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Energy performance enhancement of steam turbines

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الإهداء

الى من أضاء الله به دروب الحائرين وهدى به قلوب التائهين، الى من أخرج البشرية من ظلمات الجهل الى نور العلم والايمان، الى سيد الخلق ونور الحق ومعلم البشرية، اليك يا رسول الله ﷺ أهدي هذا العمل، راجيًا من الله أن يجعلني من أتباعك المخلصين

إلى من كان ظله أمانًا، وصوته عزيمة، ونظرته حافزًا يدفعني للمضي قُدمًا، إلى من سكب من عمره نورًا لطريقي، ومن تعبه راحتي، ومن سكونه سكينةً لقلبي، إلى من كان دعاؤه زادي، ودعمه سلاحي، وفخره بي أغلى أوسمة الحياة، الى والدي تاج رأسي وسندي في الحياة، أهديك هذا العمل المتواضع، لا وفاءً لجميلك، فجميلك لا يكافأ ولكن عرفانًا بالفضل، وامتنانًا لا تسعه الكلمات، حفظك الله لي ذُخرًا، وأدامك نورًا يضيء دروبي

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﴿سَنَشُدُّ عَضُدَكَ بِأَخِيكَ﴾، إليكما، يا من كنتم سندًا في الشدة، وعونًا في المسير، يا من شدّ الله بكما عضدي، وثبّت بكما خُطاي، أهديكما هذا الجهد المتواضع.

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إلى الأرض التي باركها الله، فكانت للحق عنوانًا وللصبر ميدانًا، إلى وطني فلسطين، منبع الحلم، ومهوى القلب، إلى غزة، مدينة الصمود التي تنزف ولا تنحني، إلى من يُواجهون الإبادة بصدور عارية وقلوب مؤمنة، إلى الشهداء، الذين خطّوا بدمائهم معاني الفداء، وإلى الجرحى، الذين تحمل أجسادهم آثار المعركة وكرامة الوطن، وإلى الأمهات، أمّهات الشهداء والجرحى، يا من جبينكنّ أعلى من قمم الجبال، وصبركنّ آية تُتلى، أهدي هذا العمل المتواضع، وقلبي يوقن أن العلم سلاح، وأن فلسطين... ستبقى ما بقيَ النبض

إلى الجزائر، أرض الشهداء والتاريخ العريق، إلى الأرض التي احتضنت غريبًا فصار فيها ابنًا، إلى جامعاتها التي منحتني العلم، وأهلها الذين غمروني بالمودة، أهدي هذا العمل المتواضع، عرفانًا بالجميل، ووفاءً لأرضٍ ما بخلت

إلى رفاقٍ زانوا العمرَ بلقياهمُ وكانت خُطاهم في الدروبِ بركةْ، إلى من شاركوني الطريق بحب، وحملونا ببساطة القلوب الطيّبة، إلى الذين جعلوا الطريق ألطف، والأيام أخف، الى من كانوا سندا ودعما، إليكم جميعًا أهدي هذا العمل

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شكر وعرفان

﴿ وَقُلِ اعْمَلُوا فَسَيَرَى اللَّهُ عَمَلَكُمْ وَرَسُولُهُ وَالْمُؤْمِنُونَ ﴾
سورة التوبة: 105

وقال رسول الله ﷺ "من لا يشكر الناس لا يشكر الله"
رواه الترمذي

الحمد لله الذي بنعمته تتم الصالحات، والصلاة والسلام على سيدنا محمد، وعلى آله وصحبه أجمعين.
احمد الله تعالى الذي مَنَّ عليَّ بفضله وتوفيقه، وأعانني على إنجاز هذا العمل، سائلًا إيّاه القَبول والإخلاص في القول والعمل.

ويسعدني أن أعبّر عن عظيم امتناني وأصدق معاني التقدير والاحترام لمشرفتي الفاضلة **البروفيسور/ بومعراف العطرة**، لما أولتني به من دعم متواصل، وتوجيهات علمية دقيقة، ونصائح نابعة من علمٍ واسع وخبرة رصينة، فكانت ركنًا ثابتًا ورافدًا معرفيًا أساسيًا في نجاح هذا العمل.

كما أتوجه بخالص الشكر والتقدير إلى لجنة التقييم والمناقشة على وقتهم الثمين وملاحظاتهم القيّمة وعلى رأسهم:

الدكتور/ جميلي عبد الوهاب

الدكتور/ قدري سليم

البروفيسور / بومعراف العطرة

كما أخص بالشكر والامتنان أساتذتي الكرام في قسم الهندسة الميكانيكية بجامعة **باجي مختار عنابة**، لما بذلوه من جهد في غرس قيم البحث، وتنمية روح التفكير العلمي، طيلة سنوات الدراسة.

ولا يفوتني أن أتوجه بجزيل الشكر والعرفان إلى عائلتي الغالية، التي كانت مصدر دعمي وسندي، ووفرت لي كل سبل الراحة والتشجيع لأبلغ هذه المرحلة.

وإلى زملائي وأصدقائي الأعزاء، الذين شاركوني رحلة العلم والمثابرة، أقول: شكرًا من القلب على كل دعم ومساندة.

أرجو من الله أن يكون هذا العمل لبنةً مباركة في صرح العلم، وخطوة في درب التقدّم وخدمة المجتمع.

Abstract

This study investigates the thermodynamic performance of steam turbines and explores enhancement techniques to improve their efficiency in industrial power systems. The research begins with a theoretical overview of turbomachinery, particularly gas and steam turbines, highlighting their classifications, working principles, and industrial relevance. A real-world context is established through the case study of the FERTIAL complex in Algeria, where steam turbines are integral to energy and fertilizer production.

A baseline analysis of a steam turbine operating under the Rankine and Hirn cycles is conducted using real operational data. Key components boiler, pump, turbine, and condenser are studied in detail, and performance indicators such as specific work output, thermal efficiency, and overall system efficiency are calculated.

Building upon this foundation, the study evaluates two thermodynamic enhancement strategies: reheating and steam extraction. These techniques are implemented and compared based on their impact on thermal performance, energy recovery, and fuel consumption. Results show that the reheated cycle achieves a thermal efficiency of 34.3% and power output of 46.75 MW, while the extraction cycle offers fuel savings with a global efficiency of 29.72%.

