-105 and K-107 are 59.361 MW each. The capital investment, earnings and return statements for this power production scale are shown in Figs. 6 and 7. To this end, the facility needs a Total Capital Investment of \$94,139,800, a Total Equipment Investment of \$102,181,400 and a Total Installed Cost of \$106,470,100. The plant operating cost is \$103,575,000/year, which is largely dominated by a substantial Total Utilities Cost of \$89,076,500/year (equivalent to \$10,161.60/h for all active process utilities).

A detailed analysis of individual processing steps shows where the capital and utility costs are heavily concentrated:

- The Power Block & Recompression Systems: The single most costly component in the entire plant configuration is the sixteen-stage compressor/turbine assembly K-103, which necessitates a mind-boggling equipment cost of \$98,541,000 (\$100,910,000 installed), and incurs a huge utility cost of \$2,889.59 /h. Recompression unit K-102 has an equipment cost of \$2,010,200 (\$2,270,400 installed) and a utility burden of \$202.271/hour. In addition, the system FH-100 consumes the largest amount of hourly utilities with \$6,985.21/hour (equaling to the total process fuel consumer cost).
- The Cooling & Separation Loop: Yet smaller units based on the aforementioned 2,988 kmol/h feed gas precooling down to -62°C have negligible cost effect. The two-phase separator V-100 has an investment cost of \$50,900 (\$228,600 installed), and the primary feed gas heat exchanger E-100 has a price of \$36,800 (\$395,900 installed) an utility use of \$0.2522/hour and the liquid pump P-100 stands as the baseline minimum featuring an equipment cost of just \$6,100 (\$36,200 installed) and a utility cost of \$0.014725/hour.

Unit / Tag	Cost (USD)		Weight (LBS)		Utility Cost (USD/HR)
	Equipment	Installed	Equipment	Installed	
LPG Recovery	System total				
Total	\$102,300	\$441,500	18,750	51,597	33.726
Individual Equipment					
E-100	\$26,100	\$287,700	5,500	23,680	0.2522
E-101	\$9,400	\$77,600	560	8,708	0.2443
EX-100	\$220,100	\$361,000	11,500	17,567	—
K-101	\$869,100	\$1,045,100	12,200	32,984	26.017
K-102	\$1,605,700	\$1,806,300	35,900	61,809	202.353
K-103	\$79,566,600	\$81,429,000	1,287,200	1,653,224	2,890.75
P-100	\$4,900	\$29,500	210	2,228	0.0147
V-100	\$34,100	\$169,200	11,800	28,013	—
V-101	\$27,300	\$157,400	7,800	23,433	—

TABLE.IV.6: Composition of streams of simulation. [22]

