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dedication

To whom I prefer it to myself, and why not; She sacrificed for me She spared no effort in making me happy always (My beloved mother). We walk the paths of life, and someone remains in control of our minds in every path we take He has a kind face and good deeds. He did not despise me throughout his life (My dear father). To my friends, and all those who stood by me and helped me with everything they had, in many ways I present this research to you, and I hope that it will satisfy you

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Abstract:

In recent years, gas turbines partially fueled by hydrogen have emerged as a promising solution for power generation, offering reduced carbon emissions and improved combustion efficiency. The MS5002C gas turbine, introduced in the 1970s and continually upgraded, exemplifies this trend with its dual-shaft design for heavy-duty service. Our study involved partially injecting hydrogen into the MS5002C's combustion chambers to assess its impact. Results showed that blending hydrogen with conventional fuels like natural gas lowered carbon emissions and enhanced combustion efficiency. This technology also supports renewable energy integration, with hydrogen serving as an energy storage medium. However, challenges remain in infrastructure and cost. Nonetheless, gas turbines like the MS5002C represent a significant stride towards sustainable energy production.

Key words: Gas turbines, Thermal efficiency, Temperature, Hydrogen injection

ملخص:

في السنوات الأخيرة، اكتسبت التوربينات الغازية المغذاة جزئياً بالهيدروجين اهتماماً كبيراً كحل مبتكر لتوليد الطاقة، نظراً لقدرتها على تقليل انبعاثات ثاني أكسيد الكربون وتحسين كفاءة الاحتراق. يعد توربين الغاز MS5002C، الذي تم تقديمه في السبعينات وتم تحديثه وترقيته على مر السنين، نموذجاً بارزاً في هذا المجال. يتميز MS5002C بتصميم ثنائي العمود للخدمة الشاقة، مما يسمح له بتحقيق كفاءة تشغيل عالية في ظروف متنوعة من السرعة والحمل.

في إطار دراستنا، تم حقن الهيدروجين جزئياً في غرف الاحتراق لتوربين MS5002C بهدف دراسة تأثيرات هذا الحقن على أداء التوربين. أظهرت النتائج أن مزج الهيدروجين بالوقود التقليدي مثل الغاز الطبيعي يسهم في تقليل انبعاثات ثاني أكسيد الكربون بفضل الاحتراق النظيف للهيدروجين، الذي ينتج عنه بخار الماء فقط كمنتج ثانوي. كما يعزز هذا المزج من كفاءة الاحتراق، نظراً لسرعة الاشتعال العالية للهيدروجين والناتج الحراري الأكبر مقارنة بالغاز الطبيعي.

تُسهم هذه التقنية أيضاً في دعم تكامل الطاقة المتجددة، حيث يمكن استخدام الهيدروجين كوسيلة لتخزين الطاقة من مصادر مثل الشمس والرياح وتحويلها لاحقاً إلى كهرباء. ومع ذلك، يواجه هذا التطور تحديات تتعلق بالبنية التحتية اللازمة لتخزين ونقل الهيدروجين بأمان، بالإضافة إلى التكلفة المرتفعة لإنتاج الهيدروجين ونقله. تتواصل الأبحاث لتطوير تقنيات اقتصادية وفعالة لإنتاج الهيدروجين، مثل التحليل الكهربائي للماء باستخدام الطاقة المتجددة، مما يعزز من الجدوى الاقتصادية والبيئية لهذه التقنية.

بهذا يمكن اعتبار التوربينات الغازية المغذاة جزئياً بالهيدروجين، مثل توربين MS5002C، خطوة متقدمة نحو مستقبل أكثر استدامة في توليد الطاقة، من خلال تقليل الانبعاثات الكربونية وتحسين كفاءة استغلال الوقود.

الكلمات المفتاحية: التوربينات الغازية , الكفائة الحرارية, درجة الحرارة , الحقن بالهيدروجين

Résumé :

Ces dernières années, les turbines à gaz partiellement alimentées en hydrogène ont attiré l'attention en tant que solution innovante de production d'énergie, en raison de leur capacité à réduire les émissions de dioxyde de carbone et à améliorer l'efficacité de la combustion. La turbine à gaz MS5002C, introduite dans les années soixante-dix et modernisée et améliorée au fil des ans, est un modèle de premier plan dans ce domaine. Le MS5002C est doté d'une conception robuste à double colonne, ce qui lui permet d'atteindre une efficacité de fonctionnement élevée dans une variété de conditions de vitesse et de charge.

Dans le cadre de notre étude, de l'hydrogène a été partiellement injecté dans les chambres de combustion de la turbine MS5002C dans le but d'étudier les effets de cette injection sur les performances de la turbine. Les résultats ont montré que le mélange de l'hydrogène avec des carburants conventionnels tels que le gaz naturel contribue à réduire les émissions de dioxyde de carbone grâce à la combustion propre de l'hydrogène, qui ne produit que de la vapeur d'eau comme sous-produit. Ce mélange améliore également l'efficacité de la combustion, en raison de la vitesse d'allumage élevée de l'hydrogène et de la puissance thermique supérieure à celle du gaz naturel.

Cette technologie soutient également l'intégration des énergies renouvelables, car l'hydrogène peut être utilisé comme moyen de stocker l'énergie provenant de sources telles que le soleil et le vent, puis de la convertir en électricité. Cependant, ce développement se heurte à des défis liés à l'infrastructure nécessaire pour stocker et transporter l'hydrogène en toute sécurité, ainsi qu'au coût élevé de la production et du transport de l'hydrogène. La recherche continue de développer des technologies de production d'hydrogène économiques et efficaces, telles que l'électrolyse de l'eau à l'aide d'énergies renouvelables, ce qui améliore la viabilité économique et environnementale de cette technologie.

Les turbines à gaz partiellement alimentées à l'hydrogène, telles que la turbine MS5002C, peuvent être considérées comme un pas vers un avenir plus durable dans la production d'électricité, en réduisant les émissions de carbone et en améliorant l'efficacité énergétique.

Mots clés : Turbines à gaz , Efficacité thermique, Température , Injection d'hydrogène

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Nomenclature

Symbol	Designation	Unit in S.I
$\dot{Q}$	Masse Flow rate	**Kg/s**
P	Pressure	**bar**
T	Temperature	**K**
LVH_i	The lower heating value	**Kcal/m^3**
LVH_{cs}	The higher heating value	**Kcak/m^3**
ΔP	Pressure drop	**bar**
N	Rotation speed	**Tr/min**
Z	Altitude	**m**
M	Atomic mass	**g/mol**
V	Volume	**m^3**
m_C	Fuel mass	**g**
n	Mole count	**mol**
P_U	Useful power	**Kw**
R	deal gas constant	**J/mol.K**
U	Internal energy	**J**
W	Work	**J**
Q	Heat	**J**
h	Enthalpy	**J**
Cp	specific heat	$\frac{Kj}{Kg}.K$

Latin Term

τ_C	Compression ratio
η	Efficiency
γ	IsentropicVariable
λ	Air excess coefficient
K	IsentropicVariable air
	Indices
adm	Intake
t	Turbine
c	Compressor
H_P	High pressure
B_P	Low pressure
C.C	Combustion chamber
th	Thermal

General introduction

General introduction:

Gas turbines are essential components in the power generation and industrial sectors due to their high efficiency and operational flexibility. Recently, there has been increasing interest in integrating hydrogen as a fuel to reduce greenhouse gas emissions and promote sustainable energy solutions. This study explores the concept of partially hydrogen-fueled gas turbines, with a specific focus on the MS5002C turbine model used by Sonatrach, Algeria's state-owned oil and gas company. The MS5002C is a robust and versatile gas turbine designed for both mechanical drive and power generation applications. Known for its reliability and efficiency, this model is widely utilized in various industrial settings, including oil and gas operations. The MS5002C features advanced combustion systems capable of operating on a variety of fuels, including natural gas and liquid fuels.

Integrating hydrogen into gas turbines offers several significant benefits. Hydrogen combustion produces only water vapor, resulting in zero carbon dioxide (CO_2) emissions, significantly reducing the environmental footprint of gas turbine operations. Hydrogen also has a higher energy content per unit mass compared to natural gas, potentially improving turbine efficiency and performance. Utilizing hydrogen in existing gas turbines, such as the MS5002C, supports a gradual transition to cleaner energy sources without requiring extensive infrastructure changes. However, integrating hydrogen as a fuel also presents several challenges. Hydrogen has different combustion characteristics compared to natural gas, such as higher flame speeds and lower ignition energy, which can affect combustion stability and efficiency. Additionally, hydrogen can cause embrittlement in certain metals, posing challenges for the durability and integrity of turbine components. Hydrogen storage and distribution require advanced infrastructure due to its low energy density by volume and the need for high-pressure storage solutions[1].

Active research is focused on addressing these challenges. Key areas include optimizing hydrogen-natural gas blends, developing advanced combustion technologies, and improving materials to withstand hydrogen’s unique properties. This research aims to enhance turbine efficiency, significantly reduce emissions, and promote sustainable energy solutions by integrating hydrogen fuel into gas turbines[2].

This study provides a general overview of different types of hydrogen, its extraction, production, and applications. It also includes a description of Sonatrach, where we completed our internship, and discusses the operation of gas turbines and their main components. The

MS5002C gas turbine is described in detail, and the calculation part involves computing the isentropic efficiency and temperatures at all points in the Brayton cycle. We also varied the gas flow with partial hydrogen addition and compared the results. The study concludes with a summary of the findings, highlighting the potential of integrating hydrogen into gas turbines to achieve enhanced efficiency and reduced emissions.

Chapter I:

Hydrogen

I.1 Introduction:

Hydrogen is a clean, efficient, and versatile energy carrier, which together with electricity, may satisfy all the energy needs and form an energy system that would be permanent and independent of energy sources . It has unique characteristics that make it an ideal energy carrier which include the fact that: it can be produced from and converted into electricity at relatively high efficiencies; its raw material for production is water available in abundance [3].

it is a completely renewable fuel; it can be stored in gaseous form (convenient for large scale storage), in liquid form (convenient for air and space transportation), or in the form of metal hydrides (convenient for surface vehicles and other relatively small scale storage requirements) ; it can be transported over large distances through pipelines or via tankers; it can be converted into other forms of energy in more ways and more efficiently than any other fuel (such as catalytic combustion, electro chemical conversion, and hydrating); it is environmentally compatible as its production, storage, transportation, and end-use do not produce any pollutants (except for small amounts of nitrogen oxides), greenhouse gases, or any other harmful effects on the environment.

Electricity and hydrogen are produced in large industrial plants as well as in small, decentralized units, wherever the primary energy source (solar, nuclear, and even fossil) is available. Electricity is used directly or transformed into hydrogen. For large-scale storage, hydrogen can be stored underground in ex-mines, caverns and/or aquifers. Energy transport to the end-users, depending on distance and overall economics, is either in the form of electricity or in the form of hydrogen. Hydrogen may be transported, by means of pipelines or super tankers. It is then u sed in transportation, industrial, residential, and commercial sectors as a fuel. Some of it may be used to generate electricity via fuel cells, depending on demand, geographical location or time of the day[3].

I.2. Origin and history:

The history of hydrogen is marked by remarkable scientific discoveries, technological breakthroughs, but also tragedies. Initially identified in the 18th century, hydrogen's properties and applications have evolved significantly over time. Jan Baptista van Helmont's rejection of Aristotle's elements and Robert Boyle's experiments laid the groundwork for understanding hydrogen's role. Despite challenges like the phlogiston theory, scientists like Henry Cavendish and Antoine Lavoisier contributed to clarifying hydrogen's nature. The discovery of electrolysis by Nicholson and Carlisle in 1800 and the subsequent synthesis of ammonia by Fritz Haber in

1909 expanded hydrogen's applications. Hydrogen's role in the Hindenburg disaster and the development of the hydrogen bomb during World War II underscored its dual nature of potential and peril. The 20th century witnessed advancements like the invention of the fuel cell by Sir William Grove in 1839 and the discovery of isotopes like deuterium and tritium. Today, hydrogen continues to be a key element in various fields, from energy storage to industrial processes, driving research into safer storage methods and efficient utilization [4].

I.3. Hydrogen properties:

Molecular hydrogen (H2) is poised to play a pivotal role in tackling numerous environmental challenges as a non-polluting energy carrier, earning it the moniker "the Energy of the 21st Century." Despite being the most abundant and simplest chemical element in the Universe, molecular hydrogen is rare in its molecular form. On Earth, hydrogen primarily exists in combination with oxygen and carbon, forming water and organic compounds. Consequently, to harness its potential as an energy source, hydrogen must undergo separation and extraction processes. This unique characteristic underscores the importance of advancing hydrogen technologies to unlock its vast energy potential and address pressing environmental concerns [5].

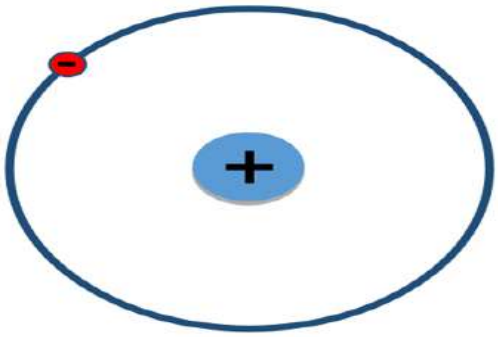


Figure 1:The hydrogen atom

Molecular hydrogen is defined by its lack of color, taste, and odor, making it imperceptible to the human senses. It is exceptionally lightweight, being 14.4 times lighter than air, and is classified as an extremely flammable gas under normal temperature and pressure conditions (1 atmosphere and 0°C, respectively). Additional physical characteristics are detailed in Table (1)[5].

Table 1: : Hydrogen properties .[5]

Characteristics	Value	Unit
Molecular weight	2.02	g/mol
Density	0.09	kg/m3
Specific energy ● Higher heating value ● Lower heating value	142 120	MJ/kg MJ/kg
Melting point	- 259.20	°C
Boiling point	- 252.77	°C
Critical pressure Critical temperature	13.0 - 240.0	Bar °C

I.4. Hydrogen production :

Hydrogen in its molecular form can be generated from a multitude of sources and through diverse methods. Within the framework of energy systems, hydrogen is best conceptualized as an energy carrier, bearing more resemblance to electricity than the fossil fuels extracted from the earth's crust. Any hydrocarbon fuel inherently contains hydrogen, making it a potential source for hydrogen production. Additionally, hydrogen can be derived from a variety of biological materials as well as from water. Electrolysis, known as the "water-splitting" process, is the oldest recognized electrochemical method for producing hydrogen [6].

Today, hydrogen is predominantly produced through the steam reformation of natural gas, although electrolysis and certain industrial processes, such as Chlorine -alkali production, also yield hydrogen as a by-product. This versatility in production methods underscores hydrogen's potential as a widely accessible energy carrier, with various pathways enabling its generation to meet diverse energy needs [6].

I.4.1. Steam Methane Reforming:

Steam methane reforming (SMR) is the process by which natural gas or other methane stream, such as biogas or landfill gas, is reacted with steam in the presence of a catalyst to produce hydrogen and carbon dioxide. When starting with natural gas, SMR is approximately 72% efficient in producing hydrogen on a lower heating value basis (U.S. DOE, 2010). [6].

The efficiency can be somewhat lower with sources of methane that include sulfur or other impurities that require a pre-treatment cleanup step to remove the impurities upstream of the SMR process. SMR produces a hydrogen rich gas that is typically on the order of 70-75% hydrogen on a dry mass basis, along with smaller amounts of methane (2-6%), carbon monoxide (7-10%), and carbon dioxide (6-14%) (Hirschenhofer et al., 2000). [6].

Costs of hydrogen from SMR vary with feedstock cost, scale of production, and other variables and range from about $2-5 per kilogram at present (delivered and stored at high pressure) (NAS/NAE, 2004). Delivered costs as low as about $1.60 per kilogram are believed to be possible in the future based on large centralized production and pipeline delivery, and delivered costs for small-scale decentralized production are projected to be on the order of $2.00-2.50 per kilogram (EIA, 2008; NAS/NAE, 2004[6].

I.4.2. Gasification of Coal and Other Hydrocarbons:

In the partial oxidation (POX) process, also known more generally as "gasification," hydrogen can be derived from a variety of hydrocarbon fuels, including coal, heavy residual oils, and other low-value refinery products. This process involves the reaction of the hydrocarbon fuel with oxygen in a less than stoichiometric ratio, resulting in a mixture of carbon monoxide and hydrogen at temperatures ranging from 1200°C to 1350°C. Hydrogen production from coal gasification currently incurs delivered costs of about $2.00-2.50 per kilogram at a large scale, with anticipated reductions to as low as $1.50 per kilogram in the future (NAS/NAE, 2004). Additionally, hydrogen can be generated through pyrolysis-based hydrocarbon gasification processes in the absence of oxygen, with comparable estimated delivered costs at a large scale (NAS/NAE, 2004). [6].

I.4.3. Electrolysis of Water:

Electrolysis is the process by which water molecules are split directly into hydrogen and oxygen molecules using electricity and an electrolyze device. The overall electrolysis reaction is

$$e^- + H_2O \rightarrow \frac{1}{2} O_2 + H_2$$

The two most common types of electrolyzes are alkaline, which utilize a potassium hydroxide electrolyte, and PEM (proton exchange membrane), which employ a solid polymer membrane electrolyte. (Figure 2) illustrates a schematic of an alkaline electrolysis system. During the electrolysis reaction, pure oxygen is produced as a by-product alongside pure hydrogen. This oxygen can subsequently be utilized for beneficial purposes, such as enhancing the oxygen content in greenhouses to support food production. [6].