The findings demonstrate that applying well-established thermodynamic modifications can lead to meaningful gains in energy efficiency and operational effectiveness. This work offers valuable insights for optimizing steam turbine systems in industrial applications and provides a foundation for further research in sustainable energy technologies.

Résumé

Cette étude examine la performance thermodynamique des turbines à vapeur et explore des techniques d'amélioration visant à accroître leur efficacité dans les systèmes de production d'énergie industrielle. La recherche commence par une présentation théorique des turbomachines, notamment des turbines à gaz et à vapeur, en mettant en avant leurs classifications, principes de fonctionnement et importance industrielle. Un contexte réel est établi à travers l'étude de cas du complexe fertial en Algérie, où les turbines à vapeur jouent un rôle clé dans la production d'énergie et d'engrais.

Une analyse de base d'une turbine à vapeur fonctionnant selon les cycles de Rankine et de Hirn est réalisée à l'aide de données opérationnelles réelles. Les composants clés chaudière, pompe, turbine et condenseur sont étudiés en détail, et des indicateurs de performance tels que le travail spécifique, le rendement thermique et l'efficacité globale du système sont calculés.

Sur cette base, deux stratégies d'amélioration thermodynamique sont évaluées : le réchauffage et l'extraction de vapeur. Ces techniques sont mises en œuvre et comparées en fonction de leur impact sur les performances thermiques, la récupération d'énergie et la consommation de combustible. Les résultats montrent que le cycle avec réchauffage atteint un rendement thermique de 34,3 % et une puissance de 46,75 MW, tandis que le cycle à extraction permet une économie de combustible avec une efficacité globale de 29,72 %.

Les résultats démontrent que l'application de modifications thermodynamiques éprouvées permet des gains significatifs en efficacité énergétique et en performance opérationnelle. Ce travail offre des perspectives concrètes pour l'optimisation des systèmes à turbines à vapeur et constitue une base pour des recherches futures dans les technologies énergétiques durables.

الملخص

تتناول هذه الدراسة أداء التوربينات البخارية من الناحية الترموديناميكية، وتستعرض تقنيات تحسين تهدف إلى زيادة كفاءتها ضمن أنظمة الطاقة الصناعية. تبدأ الدراسة بعرض نظري شامل للتوربينات(Turbomachinery) ، مع التركيز على التوربينات الغازية والبخارية، من حيث تصنيفها، مبدأ عملها، وأهميتها في السياق الصناعي. كما يتم تقديم السياق التطبيقي من خلال دراسة حالة لمجمّع فرتيال (FERTIAL) في الجزائر، حيث تُستخدم التوربينات البخارية بشكل أساسي في إنتاج الطاقة والأسمدة.

يتم بعد ذلك تحليل التوربين البخاري الأساسي العامل وفق دورتي رانكن وهيرن باستخدام بيانات تشغيل فعلية. وتشمل الدراسة تحليلًا دقيقًا للمكوّنات الرئيسية مثل الغلاية، المضخة، التوربين والمكثف، إلى جانب حساب مؤشرات الأداء كالشغل النوعي، الكفاءة الحرارية، والكفاءة الإجمالية للنظام.

بناءً على هذا الأساس، تم تقييم تقنيتين لتحسين الأداء الترموديناميكي، وهما: إعادة التسخين والاستخراج البخاري. وقد أظهرت النتائج أن دورة إعادة التسخين تحقق كفاءة حرارية تصل إلى 34.3% وقدرة كهربائية تعادل 46.75 ميغاواط، بينما توفر دورة الاستخراج وفراً ملحوظاً في استهلاك الوقود مع كفاءة إجمالية قدرها 29.72%.

تُظهر هذه النتائج أن اعتماد تعديلات حرارية مدروسة يمكن أن يؤدي إلى تحسين ملموس في كفاءة الطاقة والأداء التشغيلي. وتشكّل هذه الدراسة مرجعًا مهمًا في تحسين أنظمة التوربينات البخارية وتفتح آفاقًا لبحوث مستقبلية في مجال الطاقات المستدامة.

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NOMENCLATURE

- **Latin letters**

Symbol	definition	unit
h	Specific Enthalpy	$J.kg^{-1}$
q	Specific Heat Transfer	$J.kg^{-1}$
P	Pressure	bar or Pas
P	Mechanical Power	W
T	Temperature	°C or K
$\dot{m}$	Mass flow rate	$Kg.S^{-1}$
W	Specific Work	$J.kg^{-1}$
LHV	Lower Heating Value	$J.kg^{-1}$

- **Greek letters**

Greek Letters	meaning
η	Efficiency

- **Subscripts**

Subscript	meaning
i	Inlet
o	Outlet
t	Thermal
T	Turbine
b	boiler
c	condenser
p	pump
tot	Total
sat	saturated
vap	vapor
liq	liquid
f	fuel
ex	extraction
re	reheating

General Introduction

Steam turbines have long been at the heart of thermal power generation, playing a central role in converting thermal energy into mechanical and, ultimately, electrical energy. As the global demand for more efficient and sustainable energy systems grows, so does the importance of optimizing the performance of turbomachinery. Among these machines, steam turbines offer particular challenges and opportunities due to the complex thermodynamic processes involved in their operation.

This study focuses on the design, analysis, and performance improvement of steam turbines, with a particular emphasis on systems used in industrial energy production. The work begins by laying out the theoretical foundations of turbomachinery in general, and gas and steam turbines in particular (Chapter I), including their principles of operation, classifications, and practical applications in sectors such as energy and petrochemicals. The case of Fertial, a major Algerian fertilizer producer, is introduced to illustrate the real-world relevance of these machines in the national industrial landscape.

In Chapter II, the focus shifts to a detailed analysis of a conventional steam turbine installation operating according to the Rankine and Hirn cycles. The key components of the system—boiler, turbine, condenser, and pump—are described and analyzed thermodynamically. The performance of the Fertial steam turbine is evaluated based on real data, and key indicators such as specific work output, thermal efficiency, and global cycle efficiency are calculated.