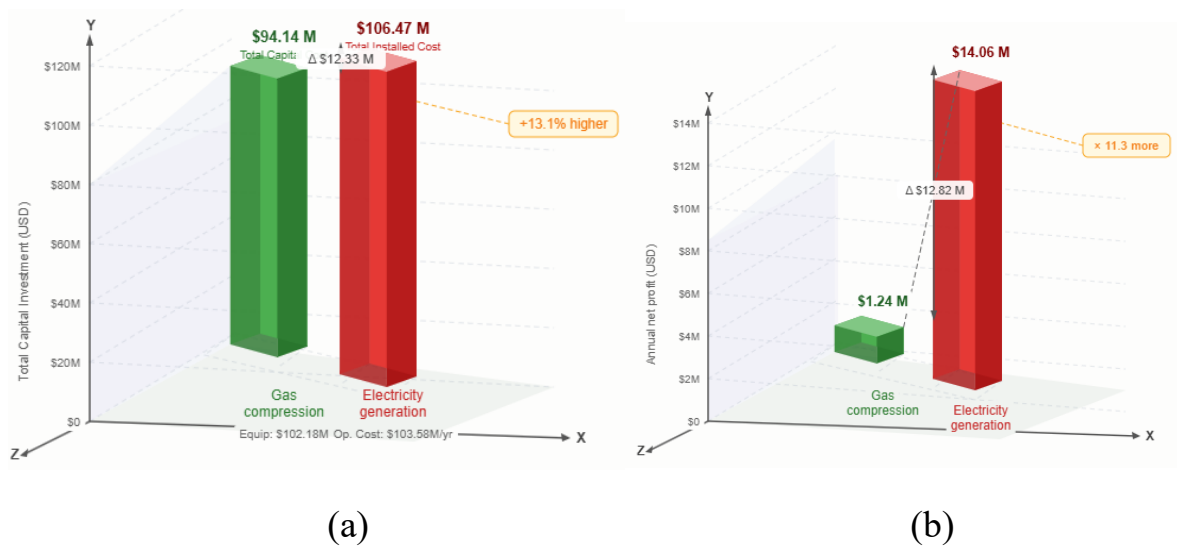


FIG. IV.8: A comparison between (a) total capital investments, and (b) annual profits. [34]

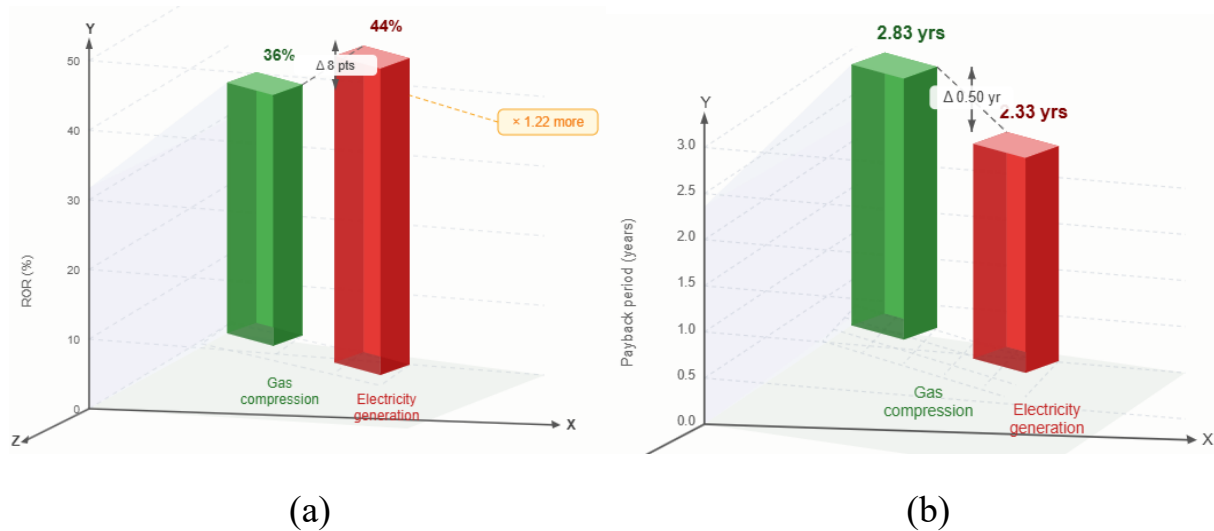


FIG.IV.9: A comparison between (a) rates of return for capacity increment, and (b) payback period. [34]

IV.7 Environmental Impact and Risk Analysis

IV.7.1. Emission Reduction Potential

Recovery and upgrading of flare gas turns an environmental burden into a powerful decarbonization tool:

- **Gas flaring diversion:** This process allows the capture of 93.4% of CH_4 (based on the Vap3 composition), avoiding the direct venting of about 4.8×10^5 tonnes of CO_2 equivalent per year.
- **Grid Displacement:** Production of 217.56 MW of power through two-stage Brayton cycle enables the replacement of dirtier fossil fuel-based energy, leading to a reduction in indirect emissions by approximately 1.1 million tonnes CO_2/yr .

IV.7.2. Scenario Risk Assessment

The risk analysis underscores the balance between the simplicity of operations of the NGL recovery process and the high economic performance of the "Power" scenario:

- **Price Volatility:** Moderate (LPG market) vs High (Electricity tariffs)
- **Technical Complexity:** Low (Liquid/gas separation) vs High (Turbomachinery)
- **Regulatory Incentives:** Limited (LPG) vs High (Carbon & Renewable credits).