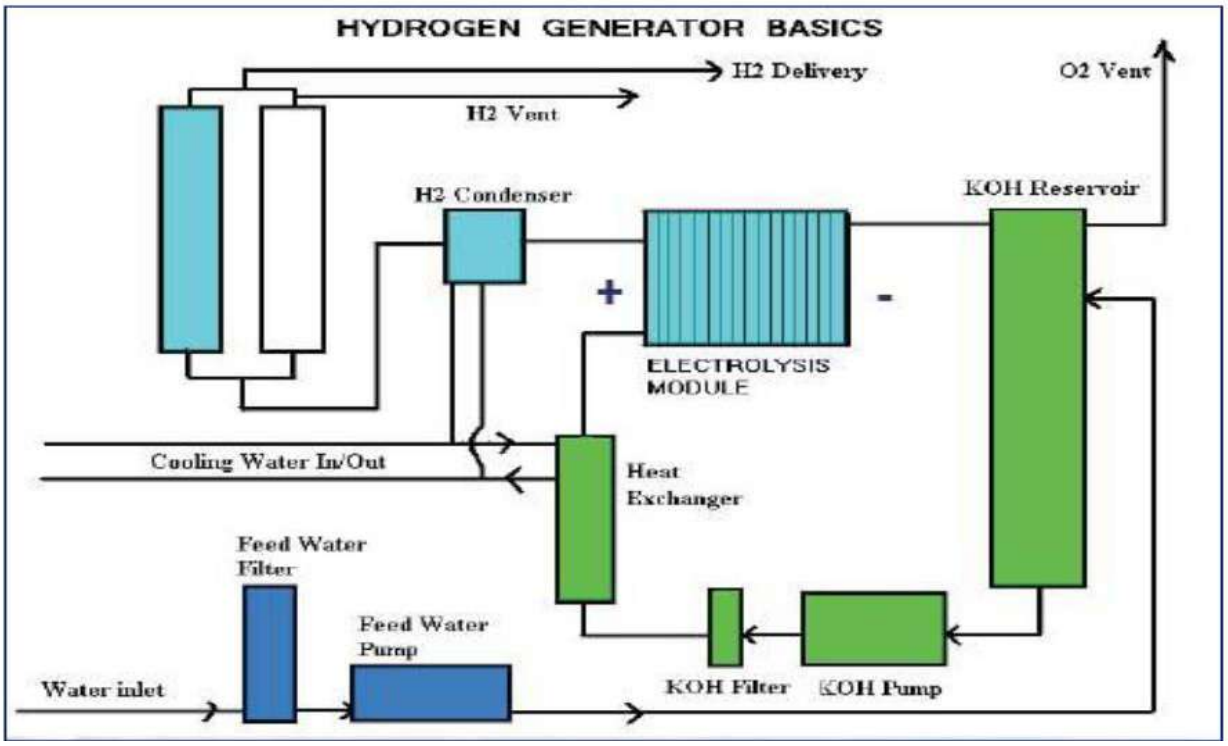


Figure 2:: Hydrogen Production by Alkaline Electrolysis

(Source: Teledyne Energy System)

Hydrogen production via the electrolysis of water can be achieved using any electrical source, including utility grid power, solar photovoltaic (PV), wind power, hydropower, or nuclear power.



Figure 3:Megawatt Scale Hydrogen Production By Electrolysis

(Source: Norsk Hydro)

Electrolysis is currently conducted across a broad spectrum of scales, ranging from a few kilowatts to up to 2,000 kilowatts per electrolyzer (refer to Figure 3). This flexibility enables hydrogen generation to be tailored to diverse energy needs and resources, fostering its integration into various energy systems. [6].

Based on estimated cost ranges provided by the National Academy of Sciences/Engineering and the US Department of Energy, which closely align and are cited below, grid power electrolysis in the US currently yields hydrogen at delivered costs of $6-7 per kilogram (kg), with the potential for future costs to decrease to about $4 per kg. Wind electrolysis-derived hydrogen currently costs about $7-11 per kg, with anticipated future delivered costs of $3-4 per kg, inclusive of the entire production costs from the wind power system. Solar hydrogen production is expected to be more expensive, ranging from $10-30 per kg currently, with future delivered costs estimated to potentially decrease to $3-4 per kg (NAS/NAE, 2004; EIA, 2008) [6].

I.4.4. Hydrogen from fossil sources:

Hydrogen gas can be derived from hydrogen-rich fossil fuels through a variety of processes. Currently, the most prevalent and least-expensive way to produce hydrogen is to derive it from natural gas through a process called steam reformation. Hydrogen can also be “harvested” from coal, through gasification. Fossil fuels can indirectly be used to produce hydrogen when they are used to generate electricity used in the electrolysis of water. Since this practice includes emissions related to the fossil fuel consumption, hydrogen R&D programs involving electrolysis from fossil energy sources tend to include work on methods to reduce these emissions, such as carbon capture and storage. The current hydrogen world production rounds to some 40 million

ton a year. Most of this hydrogen is produced from steam reforming of natural gas and used in refinery as a process gas, in chemical industry and in metal manufacturing [7].

I.4.5. **Hydrogen from renewable energy sources:**

The concept of a hydrogen economy based on renewable energy sources is steadily gaining traction, primarily driven by growing concerns over escalating energy demand, global warming, and fuel supply security. Consequently, renewable energy sources are anticipated to play a pivotal role in powering hydrogen production in the long term. However, the realization of this vision hinges on the establishment of large-scale renewable energy production as a fundamental prerequisite for the viable implementation of a sustainable hydrogen economy. In the interim, hydrogen technologies can aid in bolstering the integration of renewable by serving as backup power for intermittent energy sources. Moreover, hydrogen production can function as an energy storage mechanism for surplus electricity, offering peak-shaving and load-leveling energy services. Electrolysis technologies will undoubtedly play a crucial role in enhancing the cost efficiency of utilizing renewable energy for hydrogen production. Notably, research and development efforts in countries like Japan have already resulted in the development and demonstration of highly efficient PEM electrolyzes [7].

I.4.5.1.Biomass:

Hydrogen extraction from biomass involves a pyrolysis/gasification process. Initially, biomass undergoes preparation by heating a biomass/water slurry to high temperatures under pressure within a reactor. This step decomposes and partially oxidizes the biomass, resulting in a gas product comprising hydrogen, methane, CO2, CO, and nitrogen, while mineral matter is separated from the bottom of the reactor. Subsequently, the gas stream is directed to a high-temperature shift reactor to enhance the hydrogen content. The production of relatively high-purity hydrogen occurs in a subsequent pressure swing adsorption unit. The overall system closely resembles a coal gasification plant, albeit with modifications such as a biomass pretreatment unit and reactor design. Due to the lower calorific value per unit mass of biomass compared to coal, the processing facility tends to be larger than that of a similarly sized coal gasification plant [3].

I.5. Hydrogen storage:

Hydrogen, serving as an energy carrier, necessitates storage solutions to address discrepancies between energy source availability and demand on both daily and seasonal scales. Various types of hydrogen storage systems can be delineated based on size and application. These include stationary large storage systems, typically located at production sites or at the endpoints of pipelines and transportation pathways. Stationary small storage systems cater to distribution or end-user needs, such as those required by industrial plants. Mobile storage systems encompass both large-capacity devices like liquid hydrogen tankers and smaller systems like gaseous or liquid hydrogen truck trailers, facilitating transport and distribution. Additionally, vehicle tanks are employed to store hydrogen for use as fuel in road vehicles. Due to hydrogen's low density, storage entails relatively large volumes and necessitates high pressures, extremely low temperatures, and/or combinations with other materials significantly heavier than hydrogen itself. Table I illustrates achievable storage densities across various hydrogen storage methods. Although some innovative hydrogen storage methods may achieve higher storage densities, their practicality, cost-effectiveness, and safety aspects remain to be substantiated [7].

I.5.1. Gaseous hydrogen:

Hydrogen, serving as an energy carrier, necessitates storage to bridge the gaps between energy source availability and demand, both on a daily and seasonal basis. Various types of hydrogen storage systems can be distinguished based on their size and application:

1. **Stationary Large Storage Systems:** Typically found at production sites or at the beginning or end of pipelines and transportation routes. These systems cater to significant storage needs.
2. **Stationary Small Storage Systems:** Positioned at distribution points or directly at end-users, such as industrial plants, to fulfill localized demands efficiently.
3. **Mobile Storage Systems:** Primarily for transport and distribution purposes, encompassing both high-capacity options like liquid hydrogen tankers and smaller solutions like gaseous or liquid hydrogen truck trailers.
4. **Vehicle Tanks:** Specifically designed to store hydrogen for use as fuel in road vehicles, addressing the unique requirements of mobility applications.

Due to hydrogen's low density, achieving storage necessitates relatively large volumes and entails either high pressures, which demand sturdy vessels, or extremely low temperatures. In

some cases, combinations with other materials are employed to enhance storage efficiency, albeit often resulting in heavier overall systems.

The achievable storage densities vary across different hydrogen storage methods, as depicted in Table (I). While certain novel storage techniques may promise even higher densities, their practicality, cost-effectiveness, and safety remain to be established [3].

I.5.2. Cryogenic liquid hydrogen:

Cryogenic storage involves storing substances at extremely low temperatures, typically around -253°C, within specially designed insulated tanks. These tanks are engineered to maintain the temperature and prevent heat transfer, enabling the storage of substances like hydrogen at a high density of approximately 71 kg/m3[8] .

I.5.3. Solid State:

- **Chemisorptions of hydrogen** (Metal hydride storage)
  - Gravimetric density mostly around 5-7 wt-%
  - Maximum achievable volumetric density till date in Mg2FeH6 (~150 kg.m-3) with a gravimetric density of 5.5 wt-%
- **Physisorption of hydrogen** (Porous systems)
  - Materials such as activated carbon, zeolites, silicas (aerogels), nanotubes, etc.
  - Limited by their gravimetric density of ~1-3 wt-%
  - Unreliable results
  - **Chemical Storage** (reaction with water)
  - A short summary of the above listed storage methods is presented in table 5.

Gravimetric density ρm, volumetric density ρv, operating temperature T and pressure P are also shown. RT stands for room temperature (25 °C) [9] .

I.6. Transport of hydrogen:

The transportation of hydrogen can be accomplished through three primary methods, which vary depending on factors such as distance, volume, and the state in which it is transported [10].

I.6.1. Pipelines:

Transporting hydrogen via pipelines tends to be the most cost-effective method for longer distances. However, constructing pipelines typically requires a certain volume of demand

certainty to justify the investment. Additionally, existing natural gas pipelines can be repurposed for hydrogen transport, provided they meet the necessary technical criteria to reduce the risk of embrittlement. This repurposing of existing pipelines also facilitates the blending of hydrogen within the natural gas networks, enabling accelerated demand creation for end users where blended hydrogen is viable [10].

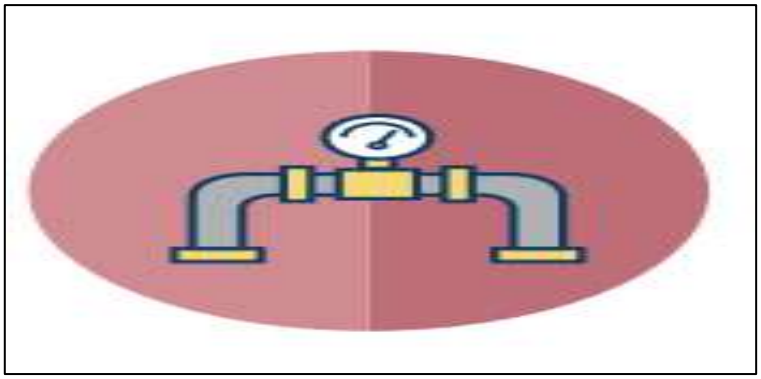


Figure 4: hydrogen transport by Pipelines

I.6.2.Trucks:

Hydrogen is also transported in smaller volumes for both local distribution and longer journeys, utilizing various methods such as gaseous and liquid forms [10].

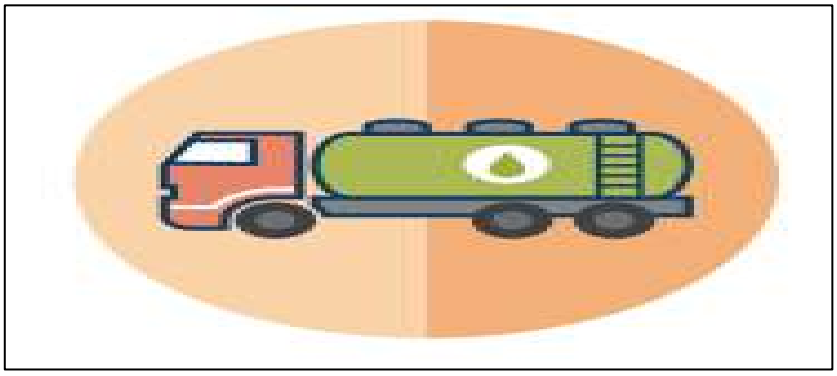


Figure 5: hydrogen transport by Trucks

I.6.3. Tanker ships:

Hydrogen transportation for larger volumes and longer distances is increasingly utilizing methods such as moving liquid hydrogen (LH2), liquid organic hydrogen carriers (LOHCs), and ammonia. However, shipping hydrogen is presently costly due to additional conversion expenses (such as liquefaction or chemical conversion), as well as the requisite structural modifications to mitigate the risk of embrittlement [10].

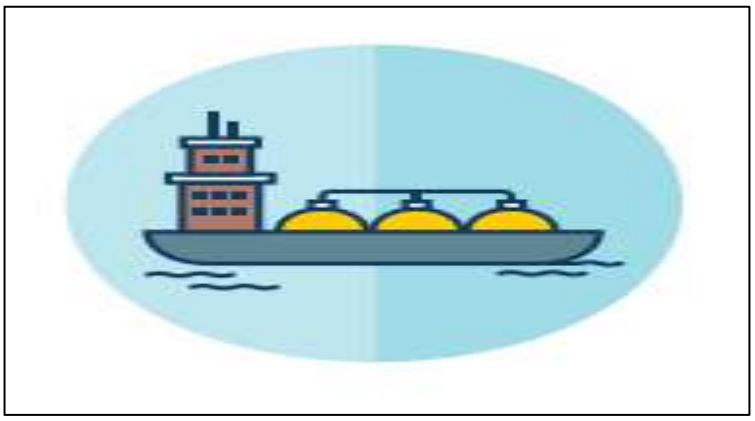


Figure 6: hydrogen transport by Tanker ships

I.7. Applications of hydrogen across sectors:

Hydrogen holds promise for achieving a clean, secure, and affordable energy future, with the potential to decarbonize various sectors. It serves as an energy carrier, finding applications in transportation, power generation, industry, and buildings [11].

Transportation: Hydrogen can power transportation through internal combustion engines (ICE), turbines, or fuel cells. While ICE technology is more mature, fuel cells offer higher energy conversion efficiency, driving faster market adoption.

Power Generation: Although currently limited, hydrogen shows potential in the power sector. Hydrogen-powered gas turbines offer flexibility in the electricity system, while Solid Oxide Fuel Cells boast high conversion efficiency. Additionally, hydrogen can serve as a long-term storage solution for balancing seasonal variations in electricity demand.

Industry: Hydrogen applications in industry include providing industrial heat or serving as a feedstock. It is widely used in processes such as oil refineries, petrochemicals, ammonia, methanol, and steel production. As electrification of transport reduces the demand for oil, hydrogen with a carbon source is expected to replace natural gas in synthetic gas production.

Buildings: Hydrogen can contribute to decarbonizing buildings by powering heating appliances. However, its potential in this sector remains debatable, with heat pumps often considered a more efficient and economical solution. Nonetheless, hydrogen offers storage and flexibility properties, addressing challenges posed by intermittent renewable energy sources in electrified systems.

I.7.1. Application of hydrogen in power sector:

Hydrogen as a Storage and Power Generation Solution: Compressed hydrogen offers potential as a storage option for electricity demand, addressing the challenge of seasonal energy storage. Hydrogen and hydrogen-based fuels can be utilized in gas turbines for power generation. Sector coupling, facilitated by power-to-gas technology, integrates gas and electricity systems to provide storage solutions essential for a sustainable, reliable, zero-emission, and cost-effective energy system [11].

Decarbonization through Renewable Integration: Hydrogen integration enables the decarbonization of energy by facilitating the integration of larger shares of renewable energy into the market. In power-based applications, hydrogen stabilizes the electricity system by offering ancillary services through flexible operations [11].

Power-to-X (P2X) Integration Challenges: Power-to-X (P2X) processes produce hydrogen and derived climate-neutral fuels. Successful integration of P2X technologies requires co-localization of production and consumption sites, combining low-cost electricity production with hydrogen demand hubs and suitable carbon sources. Heat-system integration is also crucial for high-temperature hydrogen applications [11].

Enabling Successful Market Integration: To ensure successful market integration of P2X technology:

- Clarify regulation frameworks to promote sectoral integration and hydrogen's role as both a producer and consumer of electricity.
- Scale up pilot P2X plants to commercial unit sizes.
- Develop hydrogen gas turbines suitable for electrical power generation, operating on blends of hydrogen up to 100%.
- Share knowledge through learning-by-using and technology integration.
- Implement innovative policies to strengthen domestic hydrogen and P2X product markets.
- Establish clear rules promoting environmental and economic benefits of P2X fuels.
- Research system integration and local aspects of consumption structures, resource availability, and infrastructure to optimize hydrogen use in the power sector [11].

I.7.2. **Application of hydrogen in transport sector:**

- Hydrogen Fuel Cell Electric Vehicles (FCEVs) offer a low carbon alternative to fossil fuels, alongside Battery Electric Vehicles (BEVs), with zero exhaust emissions.
- BEVs may be more competitive in light-duty and lower utilization applications, while FCEVs have advantages in heavier-duty and higher utilization scenarios.
- Hydrogen can be utilized in any road transport through fuel cells or hydrogen-based fuels.
- Early adoption of hydrogen in transport is feasible in captive uses such as urban buses, commercial taxi fleets, or specific railway routes where electrification is challenging.
- The existing market for hydrogen-powered forklifts, buses, trucks, and logistic vehicles includes approximately 2,000 buses, 1,500 trucks, and 30,000 forklifts in use. The number of passenger hydrogen FCEVs is expected to increase rapidly with the availability and cost-effectiveness of fuel cell technology.

  Hydrogen Costs and Infrastructure:
- Current estimates for hydrogen costs at the pump range between €7-9/kg, projected to decrease to less than €6/kg by 2030, making hydrogen competitive with fossil fuels.
- Filling station infrastructure is a key barrier for FCEV market expansion, similar to electric transport. Charging time for electric vehicles can take up to 2 hours, while hydrogen vehicles can be fully recharged in minutes.
- Hydrogen refueling stations can be supplied by regional or local electrolyzers or low-carbon H2 (via pipelines). Deployment of electrolyzers requires clear analysis of fleet demand and differing requirements for light and heavy-duty vehicles.
- By 2030, the US is projected to have over 7,000 hydrogen refueling stations and 5.3 million FCEVs, with Europe close behind with 3.7 million FCEVs. Assuming zero-carbon sourced hydrogen, this could save over 29MtCO2 in transport emissions annually **[11]** .

I.7.3. **Application of hydrogen in industrial sector:**

Certainly! Here's a reformatted version of the text: Hydrogen's Role in Industry Transformation Current Applications and Future Potential Hydrogen stands at the forefront of industrial transformation, offering a pathway to carbon neutrality and sustainable production processes. Although its current applications primarily revolve around oil refining, ammonia production, and various hydrogenation reactions, there are promising signs of broader integration.**[11]**

Current Applications:

- Oil Refining: Hydrogen serves as a crucial element in oil refining processes.
- Ammonia and Methanol Production: Hydrogen is essential in the production of ammonia, methanol, and other hydrogenation reactions, vital for various industrial processes.
- Hydrogen from Natural Gas: Presently, hydrogen production relies heavily on natural gas through Steam Methane Reforming (SMR) without Carbon Capture and Storage (CCS).

Emerging Applications:

- Carbon-Free Iron Ore Production: Recent multi-billion-dollar plans in Sweden aim to produce carbon-free iron ore using hydrogen, signaling a potential shift in "hard to decarbonize" sectors.
- Prospects for Other Sectors: The success of hydrogen in iron ore production could inspire other industries to adopt it for high-temperature heat requirements, displacing fossil fuels.