Building upon this foundation, Chapter III explores two well-established enhancement techniques: reheating and steam extraction. These modifications aim to increase the average temperature of heat addition, reduce moisture content at the turbine outlet, and recover thermal energy for other uses. Each configuration is modeled, analyzed, and compared in terms of thermal performance, efficiency, and fuel consumption.

By combining theoretical understanding with industrial context and performance modeling, this work aims to contribute to the development of more efficient and economically viable steam power systems, with practical insights relevant to both engineering practice and academic research.

Chapter I

General information on turbomachines

I.1. Introduction

Turbomachinery plays a pivotal role in modern power systems and industrial applications, serving as a fundamental pillar of mechanical operations in large-scale energy generation and manufacturing processes. This chapter aims to provide a coherent theoretical foundation for understanding these machines, beginning with their definitions and classifications, followed by an in-depth analysis of their main types particularly gas and steam turbines due to their strategic importance across various industrial sectors. A section of this chapter is dedicated to a case study of the Fertial complex, presented as a practical example that illustrates the integration of theoretical concepts with real-world industrial applications in the Algerian context. The chapter seeks to establish a solid conceptual framework that paves the way for the technical and applied analyses of steam turbines in the subsequent chapters

I.2. Presentation of fertial

I.2.1. History of the company

It was in 1967 that sonatrach decided to build two petrochemical complexes to produce nitrogen and phosphate fertilisers in Annaba and Arzew. The construction of these complexes represented ‘an important milestone in the promotion of the petrochemical industry in Algeria’ and also reflected ‘Algeria's determination to opt for a process of industrialisation’. This major project was already shaping the country's economy. The first phase involved the laying and construction of the Arzew platform, on which were built an ammonia unit, a nitric acid unit, an ammonium nitrate and urea unit, and two nitrate, urea and ammonia storage and shipping units. The same platform is equipped with a utilities plant. In Annaba, there are units producing sulphuric and phosphoric acid and a wide range of fertilisers, as well as a number of supporting utilities. The second phase involved the construction of a second platform at Arzew, on which two ammonium units, two nitric acid units, an ammonia unit, two utility plants and two nitrate storage units were built between 1975 and 1981. As for Annaba, it was in 1975 that the nitrogen fertiliser complex was created, which was extended in 1982 with the installation of nitric acid, ammonium nitrate and sodium trypolyphosphate units. The ammonia unit went into production in 1987. In September 1984, the Arzew plant was integrated to the Annaba plant and all the units of the two complexes entered in portfolio under the new entity Asmidal which will become a joint stock company in 1996.With the economic reforms undertaken by the Algerian government, a partnership agreement was concluded between Asmidal and the Spanish group Villar Mir. This led to the creation of Fertial, which grouped together the Annaba and Arzew units. After colossal investments aimed at improving, renovating and modernising equipment and installations, Fertial is still considered to be a flagship of the petrochemical industry in Algeria.

I.2.2. Platform management

There are two industrial centers:

1. ANNABA platform: complex manufacturing phosphate fertilisers, nitrogen fertilisers and ammonia (NH3: 1000T/d and 1000T/d ammonium nitrate)
2. ARZEW platform: complex manufacturing nitrogen fertilisers and ammonia (NH3: 1000T/d and 1500T/d ammonium nitrate)

I.2.3. Presentation of the platform -annaba

It is run by a management team and employs around 800 workers, distributed as follows:

- Senior management: around 50
- Management: around 350
- Supervisors: around 400

Within the complex, there are two zones: the southern zone, which includes the old ‘phosphate fertiliser’ workshops that started up in 1972, and the northern ‘nitrogen fertiliser’ zone, which includes the so-called new workshops that started up in 1982

1. Phosphate fertiliser’ southern zone: composed of three main workshops:
   - Fertilizer workshop: NPK and liquid UAN
   - Super simple phosphate workshop: SSP
   - Utilities plant 1
2. Northern zone ‘nitrogen fertilizers’ this zone also includes five units:
   - Nitric acid workshop
   - Ammonium nitrate workshop
   - Ammonia workshop
   - Handling and storage facility
   - Utilities plant 2

I.2.4. Main activities

Fertial annaba has several activities, the most important of which are listed below:

Figure I.1: Some of Fertial's products

List of products manufactured or sold by fertial

- Production of ammonia ◊capacité 1000 t/d
- Production of ammonium ◊02 line of 500 t/d each
- Production of nitric acid ◊02 line of 400 t/d each
- Production of phosphate fertilizers : 1000 t/d
- SSP ‘ Super Simple Phosphate ’ ◊capacité 1200 t/d
- UAN ‘ Urea Nitric Acid ’ ◊capacité 600t/d
- Nitrogenous fertilizers :
    - Ammonium nitrate
    - UAN 32%
    - Urea 46% (imported)

Fertial uses some of its own nitrate and ammonia to produce other products
The table below summarises the countries in which fertial exports its products

Production	Country
NH_3	Spain, France, Italy, Greece, Belgium, Cuba
Nitrate	Tunisia, Morocco
UAN	France, Spain, USA
SSP	Morocco, Greece, France, Italy , Brazil

Table I.1: Countries to which fertial exports

I.2.5. Objectives of the company

Within the national framework of the economic and social development of the country, the company is responsible for:

- Promoting and developing the fertilizer and phytosanitary product industry
- Exploiting, managing and making the most of the human, material and financial resources at its disposal
- With a view to satisfying the needs of the national and international markets
- Encouraging the use of imagination and initiative and making use of local resources.

I.3. Turbomachines

I.3.1 Introduction

A turbomachine is a device in which energy transfer occurs between a flowing fluid and a rotating element due to dynamic action, and results in a change in pressure and momentum of the fluid. Mechanical energy transfer occurs inside or outside of the turbomachine, usually in a steady-flow process. Turbomachines include all those machines that produce power, such as turbines, as well as those types that produce a head or pressure, such as centrifugal pumps and compressors. The turbomachine extracts energy from or imparts energy to a continuously moving stream of fluid. however in a positive displacement machine, it is intermittent. The turbomachine covers a wide range of machines, such as gas turbines, steam turbines, centrifugal pumps, centrifugal and axial flow compressors, windmills, water wheels, and hydraulic turbines. In this text, we shall deal with incompressible and compressible fluid flow machines.