IV.8 Comparative Evaluation of Power Generation and Stream Profiles Bid Boland (Iran) vs Skikda (Algeria)

A full comparison reveals that the Iranian Bid Boland gas stream yields the highest power output of 223.07 MW in the process arrangement, which is well above the Algerian Skikda stream with the lowest power output of 217.58 MW. This 5.49 MW thermodynamic difference is essentially determined by the design parameters given in Table.IV.7 and Table.IV.8. The higher content of fractional intermediate hydrocarbures (C_2H_6 and C_3H_8) in the Bid Boland stream gives a more concentrated calorific matrix. On the other hand, the Skikda feed, a high purity methane source, also suffers a slight energy loss due to the sensible heat content of its 1.49% nitrogen content, an internal thermal ballast in the simulation environment.

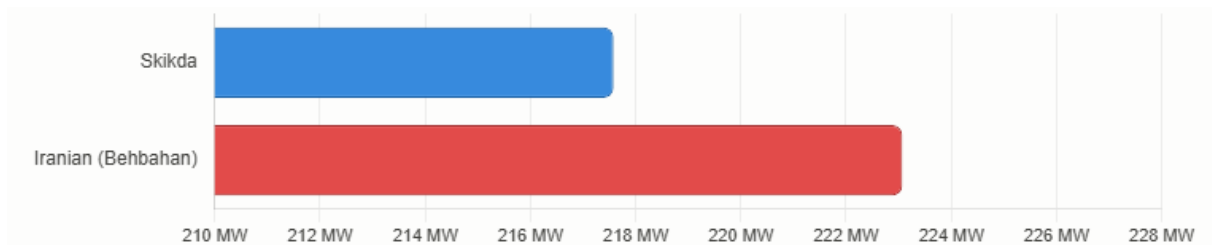


FIG.IV.10: Power output side by side. [34]

IV.8.1 Thermodynamic Discussion and Chemical Profile Analysis

The results of the simulation show a positive net power of 5.49 MW for the Bid Boland system (223.07 MW) over the Skikda system (217.58 MW)). This difference is simply determined by the thermodynamic properties of the base materials:

- **Hydrocarbon Richesse (C_2+ Fractions)** Although the Skikda Stream Table.IV.8 shows a very high level of methane purity (91.22%), the Iranian stream Table.IV.7 is a “rich” gas in terms of composition, with 12% Ethane and 3.5% Propane. Heavier alkanes have much larger molar LHVs compared than that of pure methane from thermodynamic calculations. When this richer molecular composition is fed into a combustion or power generation cycle in Aspen HYSYS, it increases the specific energy density of the fuel and leads to more thermal energy delivered per unit volume of fuel.
- **Effect of Dilution by Inerts** the Skikda feed mixture Table.IV.8 contains a significant inert component made up of 1.49% Nitrogen (N_2) and 0.20% Carbon Dioxide (CO_2). Since these molecules are strictly non-reactive during combustion, they don’t have any role in the energy output. They serve as a thermal mass that extracts sensible heat from

the zone of combustion and needs to be compressed more, thereby exerting an intrinsic limitation on the upper value of electrical efficiency of the turbine cycle.

- **apor-Liquid Equilibrium (VLE) Discrepancies (Table.IV.7)** manifests a significant technical flaw in the difference in composition of the Fractions Molaires and Phase Vapeur (for example 1.47% Nitrogen, 0.20% CO₂ entre dans la phase vapeur). This means that the Iranian simulation represents an upstream flash separation (equilibrium stage). This vapor liquid equilibrium (VLE) splitting changes the real-time composition of the gas at the inlet of the power cycle, and thus leads to the requirement of using rigorous equations of state (EOS) (e.g., Peng-Robinson) in order to accurately track the phase envelopes [33].

IV.8.2 Industrial Philosophy & Strategic Destination

The structural contrasts of the two sets of data reveal two separate industrial mindsets:

- **The Iranian Facility (Bid Boland Field)** This arrangement serves as an onshore, conservation-based recovery mechanism. Its main engineering objective is to capture flaring associated rich gas streams, send the heavy fractions (C₂, C₃, C₄) to petrochemical crackers and produce high-power domestic electricity.
- **Algerian infrastructure (Skikda Complex)** This functions as a significant coastal, export focused terminal. As its main function is cryogenic liquefaction (liquid natural gas (LNG) production), the feed stream should be a lean, very homogeneous methane-rich gas. There are more stringent limits applied to the heavier fractions (C₅+) and acids to systematically avoid freezing or plugging of the MCHEs (main cryogenic heat exchangers) with solid.