Challenges and Opportunities:

- Short-Term Challenges: Despite its potential, hydrogen faces competition from cheaper, high-carbon-emitting fuels in the short term.
- Long-Term Potential: With advancements and shifting priorities towards sustainability, hydrogen could eventually replace fossil fuels as the primary fuel for industrial high-temperature heat.

Environmental Impact:

- Carbon Emissions Reduction: Industries like iron and steel, contributing nearly 10% of global greenhouse gas emissions, could significantly reduce their carbon footprint by transitioning to low or zero-carbon energy sources like hydrogen.

Synthetic Hydrogen-Based Fuels and Feedstocks:

- Ammonia: With double the energy density of liquefied hydrogen, ammonia can serve as a hydrogen storage medium. The Bosch-Haber Process facilitates its production by combining nitrogen from the air with hydrogen.
- Synthetic Methane and Methanol: Hydrogen, combined with CO or CO2, can produce synthetic methane and methanol, offering higher energy density alternatives to hydrogen.
- Synthetic Fuels: Processes like methanation and Fischer-Tropsch synthesis enable the production of synthetic fuels, including gasoline, diesel, and kerosene, crucial for areas like aviation [11].

Strategies for Industry Transformation:

- Business Model Transformation: Industries can transition from chemical producers to fuel suppliers, embracing hydrogen as a central component.
- Incentivization and Support: Governments and stakeholders must incentivize hydrogen applications to decarbonize steel and iron production.
- Cross-Sector Integration: A cross-sector approach is essential for the seamless integration and deployment of hydrogen across various industries, fostering collaborative efforts towards sustainability [11].

I.7.4.Application of hydrogen in residential & commercial sector:

Hydrogen-Powered Buildings: From Trailblazing to Mainstream Current Initiatives and Future Prospects The concept of hydrogen-powered buildings, once considered eccentric, is now gaining momentum among both industry and governments. Notably, in the United Kingdom, ambitious plans are underway to construct homes with appliances fueled entirely by hydrogen, including the development of a 'hydrogen town' by the decade's end. Similarly, Scotland aims to retrofit 300 homes with hydrogen-powered appliances for heating by 2022.

Key Initiatives:

Strong Support Requirements: Existing pilot schemes have thrived with substantial support from both government and industry. For instance, building two hydrogen-powered homes required approximately $350,000 in funding, matched by contributions from the local energy industry, along with support from national energy regulators.

National Strategies: These projects align with broader national hydrogen strategies such as Hy4Heat and H100 Fife, indicating a concerted effort towards hydrogen integration into residential infrastructure [11].

Cost Reduction Outlook: While upfront costs are significant, future projections suggest a rapid decrease in costs with scale. Ultimately, hydrogen's final energy prices are anticipated to become competitive with natural gas and electricity in major markets.

Environmental Impact and Technological Integration:

Toward Carbon Neutrality: Transitioning to sustainable hydrogen offers a green alternative in the pursuit of carbon neutrality.

Hybrid Systems: Integration of fuel cells and other technologies into hydrogen-powered buildings can support various energy demands, including heating, cooling, and electricity, thereby advancing decarbonization objectives.

Grid Flexibility: Hydrogen, complementing a diverse range of energy sources, enhances grid flexibility, particularly in systems with high shares of variable renewable energy [11].

Strategies for Further Advancement:

Encourage Pilot Projects: Financing and supporting pilot projects across the UNECE region can explore hydrogen's potential in diverse population settings, especially in urban areas.

Incorporate Residential Actions: National hydrogen strategies should include specific provisions for residential hydrogen applications, ensuring comprehensive integration.

Knowledge Sharing: Leveraging existing pilot projects to disseminate knowledge and best practices to international partners facilitates global collaboration.

Inter-Connectivity: Foster industry-government partnerships to build interconnected energy systems, optimizing the integration of hydrogen and other renewable energy sources [11].

I.8. Hydrogen use:

Hydrogen can be burned either to provide heat, or to drive turbines, or in internal combustion engines for motive and electrical power. It is used in a wide variety of applications: ammonia and fertilizer manufacturing, poly-silicon production, margarine manufacturing, power plant cooling, etc. The transport sector is also one of the fields of use of hydrogen as an energy carrier through electric vehicles powered by fuel cells or directly mixed with CNG compressed natural gas [12].

I.9. Conclusion:

In the realm of hydrogen energy development, significant strides have been made in materials science, addressing challenges across production, purification, storage, and energy conversion. Notable methods like water electrolysis and catalytic conversion of natural gases play pivotal roles. Yet, issues persist, including CO emissions and catalyst poisoning. Palladium alloy-based membranes offer promise for purification but face cost and performance hurdles. Hydrogen storage via high-pressure compression or liquefaction demands substantial energy input,

prompting exploration into adsorption technologies on alloys and alternative methods like hydrogenation of organic compounds. Fuel cell (FC) power systems stand out for their efficiency and versatility, but challenges like efficient oxygen reduction catalysts and CO tolerance in electrodes persist. Addressing these, advancements include binary-platinum alloys, innovative membrane designs, and materials modification with nanoparticles. Solid oxide fuel cells (SOFCs) face hurdles related to temperature reduction and ohmic losses, being tackled through thin-film materials and proton-conducting systems. This review underscores the multifaceted efforts to advance hydrogen utilization across various technologies, with implications for a sustainable energy future [13].

In summary, the utilization of hydrogen in gas turbines offers a promising pathway towards efficient energy conversion, with ongoing research focusing on addressing key challenges related to catalyst efficiency, membrane materials, and operating temperature optimization [13].

Chapter II:

Presentation of the Hassi Messaoud Field

II.INTRODUCTION:

Algeria is one of the largest hydrocarbon-producing countries. With its vast underground reserves, it has been able to build an economy based primarily on an energy heritage, which alone constitutes over 97% of the country's total export revenues for over forty years. Today, SONATRACH undertakes strategic missions focused on the exploration, production, transportation, processing, and liquefaction of natural gas, as well as the separation of GPL, and the supply of the domestic market and the marketing of liquid and gaseous hydrocarbons on the international market.

The Production Division (DP) is one of the most important structures within SONATRACH. It operates across all oil and gas fields. The regional direction of Hassi Messaoud is a part of DP, responsible for executing development, exploitation, and crude treatment projects in the field.

During our internship, we were assigned to the liquefied petroleum gas (GPL) recovery unit known as GPL(2), located at the Southern Industrial Center of the regional direction of Hassi Messaoud (DP).

The main objective of this modest work is to understand the operational processes of the GPL (2) unit while assisting in some mechanical revisions and repairs (such as multi-stage vertical centrifugal pump, hot oil reboiler pump, air coolers, safety valves, lubrication filter).

II. 1. Presentation of the hydrocarbon company SONATRACH:

Sonatrach is a major Algerian national company with international scope, established on December 31, 1963. It is the cornerstone of the Algerian economy, engaging in the exploration, production, pipeline transportation, processing, and marketing of hydrocarbons and their derivatives. It also expands into petrochemical, power generation, renewable energy, seawater desalination, and mining activities.

Sonatrach is a multinational corporation operating in Algeria and several regions worldwide, notably in Africa (Mali, Tunisia, Niger, Libya, Egypt, Mauritania), Europe (Spain, Italy, United Kingdom, France, Portugal), Latin America (Peru), and the United States.

It employs 41,204 employees (12,000 with its subsidiaries) and generates 30% of Algeria's PNB. In 2005, its production reached nearly 232.3 million tons of oil equivalent (TEP), with 11.7% destined for the domestic market. Additionally, it ranks as the 12th largest oil group globally, the first in Africa and the Mediterranean basin, the 4th largest exporter of liquefied natural gas (GNL), and the 3rd largest exporter of liquefied petroleum gas (GPL).

II.2. Presentation of the Hassi-Messaoud oil field:

II.2.1. Geographical and geological location of the deposit:

The Hassi-Messaoud field is located 850 km southeast of Algiers, 300 km from the Tunisian border, and 80 km east of Ouargla. It occupies the central part of the Triassic province. Due to its size and reserves, covering nearly 4200 km², it is the largest oil field in Algeria and the entire African continent. It is bounded by:

- To the northwest by the Ouargla field (Gellala, Ben Kahla, and Houd Berkaoui).
- To the southwest by the El-Gassi, Zotti, and Agreb fields.
- To the southeast by the Rhoude El Baguel field.

Geologically, it is bounded by:

- To the west, by the Oued Mya depression.
- To the south, by the Amguid-El Biod high ground.
- To the north, by the Djamaa-Touggourt structure.
- To the east, by the Dahar, Rhoude El Baguel, and Ghadames depressions

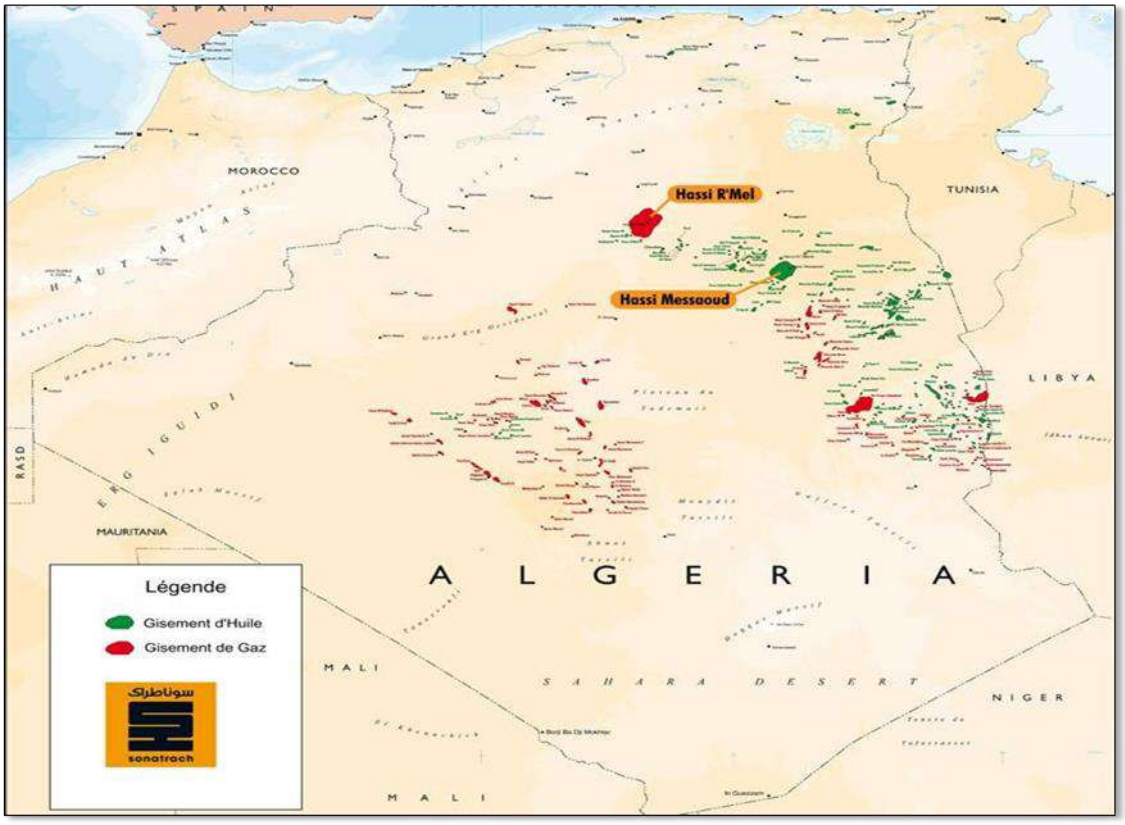


Figure 7:: Characteristics and geographical location of the Hassi-Messaoud field

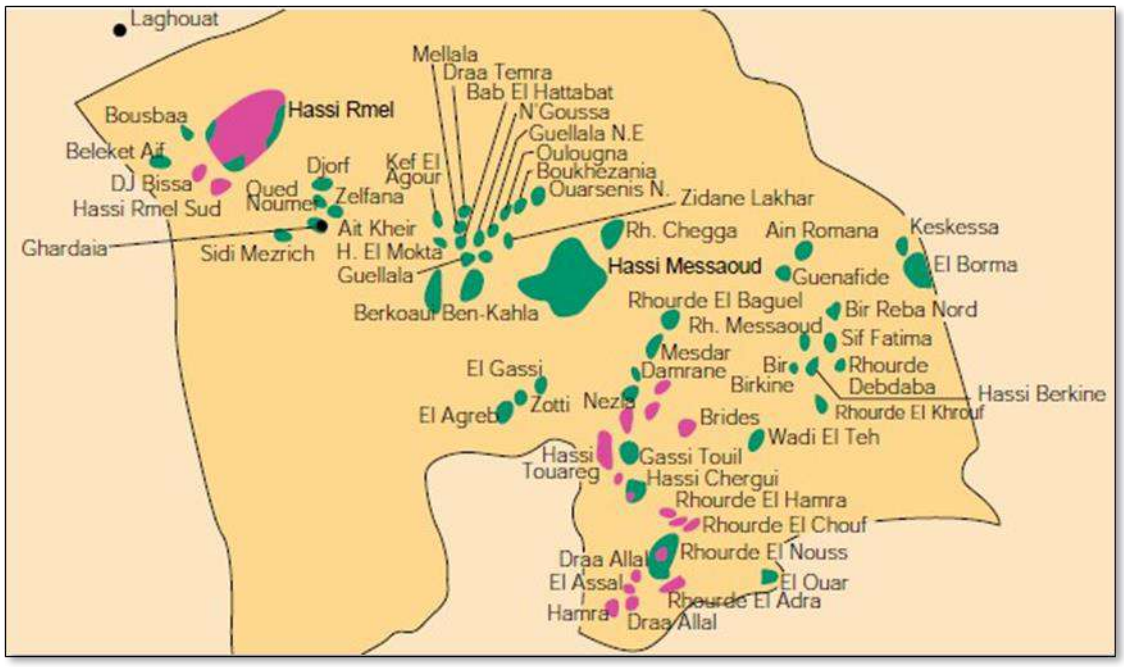


Figure 8:Various oil and gas fields in the Algerian Sahara.

II.2.2.History of the deposit:

The Hassi-Messaoud region emerged from anonymity in 1956 when the French company "SNREPAL" discovered oil in its subsoil, specifically in impregnated sandstone. This discovery resulted from the drilling of the first well, named MD1. However, the actual exploitation of the field began on January 7, 1958. By that year, nine wells were in production: four on the CFPA permit (later acquired by Total and based in Ouargla): OM1, OM6, OM7, OM81, and five on the REPAL permit (later acquired by Elf): MD1, the discovery well, MD3, MD4, MD5. Since then, the number of wells has continued to increase, driving crude oil production from 550 Kbbls/day in the 1970s to around 700 Kbbls/day at the beginning of this decade.

The estimated reserves of the field are around 9 billion barrels of good-quality oil; however, between 4 and 5 billion barrels have already been extracted.

II.3.Organization of the regional management of Hassi-Messaoud:

The regional direction of Hassi-Messaoud has two industrial complexes: the Southern Industrial Complex (CIS) and the Naili Abdelhalim Industrial Complex (CINA):

- ***Southern Industrial Complex (CIS):***

Located south of the production field, it consists of:

- 05 oil separation and treatment units.
- 03 LPG and condensate extraction units.
- 11 gas reinjection stations.

➢ ***Naili Abdelhalim Industrial Complex (CINA):***

Located north of the production field, it consists of:

- 03 crude oil separation and treatment units.
- 21 boosting lines (motor-turbo compressors).
- 01 GPL unit.
- 02 gas reinjection stations.
- 02 water reinjection stations (9 lines).
- 02 nitrogen units.

Each of the two complexes mentioned above is connected to separation and compression units in the field called "Satellite Units".

II.3.1.Organizational chart of the Production Division, Regional Directorate of Hassi-Messaoud:

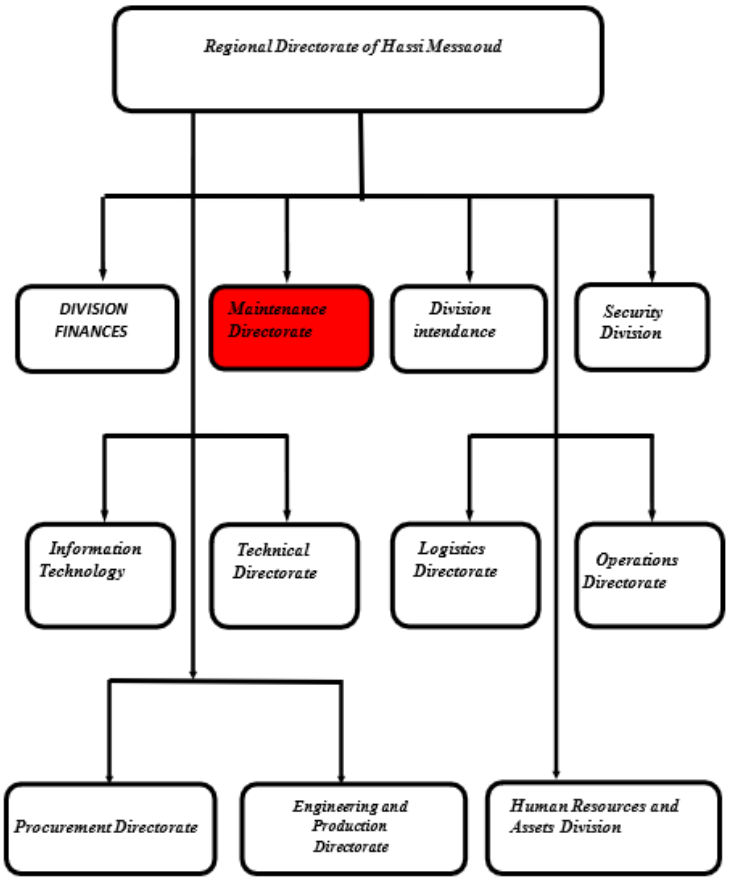


Figure 9: Organizational chart of the Production Division, Regional Directorate of Hassi-Messaoud

II.3.2.Maintenance Directorate :

The maintenance directorate is a structure responsible for the maintenance (preventive, corrective, and systematic) and upkeep of the equipment in the operational units of both complexes (CIS, CINA) and the satellite units.