I.3.2. Classifications of turbomachines

Turbomachines can be classified in several ways based on their(function, flow direction, fluid type, and operating principle **)** we will just classified based on energy transfer:

a) Power absorbing machines

Convert mechanical energy into fluid energy (increase pressure/head).

Examples:

- **Fans**: machines that impart only a small pressure-rise to a continuously flowing gas; usually the gas may be considered to be incompressible.
- **Compressors**: machines that impart kinetic energy to a gas by compressing it and then allowing it to rapidly expand. compressors can be axial flow, centrifugal, or a combination of both types, in order to produce the highly compressed air. In a dynamic compressor, this is achieved by imparting kinetic energy to the air in the impeller and then this kinetic energy is converted into pressure energy in the diffuser.
- **Pumps** are a category of turbomachines designed to transfer fluids (usually liquids) by converting mechanical energy into hydraulic energy (pressure energy)

b) Power generating machines

Convert fluid energy into mechanical energy.

Examples:

- **Turbines**: Machines that produce power by expansion of a continuously flowing fluid to a lower pressure or head and we will get to know some of its types in this chapter.

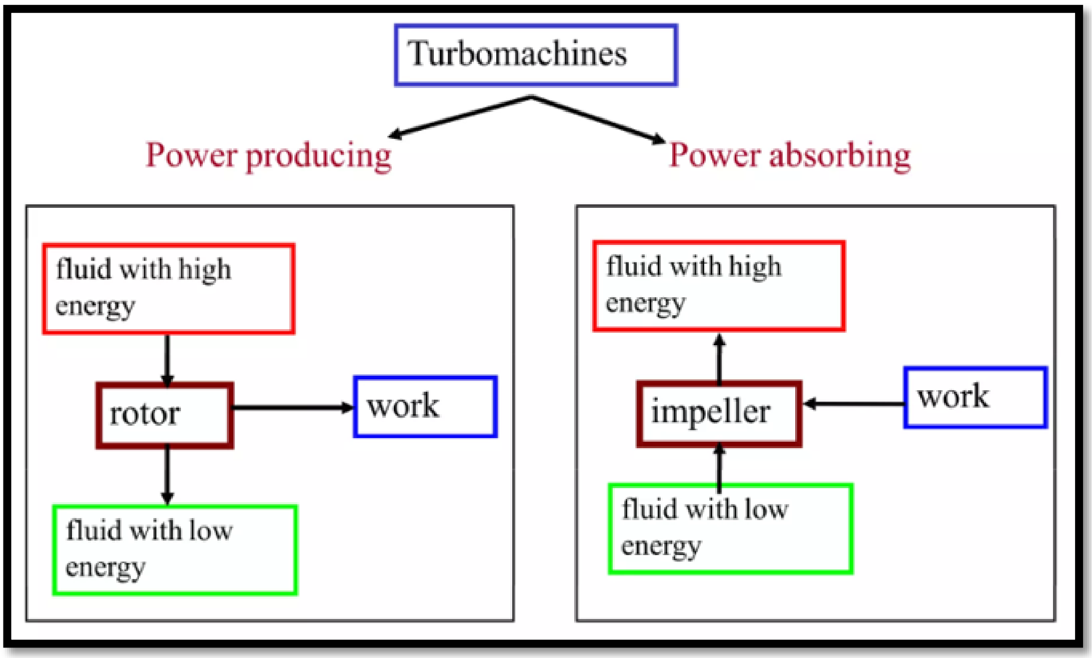

Figure I.2: Classifications of turbomachines

I.4. Gas turbine

I.4.1. Introduction

A gas turbine, often referred to as a jet engine, is a powerful and versatile mechanical device used in various applications, including aircraft propulsion, power generation, and industrial processes. It operates on the principle of compressing and combusting air with fuel to produce high-speed exhaust gases that drive a turbine, converting energy into useful mechanical work. This efficient technology plays a crucial role in modern transportation and energy production.

1.4.2. What is a gas turbine?

A gas turbine is a mechanical device that harnesses the energy of pressurized gas, typically air, to generate power. It operates by compressing incoming air, mixing it with fuel, igniting the mixture, and then allowing the high-speed exhaust gases to drive a turbine. This technology finds extensive use in aircraft engines, power plants, and various industrial applications, providing efficient and reliable power generation and propulsion.

I.4.3. Components of a gas turbine

A gas turbine consists of several essential components, including a compressor, combustion chamber, turbine, and sometimes a power turbine. The compressor compresses incoming air, which then mixes with fuel in the combustion chamber, where it ignites. The high-velocity exhaust gases drive the main turbine, producing mechanical energy for various applications, like aircraft propulsion or electricity generation.

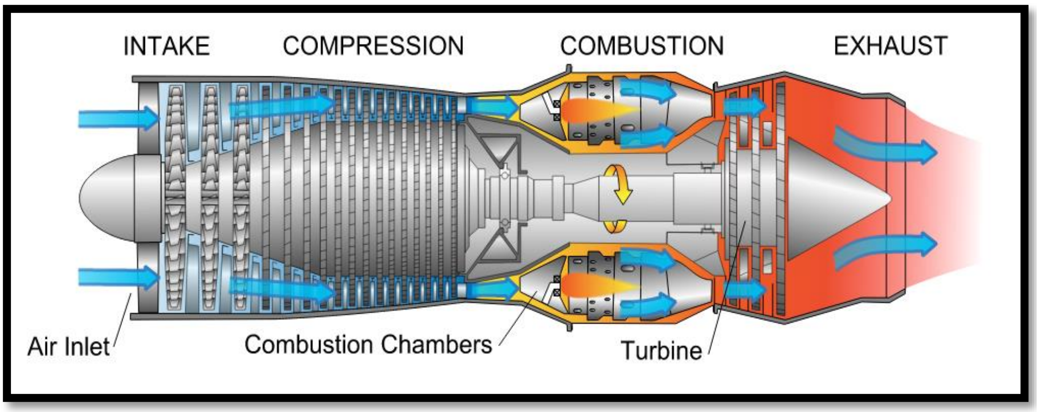

Figure I.3: Components of gas turbine

Gas turbines consist of four primary components:

1. Air compressor

Positioned between the combustion chamber and the turbine, both the air compressor and the turbine are mounted on a common shaft. Gas turbines require a starting motor as they lack self-starting capabilities. The air compressor's role is to draw in and compress air, elevating its pressure. Axial design compressors with multiple stages are preferred for advanced and large gas turbines.