TABLE.IV.7 : iranian (behbahan, khuzestan) natural gas composition.[32]

Composant	Fractions Molaires	Phase Vapeur
Méthane	0,8300	0,8300
Éthane	0,1200	0,1200
Propane	0,0350	0,0350
i-Butane	0,0050	0,0050
n-Butane	0,0100	0,0100
i-Pentane	0,0000	0,0000
n-Pentane	0,0000	0,0000
n-Hexane	0,0000	0,0000
CO ₂	0,0000	0,0000
Nitrogen	0,0000	0,0000
Oxygène	0,0000	0,0000
H ₂ O	0,0000	0,0000
CO	0,0000	0,0000

Table.IV.8: skikda natural gas composition.[33]

Composant	Fractions Molaires	Phase Vapeur
Méthane	0,9122	0,9122
Éthane	0,0496	0,0496
Propane	0,0148	0,0148
i-Butane	0,0026	0,0026
n-Butane	0,0020	0,0020
i-Pentane	0,0010	0,0010
n-Pentane	0,0006	0,0006
n-Hexane	0,0003	0,0003
CO ₂	0,0020	0,0020
Nitrogen	0,0149	0,0149
Oxygène	0,0000	0,0000
H ₂ O	0,0000	0,0000
CO	0,0000	0,0000

IV.9 Conclusion

The time-based evaluation proved the technical feasibility of both NGL recovery and power generation options. rate is higher power obtained (217.56 MW), the environmental benefits related to CO₂ emission are higher (about 1.1 million tonnes of CO₂ per year are avoided), and the economic profitability is greater (about 11.3 times higher net profit with the shortest payback period of 2.33 years). Although it comes with higher complexity and capital costs (102.18 million for key equipment), its scalability and unmatched annual net profit of \$14.06 million with the alignment of global climate policy goals makes it the best option for efficient flare gas recovery at the Skikda refinery.

General conclusion

General conclusion

Worldwide gas flaring has long been a major environmental waste and a significant source of greenhouse gases and local air pollution. Driven by increasingly stringent environmental regulations and growing ecological consciousness, modern refineries are now designed and operated with a strong focus on minimizing flaring as a vital means of balancing environmental sustainability with economic viability.

While the Flare Gas Recovery (FGR) system is an efficient solution for recovering low-pressure off-gases, it introduces a unique engineering paradox: the compression systems required for these streams demand substantial electrical power, creating an indirect carbon footprint from power generation that must be carefully managed. To resolve this trade-off for the Skikda gas refinery, a steady-state simulation model was established using Aspen HYSYS. This model demonstrated that continuous gas recovery is structurally and safely feasible across one-, two-, and three-stage compression configurations.

A critical time-based evaluation further confirmed the technical feasibility of both NGL recovery and direct power generation options. The comprehensive assessment definitively showed that while both are viable, directing the captured gas to a turbine network for direct electricity production is the superior financial and environmental strategy. This route demonstrably outperforms NGL recovery, yielding a significantly higher power output (217.56 MW), generating a considerably larger annual net profit—roughly 11.3 times greater—and achieving the shortest payback period of just 2.33 years. Moreover, this approach provides substantial environmental benefits by avoiding approximately 1.1 million tonnes of CO₂ emissions annually.

The performance measures for this optimization identify a design sweet spot with two gas turbines in series utilizing a conveyance pipeline of 0.0889m internal diameter, which achieves the maximum annual net profit at a perfectly balanced capital investment. Although this option entails higher complexity and upfront capital costs (USD 102.18 million for key equipment), its unmatched annual net profit of \$14.06 million and exceptional scalability make it the best option for efficient flare gas recovery. This alignment with global climate policy goals and the ability to transform a legacy waste stream into high-yield, sustainable utility power ultimately offers a replicable, data-driven blueprint for the development of modern, sustainable refining infrastructure.