II.4.Industrial Maintenance :

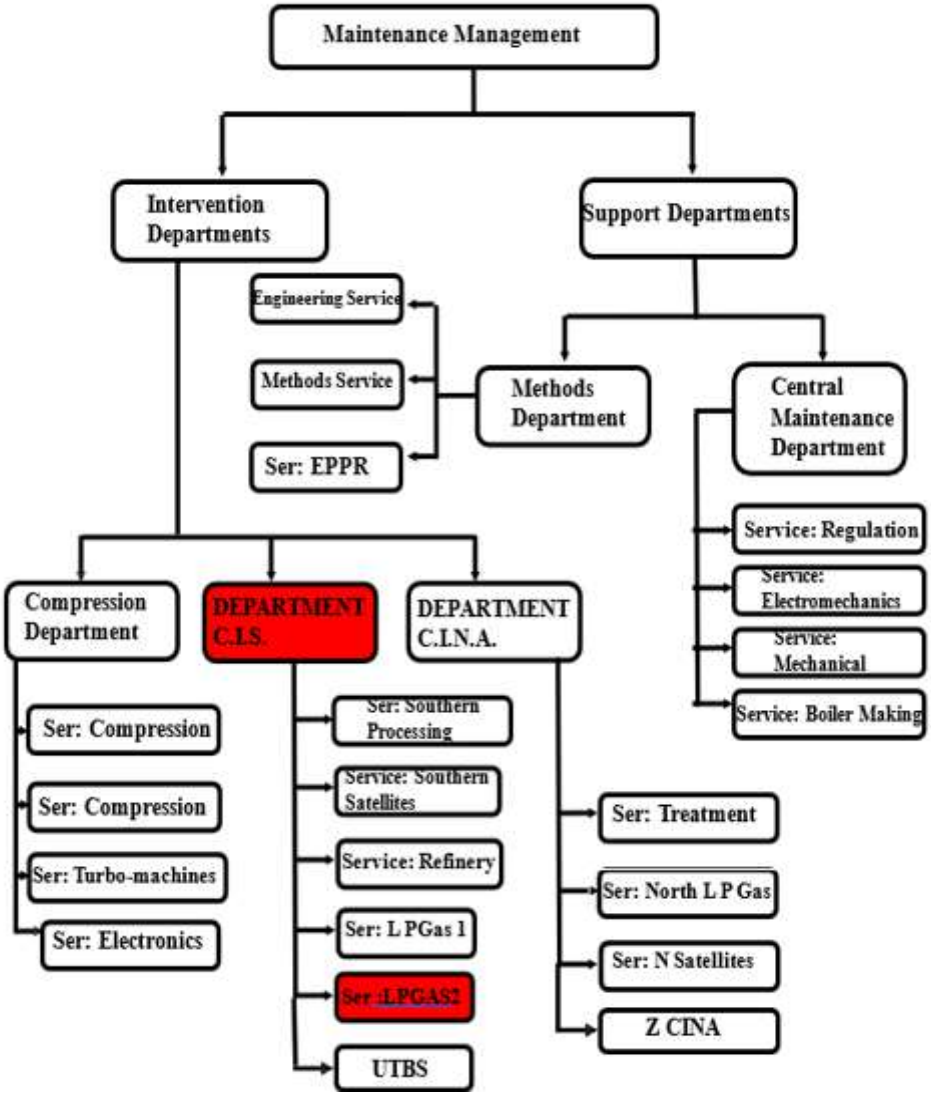


Figure 10: Industrial Maintenance

II.4.1.Definition:

According to the AFNOR standard NFX-60-010, maintenance is a set of actions or tasks aimed at maintaining or restoring an asset to a specified condition so that it can provide a specified service.

Furthermore, maintenance is a set of necessary means deployed to enable a system to be maintained in an operational state.

II.4.2.Types of machine maintenance:

There are three complementary ways to organize maintenance actions:

- Corrective maintenance
- Preventive maintenance
- Predictive maintenance

II.4.2.1.Corrective maintenance :

This involves intervening on equipment once it has failed, i.e., addressing a malfunction or deterioration in the operation of a material element or equipment by repairing it, restoring it to its previous state, or replacing it.

II.4.2.2.Preventive maintenance :

This involves intervening on equipment before it fails, in an attempt to prevent breakdowns. Preventive maintenance is carried out either for safety reasons (the consequences of a failure are unacceptable), for economic reasons (it is cheaper), or sometimes for practical reasons (the equipment is only available for maintenance at certain specific times).

II.4.2.2.1.Systematic maintenance:

This refers to operations carried out systematically, either according to a schedule (fixed time intervals) or according to a frequency of use (operating hours, number of units produced, number of movements performed, etc.).

II.4.2.2.2.Conditional maintenance:

Performed following readings, measurements, or checks revealing the degradation state of the equipment (such as adjusting contacts of certain circuit breakers, replacing brushes due to wear, etc.).

II.4.2.2.3. Predictive Maintenance:

Performed following the monitoring of equipment condition, readings, measurements, and checks revealing the degradation state of the equipment, as well as periodic analysis to determine the evolution of equipment degradation and the intervention period.

To facilitate equipment maintenance monitoring, there is a computer software installed at the maintenance department called CMMS.

Chapter III:
General Overview of Gas Turbines

III.1. Introduction:

The use of gas turbines is widespread in the hydrocarbon industry and mechanical energy production.

The gas turbine is an internal combustion engine that draws in and compresses atmospheric air and converts it into mechanical energy, making it a self-contained machine with continuous flow and a thermodynamic rotating machine [14].

III.2. History of the gas turbine:

The gas turbine was invented in 1791 by the British John Barber. His superiority technical and economic compared to piston steam engines has been recognized from the 19th century. However, the lack of knowledge about materials prohibited at the time from realizing the hopes placed in it. It was in fact necessary wait until 1904 for Franz Stolze to develop a gas turbine in Berlin capable of working, but still not delivering any useful power [15].

III.3. Functional description:

The immense power, reliability, and superior performance of gas turbines position them as highly coveted assets for driving mechanical loads. They find extensive application in industries such as hydrocarbons, propulsion, and electricity generation [16].

Functionally, a gas turbine operates as an internal combustion engine. It first draws in and compresses atmospheric air using its axial compressor. Subsequently, the compressed air's energy is augmented through heat generated within the combustion chamber. During the expansion phase within the turbine section, this thermal energy is converted into valuable mechanical energy. This resultant mechanical energy is then transmitted via a coupling to power a variety of machines, such as compressors or alternators [16].

In comparison to other thermal engines, gas turbines share a dual characteristic with steam turbines: they operate as continuous flow machines, devoid of periodic variations in fluid state. Essentially, the gas turbine, encompassing the entire transformation assembly defining the thermodynamic cycle of the fluid, mirrors the functionality of internal combustion engines. However, these transformations occur within separate and spatially juxtaposed chambers [16] .

III.4. Types of turbines:

GE Energy manufactures a complete range of gas turbines for all major applications in the oil and gas industry. They are installed in natural gas plants, gas compression stations, oil pumping stations, petrochemical plants, power generation facilities, and cogeneration plants worldwide. The basic models produced by GE Energy cover a power range from 5,000 to 124,000 kW. They can be provided in single or combined cycle configurations for mechanical drive or generator drive applications. Below are some of the main turbines offered by GE:

- GE5 Gas Turbines
- GE10 Gas Turbines
- MS5001 Gas Turbines
- MS5002C-D Gas Turbines
- MS5002E Gas Turbines
- PGT16 Aeroderivative Gas Turbines
- PGT25+ Aeroderivative Gas Turbines
- LM6000 Aeroderivative Gas Turbines
- PGT25 Aeroderivative Gas Turbines [17] .

III.5. Areas of application of gas turbines:

Gas turbines are highly useful in various industries. They can be used for driving:

- ✓ Electricity generators
- ✓ Compressors
- ✓ Pumps

They are also utilized as thrust-generating systems, particularly in:

- ✓ Railways
- ✓ Maritime propulsion
- ✓ Aviatio[16].

III.5.1. Classification of gas turbines:

- ✓ Turbines can be classified according to various criteria:

- ✓ According to the mode of construction.
- ✓ According to the mode of operation.
- ✓ According to the types of architectures.
- ✓ According to the thermodynamic operating mode [18] .

III.5.1.2. According to the mode of construction:

❖. Single-shaft turbine:

The compressor and turbine sections are mounted on the same shaft, allowing them to rotate at the same speed. This type is used for applications that do not require speed variations, such as driving generators for electricity production [18] .

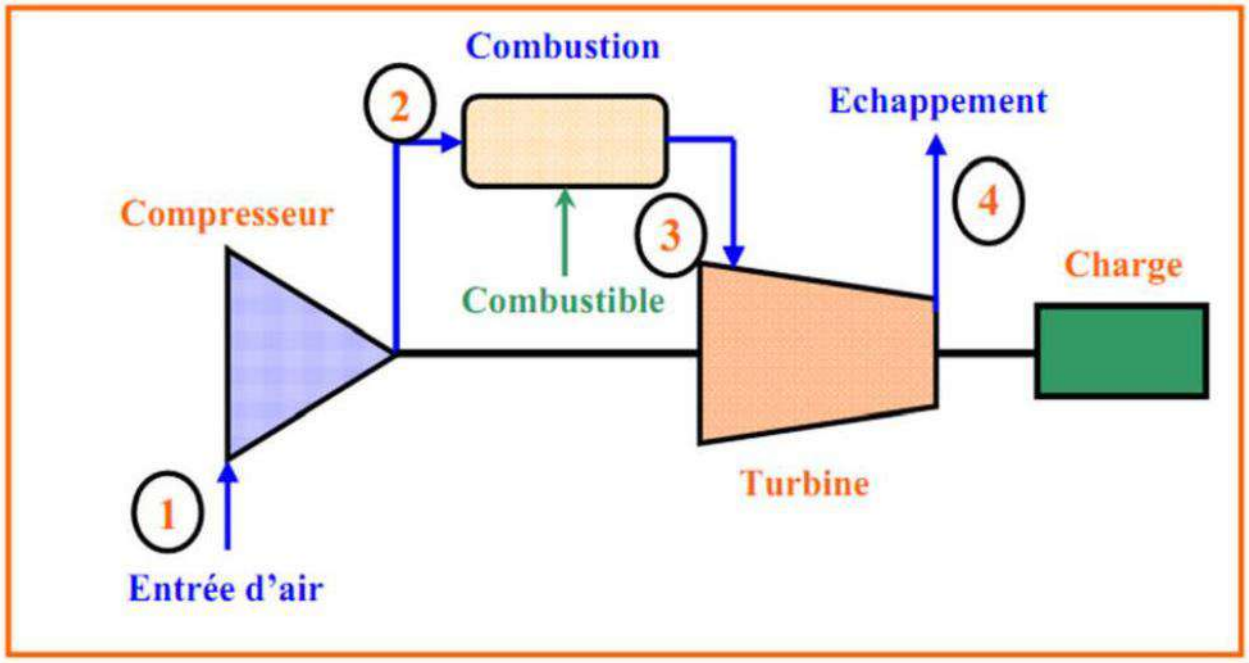


Figure 11:Diagram of the single-shaft turbine

❖. Double-shaft turbine:

Unlike single-shaft gas turbines, dual-shaft turbines have two turbine sections that are not mechanically connected, allowing them to rotate at different speeds. This type is used in applications that require a wide range of speed variation, such as compressor drive [18] .

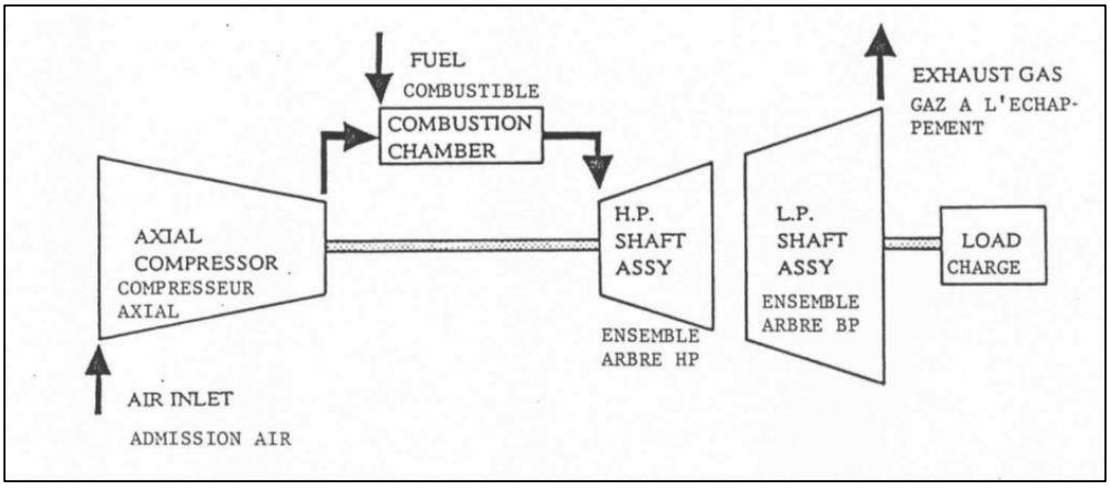


Figure 12:Diagram of a dual-shaft gas turbine

III.5.1.3. According to the mode of operation:

Two types of turbines are distinguished:

❖. Turbine of action:

In an action turbine, the thermodynamic transformation of the fluid occurs solely in the stator (between fixed blades). The role of the moving blades is to convert the kinetic energy acquired during expansion (p1 > p2) into mechanical work imparted to the rotor. The gases in the wheel evolve without variation of static pressure (p2 = p3). (See figure13) [18] .

❖. Reaction turbine:

In reaction turbines, we understand that expansion occurs in both the stationary and moving passages, indicating that some of the thermal energy is converted into kinetic and mechanical energy within the turbine wheel. The gas evolution within the wheel takes place with a change in static pressure, where p1 > p2 [18].

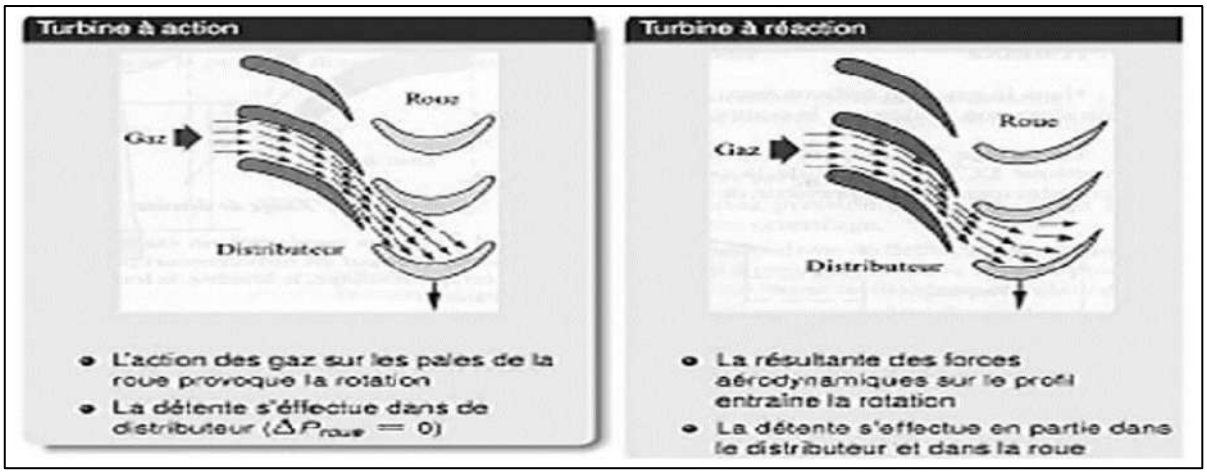


Figure 13:Diagram of an impulse turbine and a reaction turbine

III.6. According to the thermodynamic operating mode:

There are two thermodynamic cycles:

III.6.1. Closed-cycle gas turbine:

In which the same fluid is recirculated after each cycle.

III.6.2. Open cycle gas turbine:

This is a turbine where the intake and exhaust occur directly in the atmosphere. This type of turbine, which is the most common, is divided into two classes:

III.6.2.1.Single cycle turbine:

It's a turbine that utilizes a single fluid for generating mechanical energy. Following expansion, the gases, which retain energy potential, are released into the atmosphere via the exhaust.

III.6.2.2. Regenerated cycle turbine:

This type of turbine employs thermodynamic cycle that utilizes multiple working fluids to enhance system efficiency. Gas turbines are currently extensively utilized owing to their broad power range and inherent advantages [18] .

III.7. Pollution:

Manufacturers of these equipment are making interesting efforts to reduce the level of pollutants emitted by the gas turbine. The use of natural gas (typically containing some sulfur) or sulfur-free liquid fuel allows for low emissions of SO2, in particular combustion chambers with specific injectors that enable low emissions of CO. Low-polluting models are primarily installed by developed countries, while less sophisticated and lower-priced gas turbines are preferred by developing countries [19].

III.7.1. Physical pollution:

- ✓ Atmospheric air contains suspended particles in variable quantities. As examples, we can mention:
- ➢ In rural areas: sand, humus, and pollen.
- ➢ In urban areas: dust, ashes, exhaust gases from vehicles and boilers.
- ➢ In industrial areas: dust, ashes, light residues carried by ventilation fans in manufacturing facilities, factory fumes. These particles may have two characteristics detrimental to the proper condition of gas turbine components
- ✓ An abrasive characteristic: Which will result in the deterioration of the airfoils by impact on the leading edges and erosion on the surface of the blades and trailing edges (example: sand) [19].

III.7.2. Chemical pollution:

Air can contain gases and suspended crystals or dust particles loaded with undesirable chemical components, such as sodium chloride (sea salt), sulfur and its derivatives, chlorine and its derivatives, and organic and inorganic acids [19].

These have corrosive actions that can damage the compressor airfoils, but more frequently, the walls of the combustion chamber and the turbine airfoils because, due to its high temperature, combustion transforms the pollutant or associates it with another pollutant brought by the fuel [19].

The solution consists of applying anticorrosive surface treatments by the manufacturer on exposed parts, and potentially adding inhibitors to the fuel. Ultimately, chemical pollution of the air is difficult to control; if it comes from a gas, there is no other means of protection than washing, which itself is difficult to carry out, in addition to being of uncertain effectiveness [19].

III.8. Advantages and disadvantages of gas turbines:

Gas turbines, like any other industrial machine or installation, have both advantages and disadvantages. Some of these include:

- **Advantages:**

- High power output in a confined space where an equivalent diesel group could not be accommod.
- Except for startup and shutdown, power is generated continuously.
- Easy startup even in very cold conditions.
- Fuel diversity for operation.
- Ability to operate at low loads.

- **Disadvantages:**

- Below approximately 3000 kW, the installation cost is higher than that of a diesel group.
- Much longer startup time than a diesel group, for example: 30 to 120 s for a turbine, 8 to 20 s for a diesel group.
- Lower efficiency than a diesel engine (single cycle). For example: 28 to 33% for a 3000 kW turbine, 32 to 38% for a diesel group [19].

III.9. Conclusion:

This chapter presented generalities related to gas turbines, including functional descriptions and classifications according to various standards used. The advantages and disadvantages of these facilities have been outlined.

Chapter VI:
Description of the MS5002C Gas Turbine

Presentation of the gas turbine installation MS5002C by Hassie Massoude

VI.1. Introduction:

The Model Series 5002 two-shaft, mechanical drive gas turbine is a machine that is used to drive a centrifugal load compressor.

Attached to the forward end of the gas turbine base, is an air inlet compartment and ducting which contains self-cleaning inlet filtration system, that attenuates the high frequency noise, and an inertial air separator, which removes foreign particles before the air enters the turbine[20] .