2. Combustion chamber

In this component, compressed air mixes with fuel, resulting in a fuel-air mixture that undergoes combustion, and the combustion products are directed into the gas turbine. The high air pressure ensures efficient fuel mixture combustion. Gas turbines commonly use liquid fuel, gaseous fuel, or natural gas. Three types of combustion chambers are typically employed: annular combustor chambers, can (multi-can) combustor chambers, and can-annular combustor chambers. Fuel is injected at the upstream end in the form of a finely atomized spray, and fuel nozzles may be of simplex or dual fuel types. Some gas turbines are "bi-fuel," allowing them to burn a mixture of gas and liquid fuel.

3. Turbine

The multistage gas turbine is where hot gases pass through, and their kinetic energy is converted into shaft horsepower. Like a steam turbine, a gas turbine features stationary and moving blades. Stationary blades serve to direct the flow of gases to the rotor blades and adjust their velocity. The turbine's shaft is connected to a generator.

4. Exhaust module

Hot gases exit the gas turbine through the exhaust section, which comprises inner and outer housing components. Additional components of a gas turbine system include:

- Cooling system
- Bearing and lubrication system
- Fuel system, among others.

I.4.4. Working Principle of gas turbine

To illustrate the gas turbine's fundamental operation, consider the analogy of a rocket engine. When fuel burns in a rocket, high-pressure exhaust gas is generated, which, according to the law of conservation of energy, converts the chemical energy of the fuel into mechanical energy. If the rocket is immobilized by a fixed structure, the high-pressure exhaust gas is expelled in the opposite direction. however, by incorporating a set of turbine blades into the rear-facing exhaust gas stream, the released mechanical energy is efficiently transformed into rotational movement of the turbine shaft.

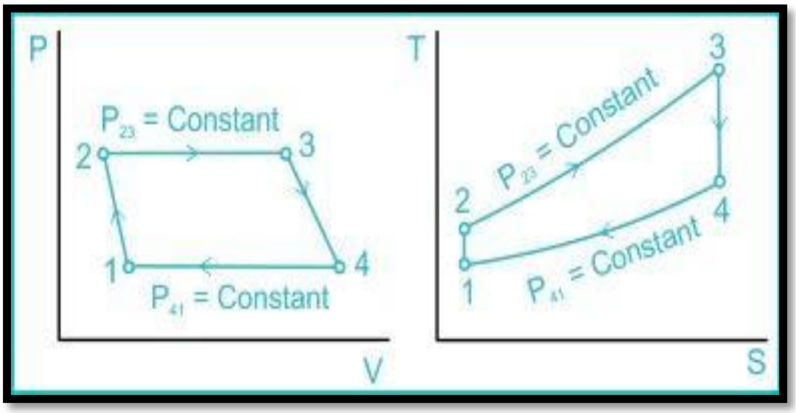

Figure I.4: Brayton cycle

A gas turbine operates based on the thermodynamic principles of the Brayton Cycle (Figure I.4), a cycle comprising two adiabatic work transfers and two constant-pressure heat transfer processes. This cycle involves several key states:

- State 1 to State 2 involves an isentropic, adiabatic compression that elevates the gas's temperature, pressure, and density.
- In State 2 to State 3, heat is added at a constant pressure, typically through a combustion process.
- State 3 to State 4 sees the gas passing through an adiabatic isentropic turbine, lowering its temperature and pressure.
- Heat is extracted from the gas between State 4 and State 1 via a heat exchanger for a closed gas turbine Brayton cycle.

In essence, the chemical energy from the fuel gas is converted into the rotational mechanical energy of the turbine shaft. In practical terms, a gas turbine functions as hot gases flow through a multi-stage gas turbine with both stationary and moving blades. These stationary blades control velocity and guide the gas flow towards the rotor blades. The turbine shaft is coupled to a generator, thus producing useful mechanical energy.

I.4.5. Classification of gas turbines

Gas turbines are classified into various types based on their applications and design features. These classifications include aviation turbines for aircraft propulsion, industrial turbines for power generation and mechanical drive, and marine turbines for ship propulsion.
Various types of gas turbines cater to a range of applications and requirements:

- Open-Cycle gas turbine

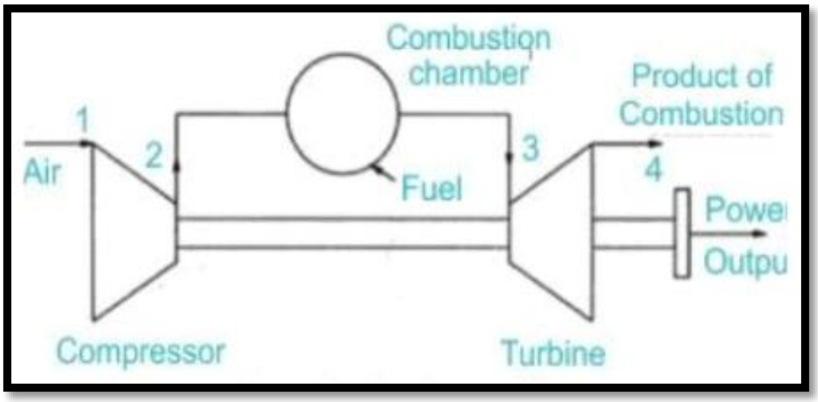

Figure I.5: Open cycle gaz turbine

The open-cycle gas turbine comprises three primary components: a combustion chamber, turbine, and compressor. The compressor elevates air pressure by drawing in ambient air, while fuel combustion in the combustion chamber raises air temperature. Heated gases from the combustion chamber expand and perform mechanical work in the turbine the above (figure I.5) presents the schematic of a open-cycle gas turbine.