References

- [1] Speight, J. G. (2014). *The Chemistry and Technology of Petroleum* (5th ed.). CRC Press.
- [2] Karellas, S., Kakaras, E., & Papageorgiou, S. K. (2016). Flare Gas Recovery in Refineries: Technologies and Applications. *Energy Procedia*, 88, 500–507.
- [3] Gary, J. H., Handwerk, G. E., & Kaiser, M. J. (2007). *Petroleum Refining: Technology and Economics* (5th ed.). CRC Press.
- [4] Mokhtab, S., Poe, W. A., & Mak, J. Y. (2015). *Handbook of Natural Gas Transmission and Processing* (4th ed.). Gulf Professional Publishing.
- [5] Boyce, M. P. (2012). *Gas Turbine Engineering Handbook* (4th ed.). Elsevier.
- [6] SONATRACH. (2021). *Rapport Annuel de Développement Durable*. Algeria.
- [7] United Nations. (1992). *Rio Declaration on Environment and Development*.
- [8] API Standard 521. (2014). *Pressure-relieving and Depressuring Systems*.
- [9] International Energy Agency (IEA). (2010). *World Energy Outlook*.
- [10] Global Gas Flaring Reduction Partnership (GGFR). (2019). *Associated Gas Utilization*.
- [11] Le Figaro. (2008). *Gaz : 150 milliards de mètres cubes gaspillés par an*.
- [12] Bay Area Air Quality Management District. *Petroleum Refinery Emissions Inventory Guidelines*.
- [13] U.S. Environmental Protection Agency (EPA). *Flare Gas Recovery Systems – Technical Overview*.
- [14] Soltanieh, M. (2016). *Review of Global Gas Flaring and Venting*.
- [15] European Environment Agency. *EMEP/EEA Emission Inventory Guidebook*.
- [16] Center for Chemical Process Safety (CCPS). *Guidelines for Pressure Relief Systems*.
- [17] World Bank. (2020). *Gas Flaring Explained*.
- [18] International Energy Agency. (2021). *Global Gas Flaring Reduction Reports*.
- [19] American Petroleum Institute. *Flare Gas Recovery and Utilization Guidelines*.
- [20] International Monetary Fund. (2021). *Project Financial Evaluation*.
- [21] Moran, M.J., Shapiro, H.N., *Fundamentals of Engineering Thermodynamics*, Wiley, 2010.
- [22] Aspen Technology, *Aspen HYSYS User Guide and Process Modeling Manual*, 2022.
- [23]. Yunus A. Çengel & Michael A. Boles, *Thermodynamics: An Engineering Approach*, McGraw-Hill.
- [24] John M. Prausnitz et al., *Molecular Thermodynamics of Fluid-Phase Equilibria*.
- [25] J. M. Campbell, *Gas Conditioning and Processing*, vol. 2: *The Equipment Modules*, 9th ed., Campbell Petroleum Series, Norman, Oklahoma, 2014.
- [26] A. Kidnay, W. Parrish, and D. McCartney, *Fundamentals of Natural Gas Processing*, 2nd ed., CRC Press, Boca Raton, Florida, 2011.

- [27] D.-Y. Peng and D. B. Robinson, "A new two-constant equation of state," *Industrial & Engineering Chemistry Fundam*
- [28] Smith, J.M., Van Ness, H.C., Abbott, M.M., *Introduction to Chemical Engineering Thermodynamics*, McGraw-Hill, 2005.
- [29] Moran, M. J., & Shapiro, H. N. *Fundamentals of Engineering Thermodynamics*. Wiley, 2018.
- [30] Çengel, Y. A., & Boles, M. A. *Thermodynamics: An Engineering Approach*. McGraw-Hill, 2019.
- [31] Sonntag, R. E., Borgnakke, C., & Van Wylen, G. J. *Introduction to Engineering Thermodynamics*. Wiley, 2017.
- [32] National Iranian Gas Company [NIGC]. (2016). *Natural Gas Industry in Iran: Associated Gas Properties and Production Criteria*. Technical Report, Tehran, Iran.
- [33] Brahim Mahfoud, Hibet E. Mahfoud, "Study on converting flare gas into usable energy at the SKIKDA gas refinery" *Studies In Engineering And Exact Sciences* 6(1):e13358, January 2025; DOI: 10.54021/seesv6n1-010
- [34] Authors' own work – Aspen HYSYS simulation. Bouchenak M. & Nadji Y. (2026).