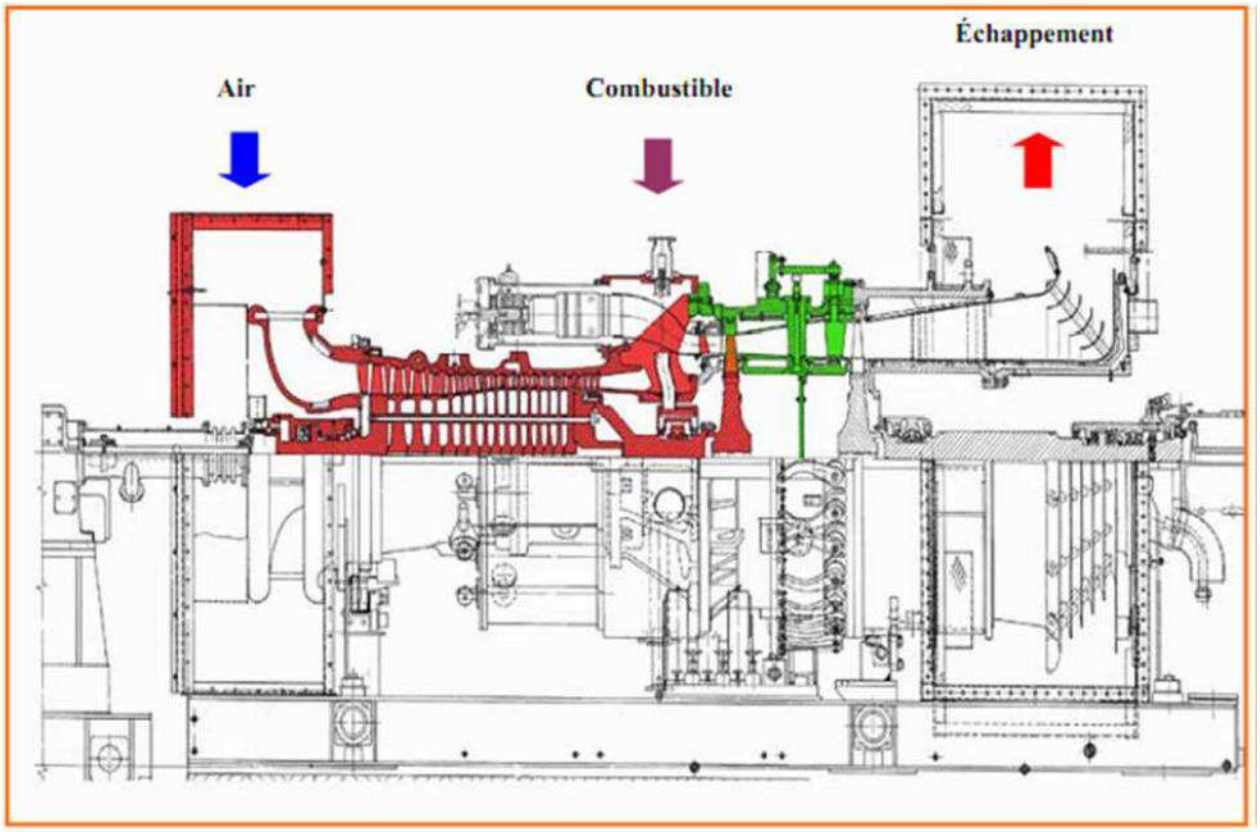


Figure 14:Presentation of the MS5002C turbine

VI.2. Principals of Gas Turbine Operation MS 5002C :

The compressor/high pressure turbine rotor is initially brought to 20% speed by a starting device. Atmospheric air, drawn into the compressor, flows to the combustion chambers where fuel is delivered under pressure.

A high voltage spark ignites the fuel-air mixture. (Once ignited, combustion will remain continuous in chambers). The hot gases increase the speed of the compressor/high pressure

turbine rotor. This, in turn, increases the compressor discharge pressure. As the pressure begins to increase, the low pressure turbine rotor will begin to rotate and both turbine rotors will accelerate to operating speed. The products of combustion, (high pressure and high temperature gases) expand first through the high pressure turbine and then through the low pressure turbine and are exhausted to atmosphere [20].

As the expanding gases pass through the high pressure turbine and impinge on the turbine buckets, they cause the turbine to spin; thus rotating the compressor and applying a torque output to the driven accessories. The gases also spin the low pressure turbine before exhausting; thus rotating the load. The rotor spins in a counterclockwise direction when viewed from the inlet end [20].

VI.3. Characteristics of the MS5002C turbine:

Gas - turbine model series MS-5002C

Gas turbine application.....Mechanical drive

Cycle.....Simple

Shaft rotation .....Counterclockwise

Type of operation.....Continuous

Shaft speed.....4670 rpm

Control .....Mark VI SPEEDTRONIC solid-state electronic control system

Protection (basic types) .....Overspeed, overtemperature, vibration and flame detection

Cooldown mechanism .....Reduction gear with ratchet

Sound attenuation .....Inlet and exhaust silencers to meet site requirements

- **GAS TURBINE NAMEPLATE RATING**

Base output .....28337 kW - ISO condition

- ***COMPRESSOR SECTION***

Number of compressor stages.....16

Compressor type .....Axial flow, heavy duty

Casing split .....Horizontal flange

Inlet guide vanes type .....Variable

- ***TURBINE SECTION***

Number of turbine stages.....2 (two - shaft)

Casing split .....Horizontal

First-stage nozzles .....Fixed area

Second-stage nozzles.....Variable

- ***COMBUSTION SECTION***

Type .....12 multiple combustors, reverse flow type

Chamber arrangement.....Concentrically located around the compressor

Fuel nozzle.....Gas fuel type 1 per chamber

Spark plugs .....2, electrode type, spring-injected, selfretracting

Flame detector .....4, ultra-violet type

- ***BEARING ASSEMBLIES***

Quantity 4

Lubrication.....Pressure lubricated No. 1 bearing assembly

(located in inlet casing assembly).....Active and inactive thrust and journal, all contained in one assembly

Journal .....Elliptical

Active thrust .....Tilting pad, self-equalizing

Inactive thrust .....Tilting pad, self-equalizing No. 2 bearing assembly

(located in the compressor discharge

casing).....Journal, elliptical No. 3 bearing assembly

(located in the exhaust frame) .....Journal, tilting pad

- ***STARTING SYSTEM***

Starting device .....Electric Motor

Reduction gear type .....Freestanding with hydraulic device ratchet

- ***FUEL SYSTEM***

Type.....Natural gas

Fuel control signal .....SPEEDTRONIC *turbine control panel Gas stop, ratio

and control valve .....Electrohydraulic servo control

- ***LUBRICATION SYSTEM***

Lubricant.....Petroleum base

Total capacity .....23530 L

Bearing header pressure.....25 PSI (1,72 Bar) [20].

VI.4. The different main sections of the MS 5002C gas turbine:

A gas turbine is divided into five sections:

- The inlet. (or Intake)
- The axial compressor.
- The combustion chambers.
- Turbine section.
- The exhaust

VI.4.1. COMPRESSOR SECTION:

The axial compressor section includes the stator and the rotor. The rotor comprises 16 compression stages, guide vanes, and 2 outlet deflectors. Rotor blades direct the air, supplying the required compression force. They are slotted into grooves and maintained axially by stacking and looping at the groove ends. Stator blades guide this airflow into successive rotor stages. Disks and the half shaft are assembled for tapering and secured by tie rods. The stator part consists of four main elements [20].:

- **Inlet casing:**

It is located at the front part, its function is to direct the air uniformly towards the compressor, it carries the first stator bearing.

- **Front casing:**

It contains the first four stages of the stator, and it also transmits structural loads from the adjacent body to the front support.

- **Rear casing:**

It contains the last stages of the stator. The extraction ports provided in this casing allow air to be drawn from the tenth stage of the compressor. This air is used for cooling, ensuring sealing functions, and controlling pulsations during startup and shutdown.

- **Discharge casing:**

It is the final component and the longest cast piece, located halfway between the front and rear supports. This casing carries the second turbine bearing. Its function is to contain the last

seven stages of compression and, together with the inner and outer walls, forms the compressor diffuser.

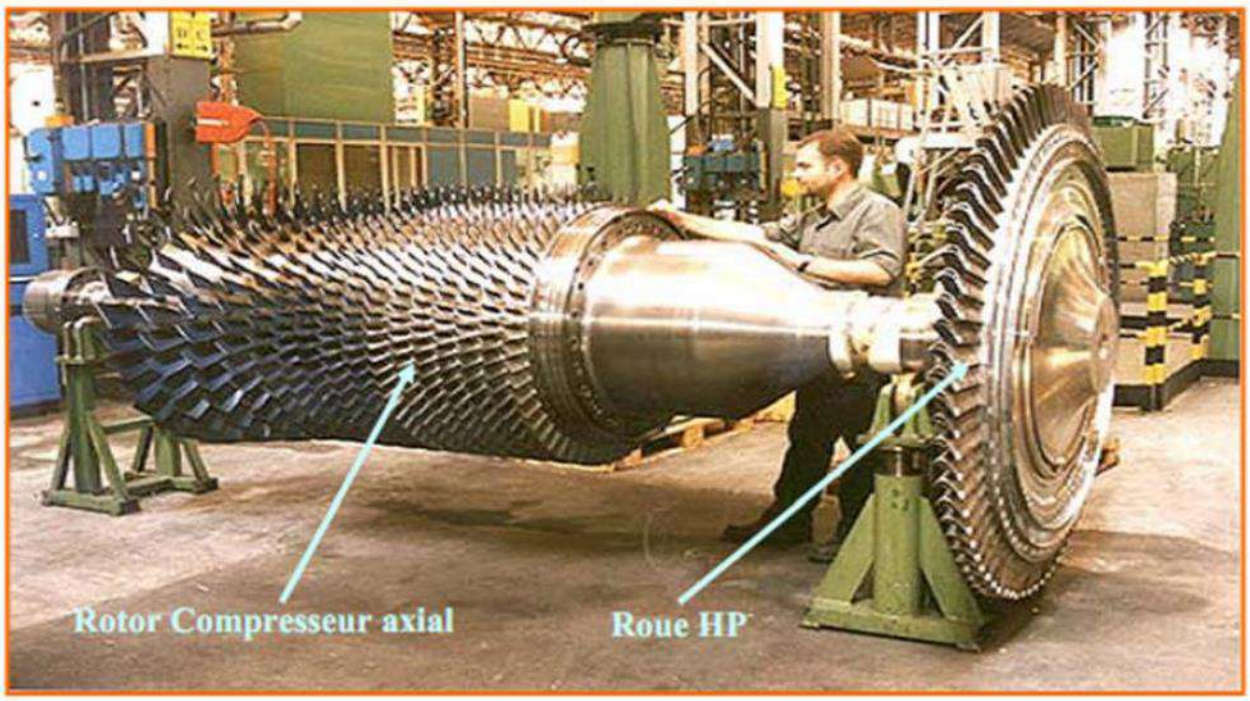


Figure 15:Compressor Rotor of Gas Turbine MS 5002C

VI.4.2. COMBUSTION SECTION:

The combustion section of the gas turbine MS5002C comprises the combustion liner, which consists of 12 outer combustion chambers, 12 cap-sleeve assemblies, 12 transition pieces, 12 fuel injectors, 2 spark plugs, 4 flame detectors, and 12 flame tubes, as well as various fittings.

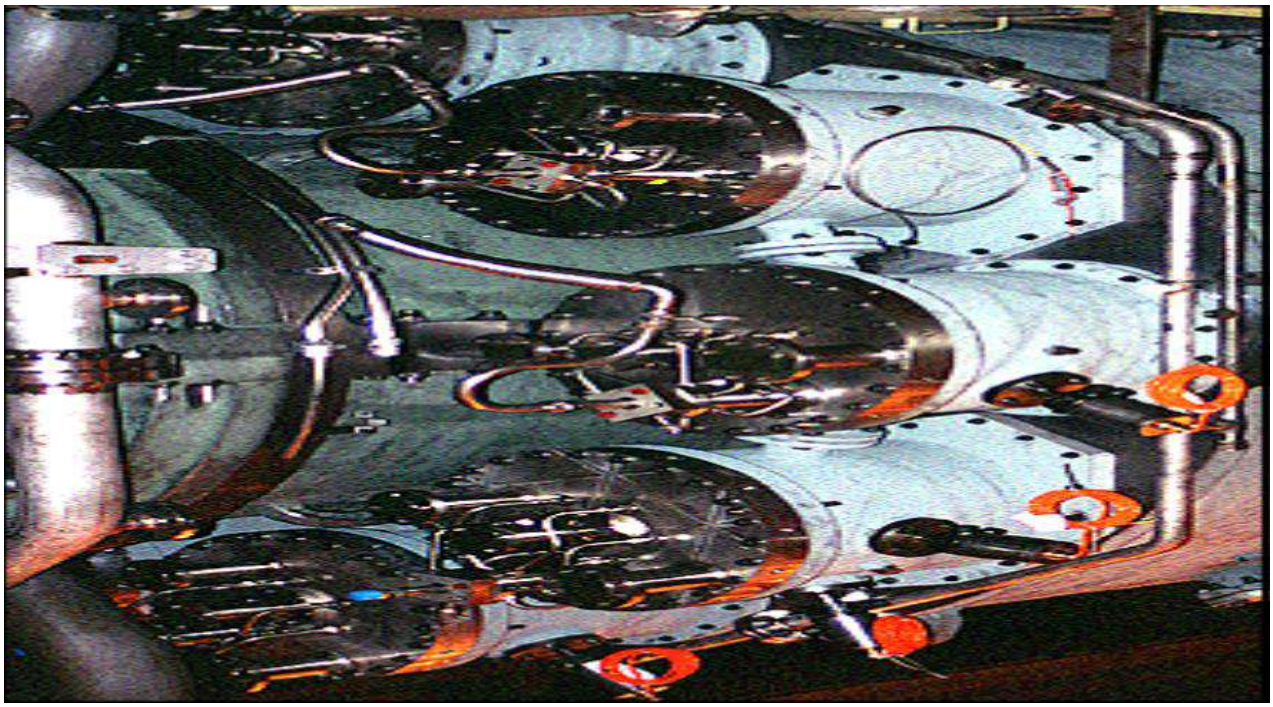


Figure 16:Combustion Chamber of Gas Turbine MS 5002C.

- **Combustion liner:**

It supports the 12 combustion chambers which enclose the 12 transition pieces. It is a welded enclosure, mounted in the rear part of the compressor discharge, receiving axial flow discharge air.

- **Combustion chamber:**

The rear flanges of the 12 combustion chambers are mounted on the front vertical surface of the combustion liner, with each chamber connected by flame tubes. The cap-sleeve assemblies are located outside each chamber. Fuel injectors are mounted in the combustion chamber covers, penetrating into the chambers to supply fuel.

The role of the combustion chamber is to provide the amount of heat required for the gas turbine cycle. The shape of the combustion chamber is designed to fulfill the following conditions:

- The longest possible lifespan.

- Minimal footprint. Ensure good ignition and flame stability.

- Ensure as complete combustion as possible.

- Reduce pressure losses. [20]

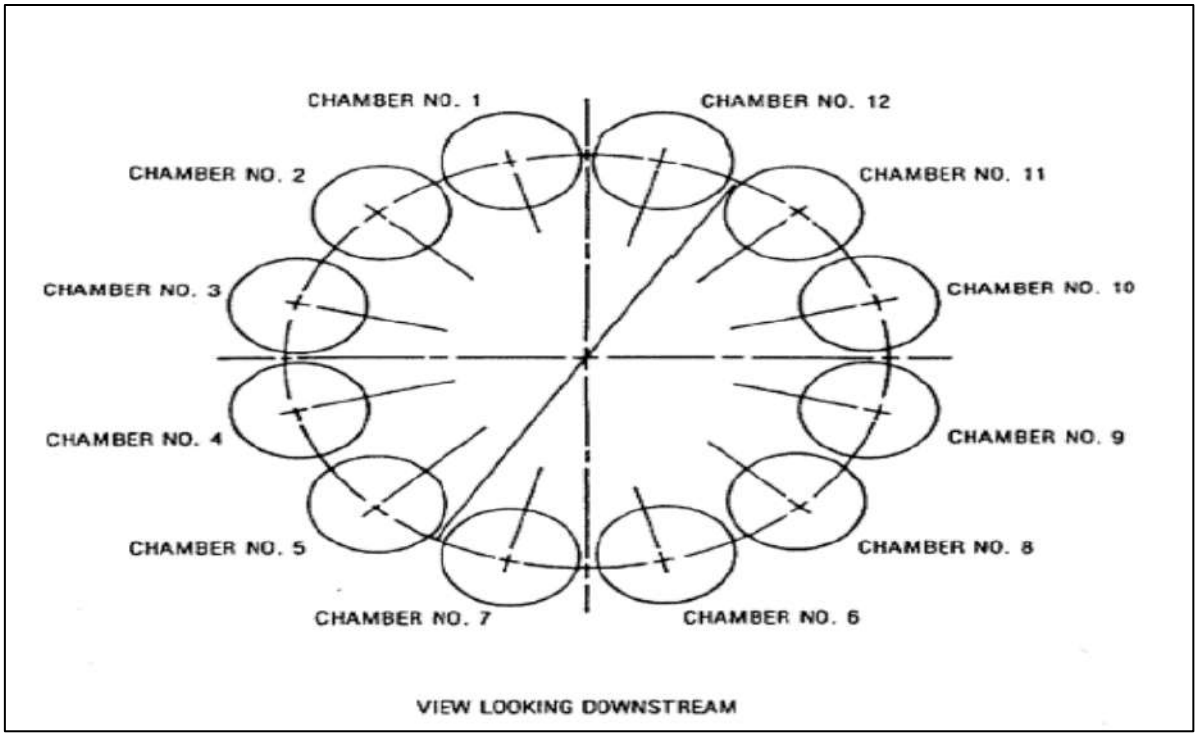


Figure 17:Diagram of a combustion chamber

Spark plug:

The ignition of the combustible mixture is ensured by spark plugs with electrodes. Two spark plugs are installed in each of the two combustion chambers 9 and 10, receiving energy from the ignition transformer. The remaining chambers are ignited through interconnection tubes[20].

- **Ultraviolet flame detector:**

During the startup sequence, an indication of flame presence or absence is sent to the control system, managed by the flame control system. The flame sensor is sensitive to the presence of ultraviolet radiation emitted by hydrocarbon flames.