- Closed-cycle gas turbine

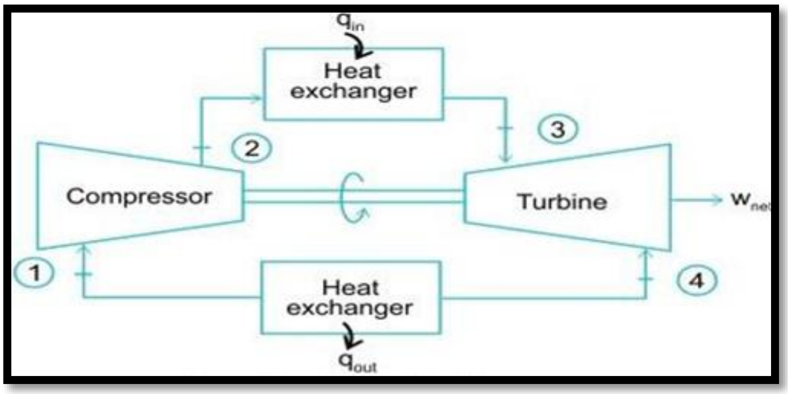

Figure I.6: Closed cycle gaz turbine

In a closed-cycle gas turbine, the working fluid, typically air or another suitable medium, exits the compressor and undergoes heating at a relatively constant pressure through an external heat source. the high-pressure, high-temperature air is then directed to the turbine. Post-turbine, the fluid is cooled to its initial temperature by an external cooling agent before being recirculated to the compressor. This closed-loop process enables consistent fluid use with minimal phase change the above (figure I.6) presents the schematic of a closed-cycle gas turbine.

- Aero-derivative gas turbine

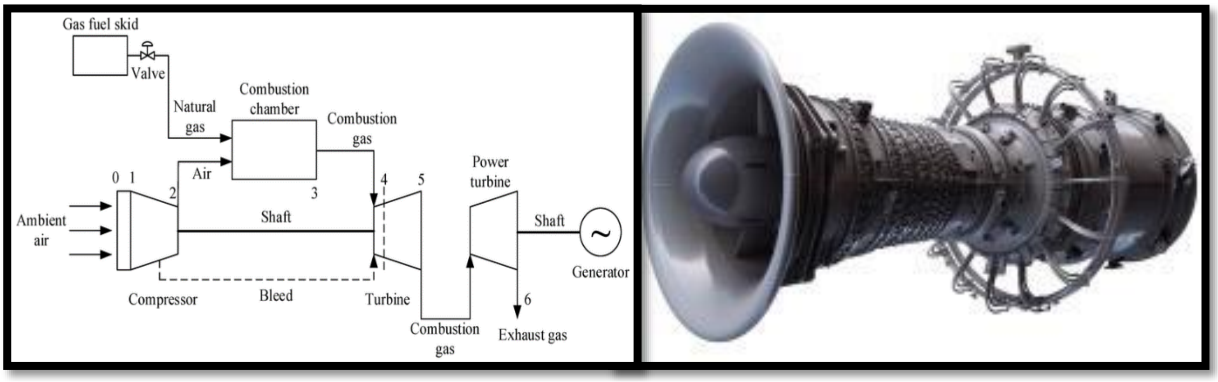

Figure I.7: Aero Derivative gas turbine

Aero-derivative gas turbines find use in electrical power generation due to their rapid load response and shutdown capabilities. they are also employed in the marine industry to reduce weight.

Scale jet engines

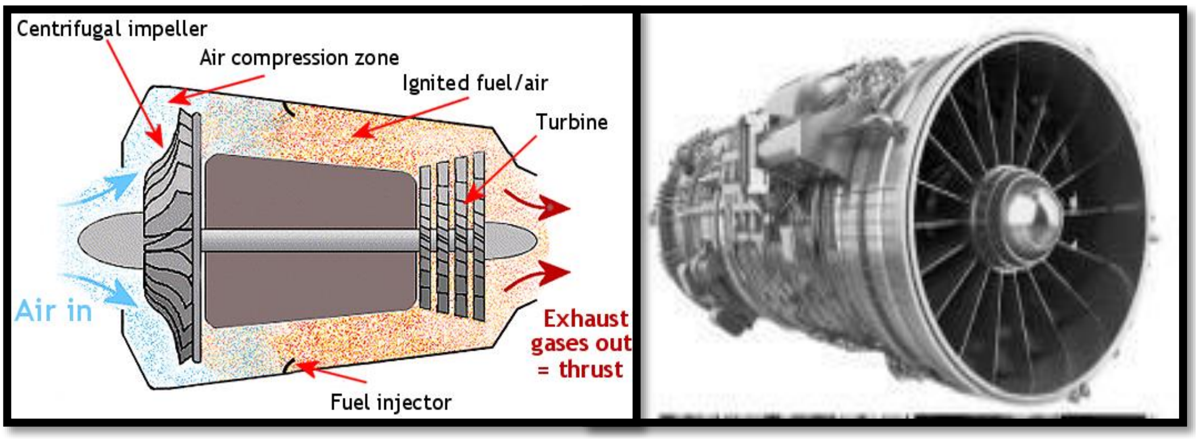

Figure I.8: Scale jet engines

Also known as miniature gas turbines, scale jet engines can produce up to 22 Newton of thrust and are easily constructible by many mechanical engineers using basic tools like a metal lathe.

Auxiliary gas turbine

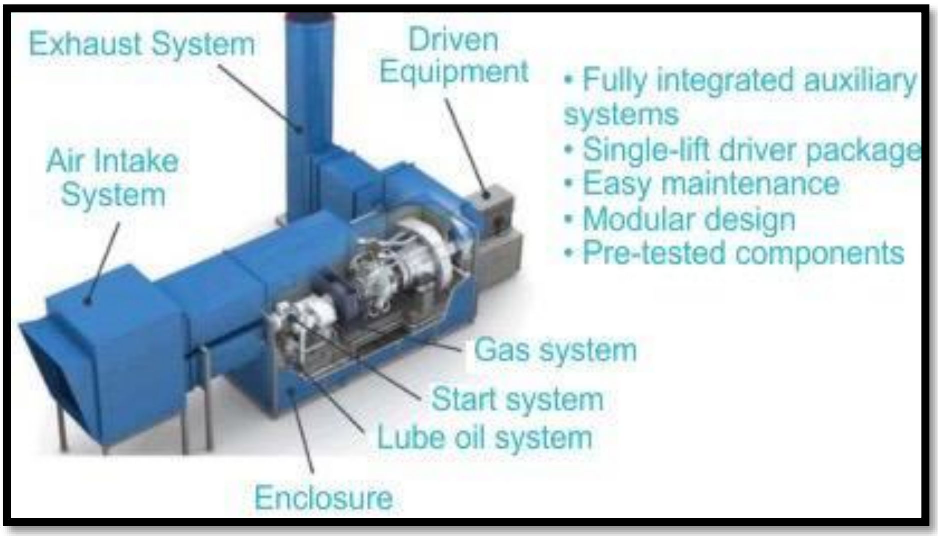

Figure I.9: Auxillary gas turbine

Smaller auxiliary gas turbines serve various aircraft functions, such as providing air conditioning, ventilation, and compressed air power for jet engines. They also supply mechanical power to start larger jet engines or drive shafted accessories.

I.4.6. Gas turbine performance

Several factors influence the performance of a gas turbine:

- Inlet air density: the density of the incoming air significantly affects turbine performance, as it impacts the compressor's ability to pressurize the air.
- Ambient air temperature: The temperature of the surrounding air affects the efficiency of the combustion process and the overall turbine performance.
- Altitude and ambient pressure: operating at higher altitudes with lower ambient pressures can reduce a gas turbine's efficiency due to decreased air density.
- Humidity: the moisture content in the air can impact combustion efficiency and turbine output.
- Inlet and exhaust pressure losses: pressure losses at the inlet and exhaust of the turbine can affect overall performance and efficiency.

I.4.7. Advantages of gas turbines

- The advantages of gas turbines are:
- Gas turbines are known for their high power output relative to their compact size and weight.
- They are smaller and lighter compared to other power generation systems of similar capacity.

- They can be rapidly started and stopped, making them suitable for meeting fluctuating power demands.
- They can operate on a variety of fuels, including natural gas, diesel, and aviation fuels.
- Gas turbines can be designed for reduced emissions, contributing to cleaner energy production.
- They offer high thermal efficiency in converting fuel into electricity.
- They run smoothly with minimal vibration and noise levels.
- They are known for their reliability and typically require less maintenance compared to some other power generation systems.

I.4.8. Disadvantages of gas turbines

- Some notable disadvantages include:
- Lower efficiency at partial loads
- High fuel consumption at idle or low loads
- Vulnerable to fluctuations in fuel quality
- Initial cost can be high
- Complex maintenance and repair procedures
- Limited efficiency improvements over the years

I.4.9. Applications of gas turbine

- Gas turbines find applications in the following areas:
- Gas turbines are used to generate electricity in power plants.
- Jet engines in airplanes are gas turbines.
- Gas turbines power some naval ships and cruise liners.
- They drive industrial equipment and mechanical systems.
- Gas turbines are used in oil drilling and processing.
- For transporting natural gas through pipelines.
- Gas turbines drive various pumps and compressors.
- Used in backup generators.
- Some tanks and vehicles use gas turbines for propulsion.

I.5. Steam turbine

I.5.1. Introduction

A steam turbine or steam turbine engine is a machine or heat engine that extracts thermal energy from pressurized steam and uses it to do mechanical work on a rotating output shaft. The steam turbine is a form of heat engine that derives much of its improvement in thermodynamic efficiency from the use of multiple stages in the expansion of the steam, which results in a closer approach to the ideal reversible expansion process. Because the turbine generates rotary motion, it can be coupled to a generator to harness its motion into electricity. Such turbo generators are the core of thermal power stations which can be fueled by fossil fuels, nuclear fuels, geothermal, or solar energy.

I.5.2. History

The first device that may be classified as a reaction steam turbine was little more than a toy, the classic Aeolipile, described in the 1st century by Hero of Alexandria in Roman Egypt. The modern steam turbine was invented in 1884 by Charles Parsons, whose first model was connected to a dynamo that generated 7.5 kilowatts (10.1 hp) of electricity. The invention of Parsons' steam turbine made cheap and plentiful electricity possible and revolutionized marine transport and naval warfare. Parsons' design was a reaction type. His patent was licensed and the turbine scaled up shortly after by an American, George Westinghouse. The Parsons turbine also turned out to be easy to scale up. Within Parsons' lifetime, the generating capacity of a unit was scaled up by about 10,000 times, and the total output from turbo-generators constructed by his firm C. A. Parsons and Company and by their licensees, for land purposes alone, had exceeded thirty million horse-power Other variations of turbines have been developed that work effectively with steam. The de Laval turbine (invented by Gustaf de Laval) accelerated the steam to full speed before running it against a turbine blade. De Laval's impulse turbine is simpler and less expensive and does not need to be pressure-proof. It can operate with any pressure of steam, but is considerably less efficient. Auguste Rateau developed a pressure compounded impulse turbine using the de Laval principle as early as 1896 .The Brown-Curtis turbine, an impulse type, which had been originally developed and patented by the U.S. company International Curtis Marine Turbine Company, was developed in the 1900s in conjunction with John Brown & Company. It was used in John Brown-engine merchant ships and warships, including liners and Royal Navy warships.

I.5.3. components and their functions within a steam power plant

1. **Boiler:** the boiler is responsible for heating water to generate steam. this is typically achieved by burning fossil fuels (such as coal, oil, or natural gas) or by using nuclear energy. the generated steam is at high pressure and temperature.
2. **Turbine:** the high-pressure steam from the boilers is directed into a turbine. The turbine is designed with blades that are turned by the force of the steam’s high-speed flow. As the steam flows through the turbine, its high-pressure energy is converted into rotational mechanical energy.
3. **Generator:** the turbine is connected to a generator, which consists of coils of wire within a magnetic field. as the turbine spins, it turns the rotor of the generator, creating

a moving magnetic field. This movement induces an electric current in the wire coils, ultimately producing electrical energy.