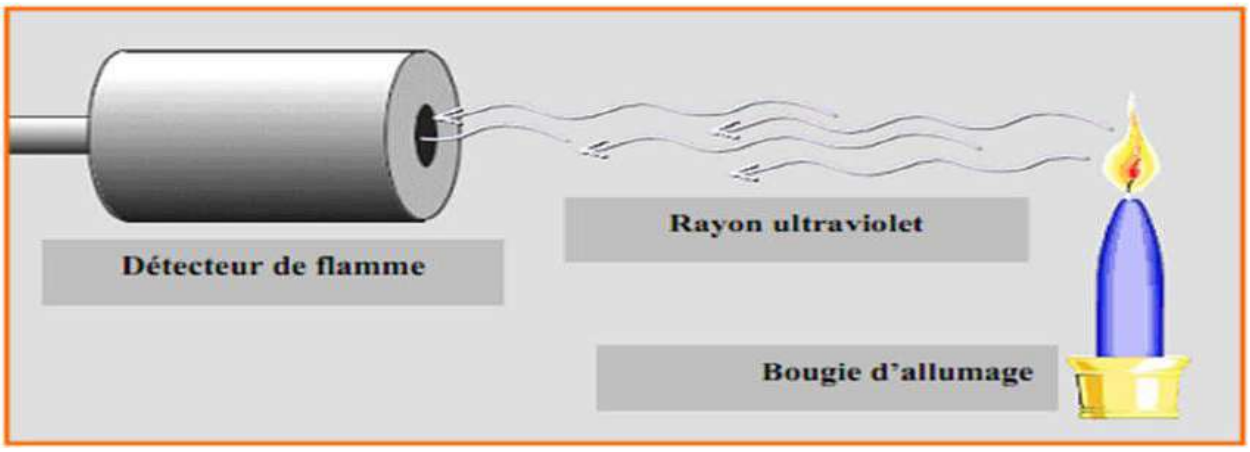


Figure 18:Ultraviolet flame detector

VI.4.3. TURBINE SECTION:

It comprises the turbine rotor body, the first-stage guide vane, the first-stage HP turbine wheel, the second-stage BP turbine wheel, the diaphragm assembly, the sealing assembly, and the inter-stage gas conduit. The stator of this section is in two parts, separated by a horizontal mid-joint plane to facilitate maintenance [20].

- **First-stage guide vanes:**

They are fixed near the gas passage provided in the turbine body.The air discharged by the compressor from the combustion liners enters the retaining support ring of the perforated vanes to escape into the gas passage towards the exhaust. This airflow allows for the cooling of the guide vanes [20].

- **Second-stage guide vanes:**

Composed of adjustable vanes, which form a variable angle with the flow direction of the gases in the annular section just before the second stage of the BP turbine. Rotation is provided through axes provided in the turbine body. The keyed levers at the end of these axes are connected by linkages to points on the control ring that are actuated by a hydraulic piston.

- **Turbine wheels:**

There are two separate wheels in this turbine, the first one is the HP turbine wheel which drives the axial compressor, and the second one is the BP turbine wheel which drives the centrifugal compressor BCL 606-3/A. The wheels are mechanically independent, allowing them to rotate differently [20].

VI.4.4. TURBINE AUXILIARY SYSTEMS:

VI.4.4.1. Intake system:

It directs the combustion air into the intake section to ensure:

- Degree of filtration for the proper operation of the compressor and turbine within the limits of the existing ambient conditions of the installation.
- Regular airflow towards the intake section, and a steady fluid-dynamic operation thereof.

The intake system comprises the intake filter, ducting, silencer, elbow, intake plenum, and other accessories.

The air enters the filter, passes through the ducting, the silencer, the elbow, and the intake plenum, and finally reaches the compressor.

The chosen filter configuration, the degree of noise reduction achieved in the silencer, and the geometry of the elbow are factors that influence the resistance encountered by the air passing through them.

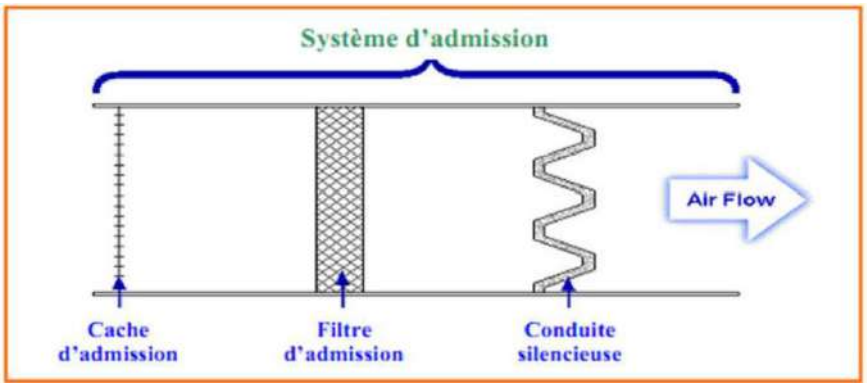


Figure 19:Ultraviolet flame detector

VI.4.4.2. Starting system:

The electric starting motor initiates the machine to reach up to 22% of the rated speed for one minute, stabilizing at 20% for two minutes. Gas circuit purging and supply last for 6 minutes, with the BP shaft at rest. The exhaust temperature Tmax slightly increases while the guide vanes are opened to 15°.

Once the above conditions are verified, the spark plugs produce sparks, and the turbine startup signal is announced. At this point, the BP shaft begins to move, and the guide vanes reach maximum opening position within the range of 50 to 60% of the rated speed. The HP shaft disengages from the starting motor; thus, the gas turbine is self-sustained.

VI.4.4.3. Exhaust system:

It includes the entire frame and the exhaust chamber. The exhaust frame is a main structure part of the gas turbine. It serves as a support for bearings 3 and 4, all piping, bearing seals, and segments of the second-stage turbine wheel. The exhaust chamber is a straight box-shaped

structure in which exhaust gases are discharged and diffused. It is located at the rear end of the turbine pedestal. From this chamber, the gases are directed towards the atmosphere.

- **Turbine base support and bearings:**

The base supports the turbine and serves as a mounting surface for access and as an oil reservoir for lubrication. The turbine is supported on the base by two flexible support plates, one located under the inlet box and the other under the exhaust box. The gas turbine has four main bearings, which support the compressor and the rotors of the two turbines.

- **Starting clutch system:**

It includes the jaw clutch, limit switch, and two cylinders. The hydraulic cylinders engage the clutch via the sequential self-control valve, and the starting devices provide torque to the turbine [20].

Chapter V:
Thermodynamic analysis

V. Introduction:

The power exchanged between the fluid and the machine is due to the conversion of combustion thermal energy into mechanical energy. For continuous flow machines (compressors or turbines), power is obtained by measuring the pressures and temperatures (at inlet and outlet) of the system.

Gas turbine cycles.

V.Ideal Brayton cycle:

The Brayton cycle, commonly employed in gas turbine power plants, includes the adiabatic compression process, addition of heat at constant pressure, adiabatic expansion process, and heat rejection at constant pressure [21].

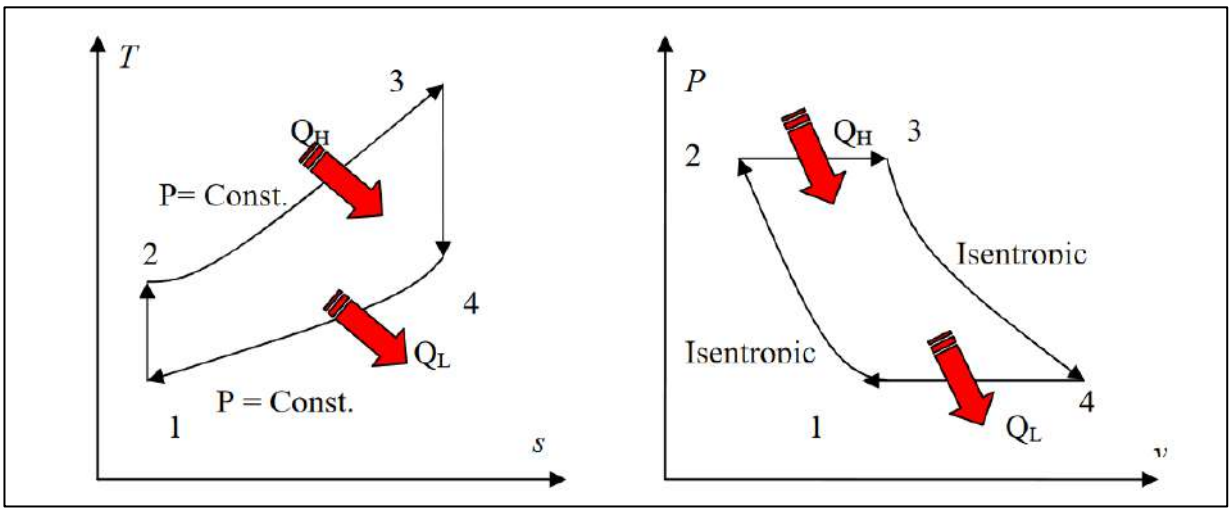


Figure 20:Diagrams of P-V and T-S of the turbine to gas.

(1-2): Isentropic compression; (2-3): Heat addition at constant pressure in the combustion chamber; (3-4): Isentropic expansion; and (4-1): Exhaust into the atmosphere.

Each of these thermodynamic processes is characterized by a mathematical equation resulting from an energy balance between the inlet and outlet of each compartment [21].

The work of the compressor is given by the following relationship [22].

$$W_{compreserr} = (h_2 - h_1) = Cp(T_2 - T_1) \quad (1)$$

The work of the turbine is given by the following relationship:

$$W_{TURBINE} = (h_3 - h_4) = Cp(T_3 - T_4) \quad (2)$$

The heat supplied in the combustion chamber:

$$Q_{CC} = (h_3 - h_2) = Cp(T_3 - T_2) \quad (3)$$

The network of the installation:

$$W_{NET} = W_{TURBINE} - W_{compresseur} \quad (4)$$

The efficiency of the installation:

$$\eta = \frac{W_{net}}{Q_{cc}} \quad (5)$$

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)}$$

$$\eta = 1 - \frac{(h_4 - h_1)}{(h_3 - h_2)}$$

$$\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

Where $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$ and $\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$

translates to: $P_2 = P_3$ and $P_1 = P_4$

Therefore: $\frac{P_2}{P_1} = \frac{P_3}{P_4} = \tau$

If we replace T3 and T2, we find:

$$\eta = 1 - \frac{(T_4 - T_1)}{\left(T_4 \times \tau^{\frac{\gamma-1}{\gamma}} - T_1 \times \tau^{\frac{\gamma-1}{\gamma}}\right)}$$

Finally, we arrive at the following relationship:

$$\eta = 1 - \frac{1}{\left(\tau^{\frac{\gamma-1}{\gamma}}\right)}$$

V.1.Real Brayton cycle:

We have just observed the limitations of the ideal Brayton model. Therefore, we must consider a more representative and convincing model. It is necessary to improve the model without complicating it too much, taking into account the isentropic efficiencies of compression and expansion. During compression and expansion, irreversibility (air viscosity, blade friction, and shocks) generate entropy and cause the gas to heat up more than expected with the ideal Brayton cycle. Thus, the actual compression work is greater than the isentropic compression work. On the other hand, the actual work transmitted to the turbine is less than that of isentropic expansion [23].

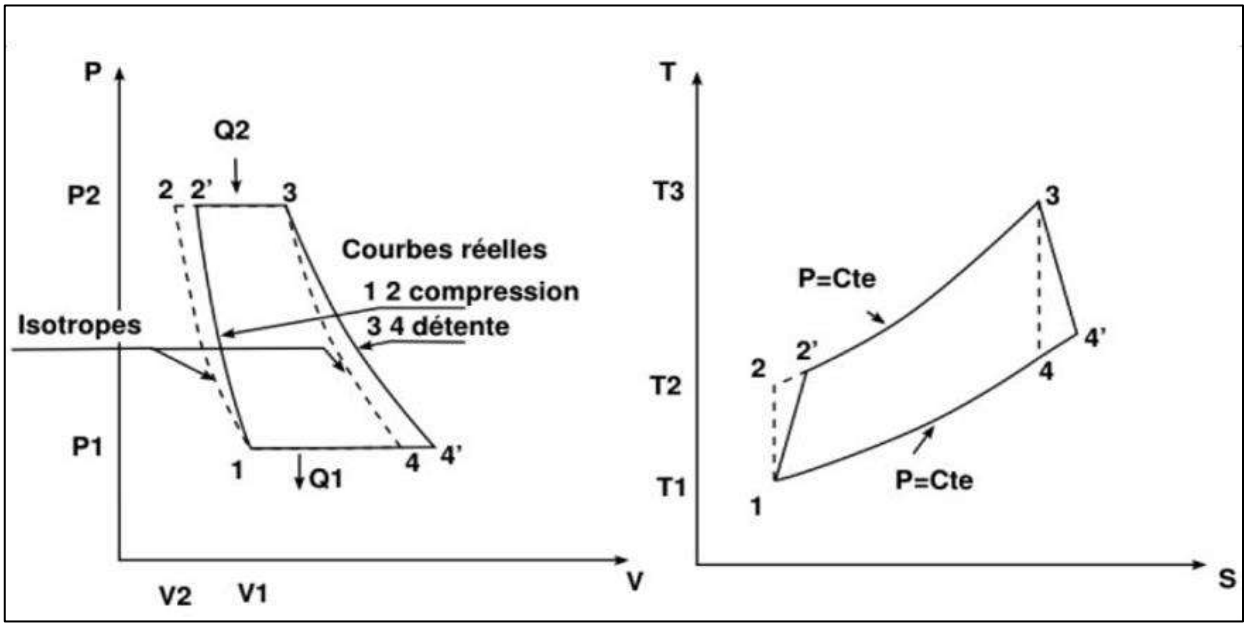


Figure 21:Diagram réel P-V and T-S of the turbine to gas

Isentropic compression efficiency:

$$\eta_{is,comp} = \frac{W_{théo}}{W_{réel}} = \frac{h_2 - h_1}{h_{2'} - h_1} \quad (6)$$

Isentropic relaxation efficiency:

$$\eta_{is,detente} = \frac{W_{réel}}{W_{theo}} = \frac{h_3 - h_{4'}}{h_3 - h_4} \quad (7)$$

V.2.Thermal Balance of the Gas Turbine 5002C:

V.2.1.Real Cycle of the Gas Turbine MS5002C:

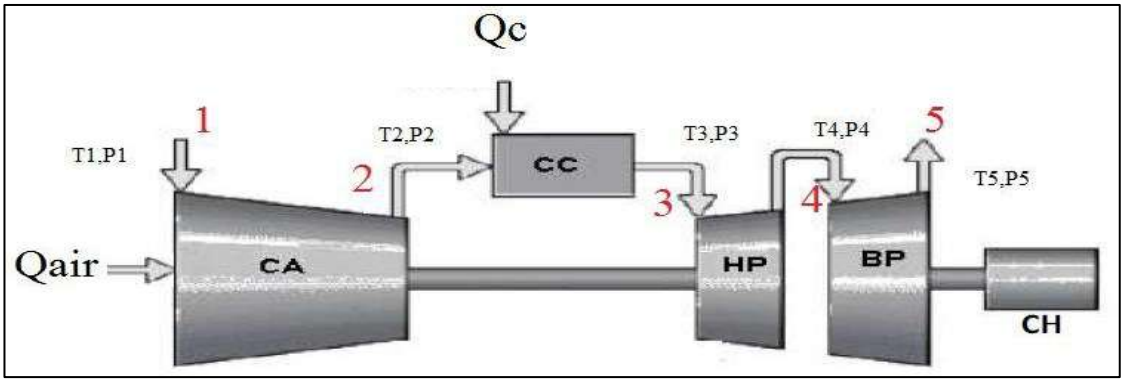


Figure 22:Diagram of the MS5002C gas turbine

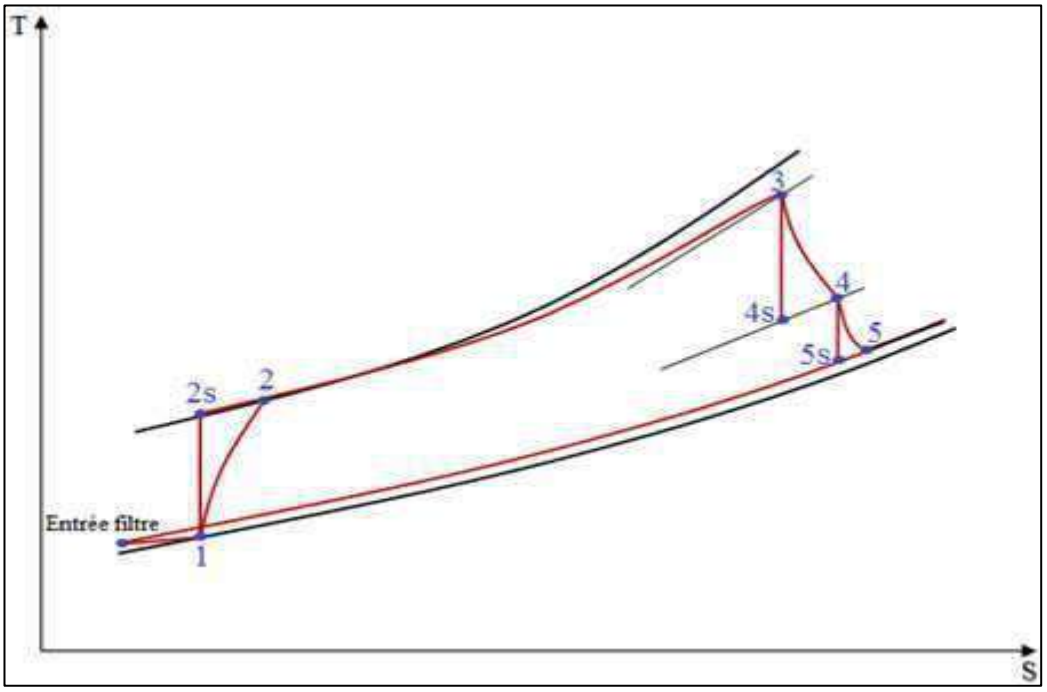


Figure 23:T-S diagram of MS5002C gas turbine

4s=4' ; 5s=5' ; 2s=2'

V.3.Compressor:

Atmospheric pressure as a function of altitude: $P_{atm} =$

$$P_{atm} = \left[1 - \left(\frac{0.0065}{288.15}\right) Z\right]^{5.255} \quad (8)$$

The pressure at the compressor inlet p_1:

$$P_1 = P_{atm} - \Delta P_{atm} \quad (9)$$

The temperature at the end of compression: T_2

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} \qquad T_2 = T_1 \times \left(\frac{P_2}{P_1}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} \quad (10)$$

The compressor power Pc:

$$P_C = Q_{air} \times C_{P(T_1.T_{2'})} \times (T_{2'} - T_1) \quad (11)$$

The isentropic exponent of air:

$$\gamma_{air} = \frac{C_{P(T)}}{C_{P(T)} - r} \quad \text{and} \quad r = 0.287 \frac{KJ}{Kg}.K \quad (12)$$

Specific heat:

$$C_{P(T)} = 0.9648 + 0.099\frac{T}{1000} \quad (13)$$

The average specific heat between 1 and 2 is given by $C_{P(T_1.T_{2\prime})}$:

$$C_{P(T_1.T_{2\prime})} = \frac{Cp_{(T_{2\prime})}\times(T_{2\prime}-273.15)-Cp_{(T_1)}\times(T_1-273.15)}{(T_{2\prime}-T_1)} \quad (14)$$

The compressor discharge pressure P_2 :

$$\tau_c = \frac{P_2}{P_1} \qquad P_2 = \tau_c \times P_1 \quad (15)$$

Isentropic compression efficiency :

$$\eta_{is,comp} = \frac{C_{P(T_2.T_1)}-(T_2-T_1)}{C_{P(T_{2\prime}.T_1)}-(T_{2\prime}-T_1)} \quad (16)$$

V.4.Combustion Chambre:

The heat balance in the combustion chamber:

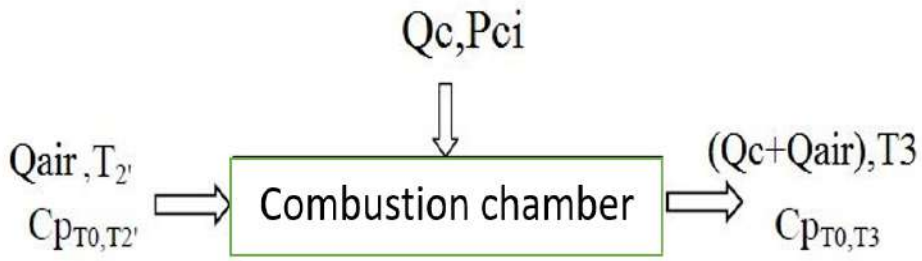


Figure 24:Heat balance in the combustion chamber

The balance at the combustion chamber level:

$$Q_{air} \times C_{P(T_{2\prime}.T_1)} \times (T_{2\prime} - T_1) + \eta_{cc} \times Q_C \times P_{Ci} = (Q_{air} - Q_c) \times C_{P(T_1.T_3)} \times (T_3 - T_1) \quad (17)$$

Specific heat in the combustion chamber: $C_{P(T)}$

$$C_{P(T3)} = 0.9718 + \frac{0.0414}{\lambda} + \left(\frac{0.0536}{\lambda} + 0.0927\right) + \frac{T_3}{1000} \quad (18)$$

The temperature at the end of combustion T_3:

$$T_3 = T_1 + \frac{C_{P(T_{2'}.T_1)}\times(T_{2'}-T_1)+\eta_{cc}\times Q_C\times P_{Ci}}{(Q_{air}-Q_c)\times C_{P(T_1.T_3)}} \quad (19)$$

The pressure at the end of combustion P_3:

$$P_3 = P_2 - \Delta P_{CC} \quad (20)$$

The power of the combustion chambe P_{cc}:

$$P_{CC} = Q_C \times P_{ci} \times \eta_{cc} \quad (21)$$

The lower heating value L_{VH}:

$$L_{VH} = P_{cs} - L_V \quad (22)$$

Calculation of the excess air coefficient λ:

$$\lambda = \frac{m_{air,r}}{m_{air,st}} \quad (23)$$

Stoichiometric air mass $m_{air,st}$:

$$m_{air,st} = \frac{m_{air}}{m_c}$$

Injection Hydrogen :

$$LVH_{m1} = X_{GN} \times LVH_{GN} + X_{H_2} \times LVH_{H_2}$$

The general formula for combustion:

$$C_nH_n + \left(m + \frac{n}{2}\right) O_2 \rightarrow mCO_2 + \left(\frac{n}{2}\right) H_2O \quad (24)$$

The mass of the fuel mc is given by the following relation:

$$\dot{m}_c = \sum X_i \times \dot{m}_i \quad (25)$$

The actual air mass:

$$m_{air.r} = \frac{Q_{air}}{Q_c} \quad (26)$$

V.5.The high-pressure turbine:

The power of the high pressure turbine P_{thp}:

$$P_{thp} = (Q_{air} + Q_c) \times C_{P(T_3.T_{4'})} \times (T_3 - T_{4'}) \quad (27)$$

All the power developed by the high pressure turbine is consumed by the compressor.

$$P_c = P_{thp} \times \eta_m \quad (28)$$

$$Q_{air} \times C_{P(T_1.T_{2'})} \times (T_{2'} - T_1) = (Q_{air} + Q_c) \times C_{P(T_3.T_{4'})} \times (T_3 - T_{4'}) \times \eta_m$$

The temperature at the end of relaxation $T_{4\prime}$:

$$T_{4\prime} = T_3 \times \frac{Q_{air} \times C_{P(T_1.T_{2\prime})} \times (T_{2\prime} - T_1)}{(Q_{air} + Q_c) \times C_{P(T_3.T_{4\prime})} \times \eta_m} \quad (29)$$

The isentropic efficiency of the high pressure turbine η_{THP}:

$$\eta_{is.THP} = \frac{C_{P(T_3.T_{4\prime})} \times (T_3 - T_{4\prime})}{C_{P(T_3.T_4)} \times (T_3 - T_4)} \quad (30)$$

$$T_4 = T_3 \times \frac{C_{P(T_3.T_{4\prime})} \times (T_3 - T_{4\prime})}{C_{P(T_3.T_4)} \times \eta_{is.THP}}$$

The pressure at the end of expansion P_4:

$$\frac{P_4}{P_3} = \left(\frac{T_4}{T_3}\right)^{\frac{\gamma_{air}}{\gamma_{air}-1}} \qquad P_4 = P_3 \times \left(\frac{T_4}{T_3}\right)^{\frac{\gamma_{air}}{\gamma_{air}-1}} \quad (31)$$

V.6.The low-pressure turbine:

The pressure at the end of low pressure expansion P_5:

$$P_5 = P_4 - \Delta P_{éch} \quad (32)$$

The temperature at the end of low pressure expansion T_5:

$$\frac{T_5}{T_{4\prime}} = \left(\frac{P_5}{P_{4\prime}}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} \qquad T_5 = T_{4\prime} \times \left(\frac{P_5}{P_{4\prime}}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} \quad (33)$$

The actual temperature at the end of low pressure expansion $T_{5\prime}$:

$$\eta_{is.TBP} = \frac{C_{P(T_{5\prime}.T_{4\prime})} \times (T_{4\prime} - T_{5\prime})}{C_{P(T_5.T_{4\prime})} \times (T_{5\prime} - T_5)} \quad (34)$$

$$T_{5\prime} = T_{4\prime} - \frac{C_{P(T_5.T_{4\prime})} \times (T_{5\prime} - T_5) \times \eta_{is.TBP}}{C_{P(T_5.T_{4\prime})}}$$

The useful power of the installation P_U:

$$P_{TBP} = P_U = (Q_{air} + Q_C) \times C_{P(T_{5\prime}.T_{4\prime})} \times (T_{4\prime} - T_{5\prime}) \quad (35)$$

The thermal efficiency of the installation η_{th}:

$$\eta_{th} = \frac{P_U}{P_{C.C}} \quad (36)$$

$$S_a = (T_A - T_B)\left[-C_V + \frac{r^2}{K-1}(T_A - T_B)\right]\frac{1}{T_m} + S_B \quad (37)$$

$$T_m = \frac{T_A + T_B}{2} \quad (38)$$

$$C_V = \frac{K \times r}{K-1} \quad (39)$$

V.7.Conclusion:

The MS5002C gas turbine is a highly complex power plant from a technical standpoint, encompassing various mechanical sections that are crucial for the energy conversion process. Each mechanical assembly must adhere to stringent requirements for precision, reliability, and safety to fulfill its intended function. This necessitates the involvement of multiple disciplines in the design and operation of the machine, including thermodynamics and materials science.

Ultimately, the significant power, high efficiency, and reliability of the MS5002C turbine make it an indispensable piece of equipment in the oil industry.

Chapter VI

Results and discussion

Introduction:

In this chapter, we will highlight the impact of partially adding hydrogen to natural gas on the performance of gas turbines. To illustrate this effect, thermodynamic calculations and standard company data are required. The goal of these thermodynamic calculations is to determine all parameters and performance metrics for the MS5002C gas turbine, which is widely used by Sonatrach in the hydrocarbons sector.

- **The first stage:**

V.8.Gas Turbine MS5002C Data:

V.9. Operating parameters:

Table 2:Operating parameters

Ambient temperature	$T_{amb} = 33°C = 306.15K$
Compression rate Air flow	$\tau_c = 6.8$ $Q_{air} = 95Kg/S$
Discharge temperature of the compressor	$T_{2,} = 300°C = 573.15K$
Elevation	$Z = 144m$
Pressure losses in the intake duct	$\Delta P_{adm} = 0.0119bar$
Fuel flow	$\dot{Q}_c = \frac{6030Kg}{h} \leftrightarrow 1.675Kg/s$
Fuel injection pressure	$P_{injcet.c} = 7\ bar$
The calorific value of the fuel	$LVH_{CS} = 10112\ Kcal/m^2$
Pressure losses in the combustion chamber	$\Delta P_{c.c} = 0.224\ bar$
Combustion efficiency	$\eta_{c.c} = 0.98\%$
Mechanical transmission efficiency	$\eta_m = 0.98\%$
High-pressure turbine speed HP	$N_{THP} = 5100\ tr/mim\ \ (100\%)$
Isentropic efficiency of the turbine	$\eta_{THP} = 0.88\%$

Turbine rotation speed BP	: $N_{TBP} = 4048\ tr/mim\ \ (87\%)$
Isentropic efficiency of the turbine	$\eta_{TBP} = 0.88\%$
Pressure losses in the exhaust nozzle	$\Delta P_{éch} = 9.81 \times 10^{-3}\ bar$

Compressor:[26]

$$P_{atm} = \left[1 - \left(\frac{0.0065}{288.15}\right) Z\right]^{5.255}$$

$$P_{atm} = 0.983\ bar$$

The pressure at the compressor inlet P_1:

$$P_1 = P_{atm} - \Delta P_{atm}$$

$$P_1 = 0.971\ bar$$

The temperature at the compressor inlet : T_{inlet}

$$T_{inlet} = T_1 = 306.15\ K$$

The compressor discharge pressure P_2:

$$\tau_c = \frac{P_2}{P_1} \qquad P_2 = \tau_c \times P_1$$

$$P_2 = 6.603\ bar$$

The compressor discharge temperature $T_{2\prime}$:

$$T_{2\prime} = 573.15K$$

From equation (13), the specific heat at temperatures T_1 and$T_{2\prime}$:

$$C_{P(T_1)} = 0.9951 \frac{KJ}{Kg}.K \quad \text{and} \quad C_{P(T_{2\prime})} = 1.02154 \frac{KJ}{Kg}.K$$

From equation (7), the average specific heat between T_1 and $T_{2\prime}$:

$$T_{(T_1.T_{2\prime})} = 1.024809 \frac{KJ}{Kg}.K$$

The isentropic exponent of air γ_{air}:

From equation (5), we calculate the average γ_{air} at the compressor inlet.:

$$\gamma_{air} = \frac{C_{P(T_1.T_{2\prime})}}{C_{P(T_1.T_{2\prime})} - r} \qquad \text{With} \quad r = \frac{0.287KJ}{Kg}.K$$

$$\gamma_{air} = 1.388$$

The relationship between pressure and temperature for an isentropic transformation is given by equation (10):

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} \qquad T_2 = T_1 \times \left(\frac{P_2}{P_1}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}}$$

We substitute into the previous equation and obtain:

$$T_2 = 523.707\ K$$

From equation (13) :

$$C_{P(T_2)} = 1.01664 \frac{KJ}{Kg}.K$$

From equation (14) :

$$C_{P(T_1.T_2)} = 1.01991 \frac{KJ}{Kg}.K$$

The isentropic efficiency of the compressor $\eta_{is,compressore}$:

Based on the obtained results, we calculate the isentropic efficiency of the compressor**:**

$$\eta_{is,compressor} = \frac{C_{P(T_2.T_1)} - (T_2 - T_1)}{C_{P(T_{2\prime}.T_1)} - (T_{2\prime} - T_1)}$$

$$\eta_{is,compressore} = 0.81\%$$

V.10.Combustion chamber:

The balance at the combustion chamber level**:**

$$Q_{air} \times C_{P(T_{2\prime}.T_1)} \times (T_{2\prime} - T_1) + \eta_{cc} \times Q_C \times P_{Ci} = (Q_{air} - Q_c) \times C_{P(T_1.T_3)} \times (T_3 - T_1)$$

The pressure at the end of combustion P_3**:**

$$P_3 = P_2 - \Delta P_{CC}$$

$$P_3 = 6.603 - 0.244 = 6.36\ bar$$

Chromatographic analyses

Table 3: Chromatographic analyses of the gas fuel

Constituents	Symbol	Chemical formula	Molar fraction (x)%	Molar mass (M)
Methane	C_1	CH_4	72.95	16.049
Ethane	C_2	C_2H_6	19.92	30.08
Propane	C_3	C_3H_8	2.0	44.11
Iso-butane	iC_4	C_4H_{10}	0.06	58.14

Normal-butane	nC_4	C_4H_{10}	0.17	58.14
Iso- pentane	iC_5	C_5H_{12}	0.02	72.17
Normal-pentane	nC_5	C_5H_{12}	0.02	72.17
Hexane	C_6	C_6H_{14}	0.04	86.17
Nitrogen	N_2	N_2	2.61	28.03
Carbon dioxide	CO_2	CO_2	2.22	44.01
Molecular weight	20.47			
$L.V.S\ (Kcal/m3)$	10112			

According to the periodic table of elements, the atomic mass:

$$M_H = 1.007 g/mol$$

$$M_C = 12.0101\ g/mol$$

$$M_O = 15.999\ g/mol$$

$$M_N = 14.006\ g/mol$$

The lower heating value LHV_i :

$$LHV_i = LHV_s - L_V$$

According to the chromatographic analysis of the gas fuel, the traces of water are negligible, so we can say that:

$$LHV_i = LHV_s$$

$$LHV_i[KCal/m^3] = LHV_i \times V_m[Kcal/m^3]$$

The molar volume at standard conditions: $= 22.44\ [m^3]$

The mass volume at standard conditions:

$$V_m = \frac{V_{mol}}{V_c}$$

$$V_m = \frac{22.4}{20.47} = 1.094\ m^3/Kg$$

$$LHV_i = 42308.6\ Kj/kg$$

The air excess coefficient γ:

$$\gamma = \frac{m_{air.r}}{m_{air.st}}$$

The mass of the fuel, mc, is given by the following relationship:

$$m_c = \sum X_i \times M_i = 20.47\ g$$

The mass of oxygen required m_{O2}:

$$m_{O2} = n_{O2} \times M_{O2}$$

$$n_{O2} = 2 \times (0.7295) + \frac{7}{2}(0.1992) + 5 \times (0.02) + \frac{13}{2} \times (0.0006 + 0.0017) + 8 \times (0.0002 + 0.0001) + \frac{19}{2} \times (0.0004)$$

The number of moles of oxygen constituting the fuel is n_{O2}:

$$n_{O2} = 2.2773\ mol$$

So the mass of oxygen m_{O2} =:

$$m_{O2} = 76.86\ g$$

The air is composed of oxygen and nitrogen in the following proportions:

76.8% of nitrogen and 23.2% of oxygen

The mass of air required for combustion m_{air}:

$$m_{air} = \frac{m_{O2}}{0.232} = 314.9\ g$$

$$C_mH_n + \left(m + \frac{n}{4}\right) O_2 \rightarrow mCO_2 + \left(\frac{n}{2}\right) H_2O$$

Table 4:Chemical formulas for combustion of gas compositions

Methane	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
Ethane	$C_2H_6 + \left(\frac{7}{2}\right) O_2 \rightarrow 2CO_2 + 3H_2O$
Propane	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$
ISO-butane	$C_4H_{10} + \left(\frac{13}{2}\right) O_2 \rightarrow 4CO_2 + 5H_2O$
Normal-butane	$C_4H_{10} + \left(\frac{13}{2}\right) O_2 \rightarrow 4CO_2 + 5H_2O$
ISO-pentane	$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$
Normal-pentane	$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$
Hexane	$C_6H_{14} + \left(\frac{19}{2}\right) O_2 \rightarrow 6CO_2 + 7H_2O$

The stoichiometric air mass:

$$m_{air.st} = \frac{m_{air}}{m_c} = \frac{314.09}{20.47} = 15.34\ Kg/S$$

$$m_{air.r} = \frac{Q_{air}}{Q_c} = \frac{95}{1.675} = 56.72\ Kg/S$$

The excess air coefficient γ:

$$\gamma = \frac{m_{air.r}}{m_{air.st}} = \frac{56.21}{15.34} = 3.69$$

The combustion temperature:

According to the thermal balance at the combustion chamber level, the temperature at the end of combustion is given by:

$$T_3 = T_1 + \frac{Q_{air} \times C_{P(T_{2'}.T_1)} \times (T_{2'} - T_1) + \eta_{cc} \times Q_C \times P_{Ci}}{(Q_{air} + Q_c) \times C_{P(T_1.T_3)}}$$

The specific heat at temperature T3 is given by relation (10) $C_{P(T_3)}$:

$$C_{P(T_3)} = 0.9718 + \frac{0.0414}{\lambda} + \left(\frac{0.0536}{\lambda} + 0.0927\right) + \frac{T_3}{1000}$$

Assuming that the temperature at the end of combustion is equal to 850 C° 1123K:

According to equations (13) and (14):

$$C_{P(T_3)} = 1.07597 \frac{Kj}{Kg}.K \qquad and \qquad C_{P(T_1.T_3)} = 1.07924 \frac{Kj}{Kg}.K$$

We redo the calculations, and after several iterations until the results stabilize, we obtain:

$$T_3 = 1220.92\ K \qquad \text{and} \qquad C_{P(T_3)} = 0.93482\ \frac{Kj}{Kg}.K$$

V.11.High-pressure turbine:

All the power developed by the high-pressure turbine is consumed by the compressor (gas generator)

$$P_c = P_{THP} \times \eta_m$$

$$Q_{air} \times C_{P(T_1.T_{2'})} \times (T_{2'} - T_1) = (Q_{air} + Q_c) \times C_{P(T_3.T_{4'})} \times (T_3 - T_{4'}) \times \eta_m$$

The temperature at the end of high-pressure turbine expansion T'4: From equation (22), the temperature at the end of expansion T4' is given by:

$$T_{4'} = T_3 \times \frac{Q_{air} \times C_{P(T_1.T_{2'})} \times (T_{2'} - T_1)}{(Q_{air} + Q_c) \times C_{P(T_3.T_{4'})} \times \eta_m}$$

We assume that: $C_{P(T_3.T_{4'})} = C_{P(T_{2'}.T_3)}$

$$C_{P(T_{2\prime}.T_3)} = 0.9102 + \frac{0.1187}{\lambda} + 0.1187\frac{(T_{2\prime} + T_3)}{1000}$$

So: $C_{P(T_{2\prime}.T_3)} = 1.15532\ \frac{Kj}{Kg}.K$

With the results obtained, we redo the calculations until the stabilization of the temperature T4', and we obtain:

$$T_{4\prime} = 983.45\ K$$

From equations (13) and (14):

$C_{P(T_{4\prime})} = 1.06216\ \frac{Kj}{Kg}.K$ end $C_{P(T_3.T_{4\prime})} = 1.15532\ \frac{Kj}{Kg}.K$

From the efficiency of the high-pressure turbine (24), the temperature T4 is:

$$T_4 = T_3 - \frac{C_{P(T_3.T_{4\prime})} \times (T_3 - T_{4\prime})}{C_{P(T_3.T_4)} \times \eta_{isTHP}}$$

We assume that: $C_{P(T_3.T_{4\prime})} = C_{P(T_3.T_4)}$

We perform the calculation, and after several iterations:

$$T_4 = 951.067\ K$$

And from equations (13) and (14):

$C_{P(T_4)} = 1.058956\frac{Kj}{Kg}.K$ end $C_{P(T_3.T_4)} = 1.155325\ \frac{Kj}{Kg}.K$

The pressure at the outlet of the high-pressure turbine P4:

From equation (31): $P_4 = P_3 \times \left(\frac{T_4}{T_3}\right)^{\frac{\gamma_{air}}{\gamma_{air}-1}}$

The isentropic exponent of the burned gases is given by the relation (5):

$$\gamma_{air} = \frac{C_{P(T)}}{C_{P(T)} - r} = 1.2997$$

SO: $P_4 = 2.15\ bar$

V.12.Power turbine (LP):

The pressure at the outlet of the LP turbine is given by the relation (32):

$$P_5 = 0.971\ bar$$

The temperature at the outlet of the LP turbine will be calculated using equation (33):

$$T_5 = T_{4'} \times \left(\frac{P_5}{P_{4'}}\right)^{\frac{\gamma_{gbp}-1}{\gamma_{gbp}}}$$

We assume that: $\gamma_{gbp} = \gamma_{ghp} = 1.4236$

After calculation, we obtain:

$T_5 = 803.90\ k$

Replacing the value of the temperature found in equations (13) and (14):

$C_{P(T_5)} = 1.0354 \frac{Kj}{Kg}.K$ end $C_{P(T_4.T_{5'})} = 1.10985 \frac{Kj}{Kg}.K$

The isentropic exponent of the burned gases:

$$\gamma_{gbp} = 1.4236$$

Finally, and after the previous results, the temperature T5:

$$T_5 = 825.44\ K$$

The actual temperature at the outlet of the high-pressure turbine T5':

According to equation (34):

$$T_{5'} = T_{4'} - \frac{C_{P(T_4.T_5)} \times (T_{4'} - T_5) \times \eta_{is.TBP}}{C_{P(T_5.T_{4'})}}$$

We assume that:

$$C_{P(T_4.T_5)} = C_{P(T_4.T_{5'})} = 0.9695 \frac{Kj}{Kg}.K$$

And we obtain: $T_{5'} = 825.44\ K$

Substituting into equations (13) and (14):

$C_{P(T_{5'})} = 1.0437\ Kj/Kg.K$ end $C_{P(T_5.T_{4'})} = 0.9695 \frac{Kj}{Kg}.K$

Recalculating with the previous results, we obtain:

$$T_{5'} = 825.44\ K$$

V.13. Summary table of thermodynamic calculations:

The table below summarizes the operations performed regarding the thermodynamic calculations (Table.5):

Table 5:Summary table of thermodynamic calculations

Points	Temperature T (K)	Pressure p (bar)
1	306.15	0.971
2	573.15	6.603
3	1220.92	6.36
4	951.067	2.15
5	825.44	0.971

V.14.Gas turbine performance:

The useful power of the installation:

$$P_{TBP} = P_U = (Q_{air} + Q_C) \times C_{P(T_{5'}.T_{4'})} \times (T_{4'} - T_{5'})$$

$$P_U = 18697.86\ KW$$

The power of the combustion chamber:

$$P_{c.c} = Q_c \times P_{ci} \times \eta_{c.c}$$

$$P_{c.c} = 69491.03\ KW$$

The thermal efficiency of the installation:

$$\eta_{th} = \frac{P_U}{P_{c.c}} = 0.21 = 21\ \%$$

Entropy (S):

After setting the temperature in annexes (1) and (2), we extract both (k) and (s):

$S_1 = S_{2'} = 0.7$ Kj/Kg.K

Substituting into equations (37):

$$S_a = (T_A - T_B)\left[-C_V + \frac{r^2}{K-1}(T_A - T_B)\right]\frac{1}{T_m} + S_B$$

$S_2 = (573.15 - 306.15)\left[-1.04226 + \frac{0.287^2}{1.38-1}(573.15 - 306.15)\right]\frac{1}{439.65} + 0.7 = 35.21463$ Kj/Kg.K

$$S_3 = S_{4'} = \frac{\dot{Q}_{GN} \times LVH_m \times \eta_{CC}}{T_m} + S_2$$

$$S_3 = S_{4'} = \frac{1.657 \times 42308.6 \times 0.98}{894.71} + 35.2146 = 809.83\ \text{Kj/Kg.K}$$

$S_4 = S_{5'} = (951.06 - 1220.93)\left[-1.1567 + \frac{0.287^2}{1.33-1}(951.06 - 1220.93)\right]\frac{1}{1085.99} + 809.83 =$ 826.86 Kj/Kg.K

Table 6: The results obtained include a schematic diagram of the MS5002C gas turbine

	1	2	2’	3	4	4’	5	5’
T(K°)	306.15	573.15	523.707	1220.925	951.059	983.44	803.90	825.44
S(Kj/Kg.K)	0.7	35.21	0.7	809.83	826.86	809.83	820.09	826.86

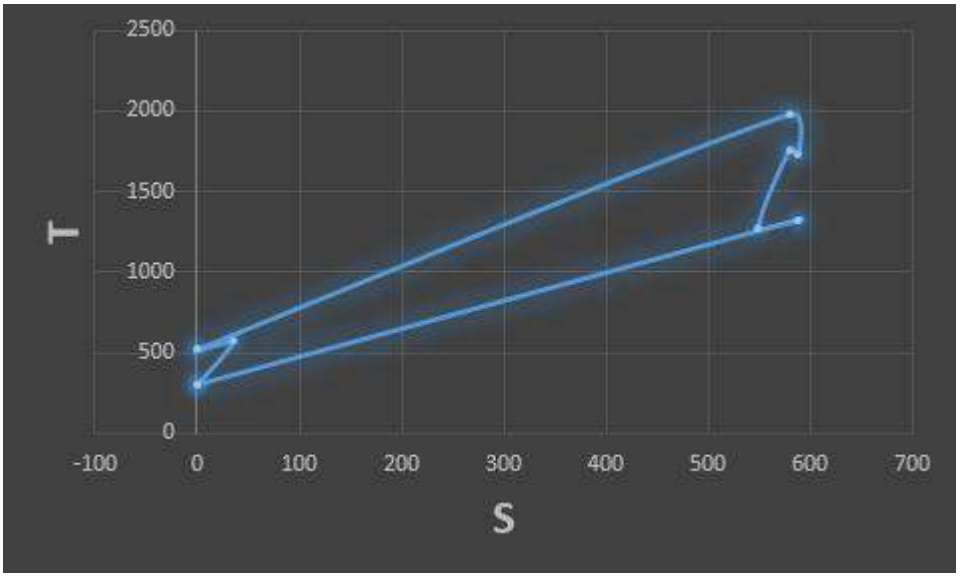


Figure 25:Results of the thermodynamic cycle (T-S)

Brayton loop in (T-S) diagram for a 5002C gas turbine showing the compression, heating, expansion and cooling phases, which helps to analyze cycle efficiency and improve turbine performance. The diagram shows the changes in temperature and entropy during each phase for optimal performance.

V.15.Hydrogen injection in the combustion chamber:

- **The second stage:**

injection of hydrogen in the combustion chamber:

we consider that the mass flow is constant.

$$LVH_{m1} = X_{GN} \times LVH_{GN} + X_{H_2} \times LVH_{H_2}$$

LVH (H_2) = 120000[24]

$$LVH_{X1} = (42308.6 \times 1.6415) + (120000 \times 0.035)$$

$$LVH_{X1} = 73469.57 \ Kj/Kg$$

We continued using the same calculation method and changed the combustion chamber to injection. The results obtained were the same, summarized in the table below:

Table 7: The amount of hydrogen and gas flow into the combustion chamber with LVHx

percent	$\dot{Q}_C(G_N)$	$\dot{Q}_C(H_2)$	LVH_X
100%	1.675	0	70866.90
2%	1.6415	0.0335	73469.57

6%	1.5745	0.1005	78674.89
8%	1.541	0.134	81277.55
12%	1.474	0.201	86482.88
15%	1.4238	0.2513	90394.98

Table 8: The obtained results for the efficiency of the combustion chamber and the thermal efficiency

η_{th}	η_{cc}	%
0.21	0.92	100%
0.45	0.96	2%
0.49	0.96	6%
0.51	0.96	8%
0.55	0.96	12%
0.58	0.96	15%

V.17.1. thermal efficiency:

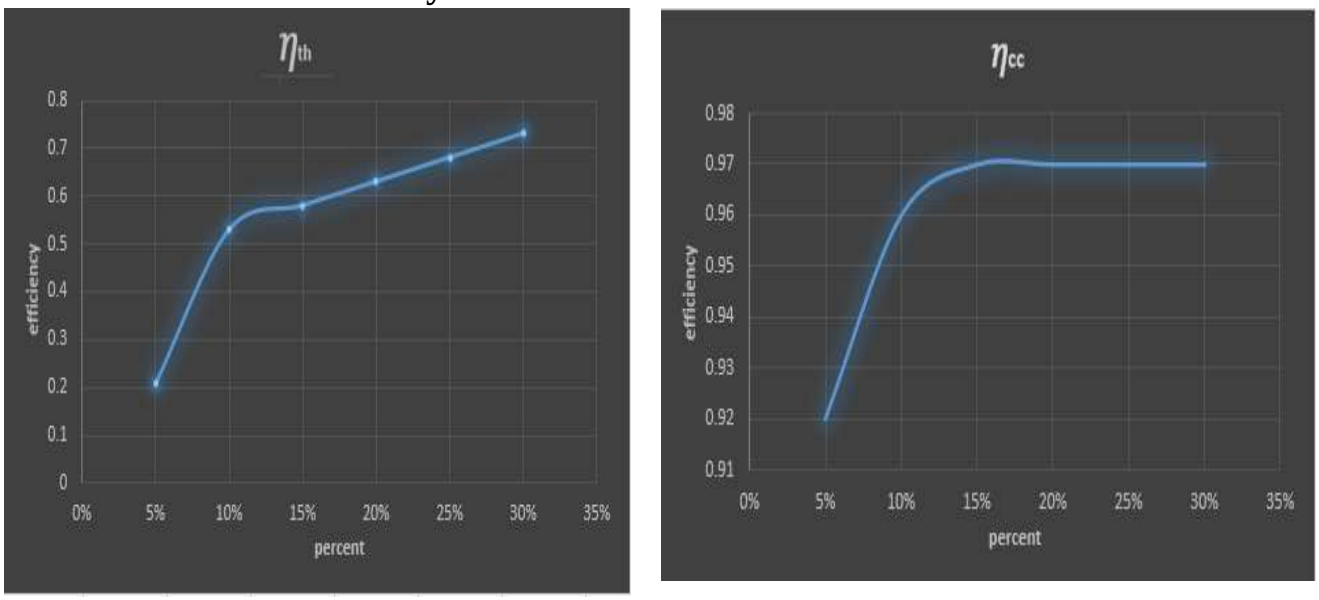


Figure 26: *Turbine thermal efficiency and Combustion chamber efficiency*

The continuous improvement in turbine efficiency with the addition of hydrogen reflects the enhancement in combustion chamber efficiency and the turbine's utilization of hotter gases resulting from efficient combustion. Starting from an efficiency of 0.92, increases in hydrogen

percentages lead to significant improvements in combustion chamber efficiency until it reaches and stabilizes at 0.96. Meanwhile, the turbine continues to improve its efficiency by benefiting from the enhancements in combustion processes and heat transfer.

V.17.2. Thermodynamic cycle:

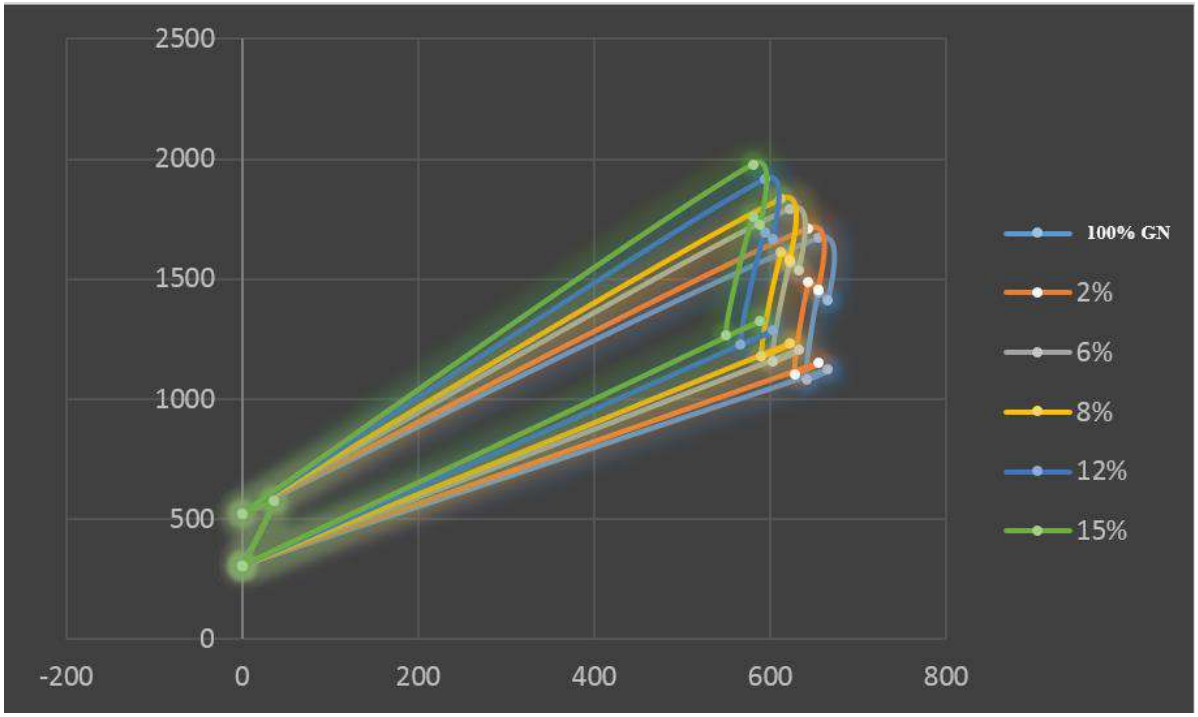


Figure 26: Brayton diagram cycle with hydrogen injection

Adding hydrogen in varying percentages to the combustion chamber in a Brayton cycle results in gradual increases in flame temperature. These temperature increases start as minor at 2%, become noticeable at 8%, significantly rise at 12%, and reach very high levels at 15%. These increases in temperature reflect the improvement in combustion efficiency, leading to enhanced overall performance of the Brayton cycle.

As the flame temperature increases due to the addition of hydrogen, the potential for formation of nitrogen oxides (NOx) increases. Nitrogen oxides form at high temperatures as nitrogen in the air reacts with oxygen [27]

V.18.Conclusion:

Adding hydrogen to gas turbine fuel increases combustion efficiency from 92% to 96%, reducing fuel costs and increasing productivity. It also contributes to environmental compliance, avoiding penalties and providing financial incentives.

General Conclusion:

In conclusion, the partial addition of hydrogen to the combustion chamber with natural gas significantly enhances the performance of the Brayton cycle, leading to increased cycle efficiency and higher temperatures. This improvement translates to better turbine performance, improved productivity, and clear economic benefits. However, these enhancements also introduce challenges related to nitrogen oxides (NOx) emissions, which form at high temperatures due to the reaction of nitrogen in the air with oxygen.

To tackle these challenges, technical and engineering modifications must be made to turbine configurations, combustion chamber design, and compressor settings, along with advanced gas dynamics studies. These adjustments ensure optimal performance and safety when using higher hydrogen ratios. Additionally, it is important to acknowledge that converting the thermal or chemical energy of the fuel into mechanical energy is never entirely perfect, as some energy is lost as heat or dissipated into the atmosphere.

Thermodynamic calculations for the MS5002C gas turbine show continuous improvements in turbine efficiency with the addition of hydrogen. These improvements reflect enhanced combustion chamber efficiency and the turbine's use of hotter gases from efficient combustion. Starting with an efficiency of 0.92, increasing hydrogen percentages lead to significant gains in combustion chamber efficiency, stabilizing at 0.96. Meanwhile, the turbine benefits from enhanced combustion processes and heat transfer. Adding hydrogen in varying percentages to the combustion chamber in a Brayton cycle results in gradual increases in flame temperature: minor increases at 2%, noticeable at 8%, significant at 12%, and very high at 15%. These temperature increases reflect improved combustion efficiency, enhancing the overall performance of the Brayton cycle.

Balancing improved turbine efficiency with reduced harmful emissions is a challenge that requires innovative and advanced solutions to ensure the sustainable and efficient use of hydrogen as a fuel.

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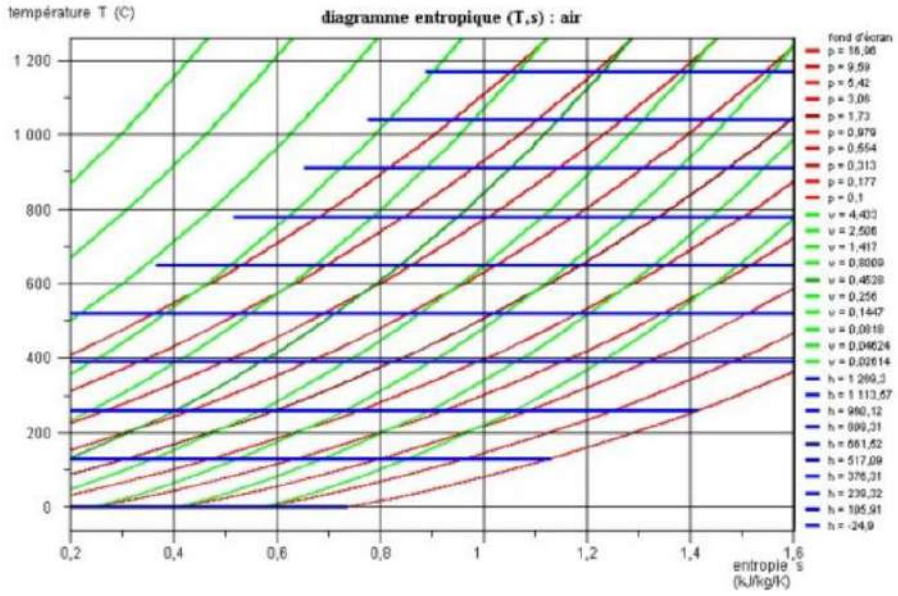
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Annexes

Annexes A:[25]



Annexes B:[22]