4. **Condenser:** After passing through the turbine, the steam is directed to the condenser. here, the steam is cooled and condensed back into water, releasing its latent heat. This process allows for the efficient reuse of the water in the boiler, reducing water consumption and increasing overall efficiency.
5. **Cooling system**: Steam power plants require a cooling system to dissipate excess heat from the condenser. this can involve cooling water from nearby water bodies, cooling towers, or other heat exchange methods.

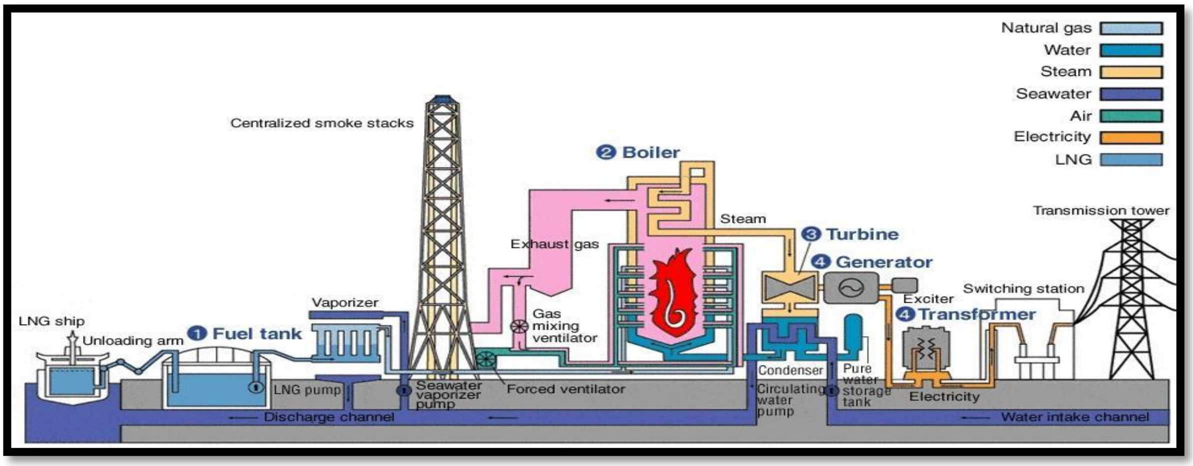

Figure I.10: Steam power plant

I.5.4. Key components of a turbine

➢ **Blades:**

The blades in a steam turbine serve a critical function, similarly to the sails on a ship. They are expertly designed to capture the force and pressure of steam. As steam is funneled onto these blades and the steam expands, their precise angling and aerodynamic shape allow them to convert the steam's thermal energy into kinetic energy and control the flow of steam, effectively transforming heat and steam pressure into mechanical motion.

➢ **Rotor:**

This component is the dynamic core of the turbine, essentially forming the backbone of the entire system. The rotor, to which the blades are attached, converts the force exerted by the steam onto the blades into rotational motion. It's this rotation that is central to the power generation process, with the rotor's speed and stability being critical factors in the turbine's overall efficiency.

➢ **Casing:**

The casing of a steam turbine plays a vital role in ensuring operational safety and efficiency. It acts as a robust, protective barrier that encloses the high-pressure steam and the rotating blades. This containment is crucial, as it not only prevents the escape of steam but also maximizes the steam's impact on the blades. the casing is designed to withstand extreme temperatures and pressures, ensuring the longevity and reliability of the turbine.

- **Bearings:**

Bearings are essential in maintaining the smooth operation of the rotor. positioned at key points along the rotor, they reduce friction and wear, allowing for a seamless and efficient rotation. The bearings must be capable of handling the high rotational speeds and significant loads of the rotor while ensuring minimal energy loss. Regular maintenance of these bearings is crucial to prevent mechanical failures and to sustain the turbine's optimal performance.

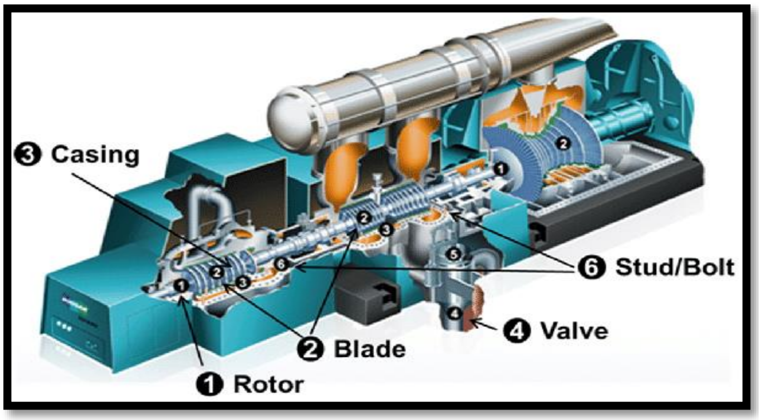

Figure I.11: Key Components of a turbine

I.5.5. The basic principle of steam turbine

The process of converting steam into mechanical power in a steam turbine is a sophisticated yet fundamental concept. It centers on the interaction between steam and a series of meticulously designed blades. These blades are strategically mounted on a shaft, a central rod that serves as the axis of rotation that rotate the turbine .When a high-pressure flow of steam is directed onto these blades, it imparts its kinetic energy to them. This action causes the blades, and consequently the shaft, to rotate. This rotational movement is more than just mechanical motion; it is the critical element in the generation of power output. The efficiency of this process is heavily reliant on the design of the blades and the quality of the steam. The blades are shaped to capture the maximum energy from the steam, converting heat and pressure into rotational force. This force is then harnessed and transferred to generate electricity or to drive other mechanical processes. The spinning of the turbine shaft is a pivotal step in transforming the latent thermal energy of steam into usable mechanical energy. this transformation is a cornerstone in various applications, notably in electricity generation, where it plays a vital role in powering homes, businesses, and industries. the elegance of this system lies in its ability to efficiently harness a natural resource like steam for substantial power production.

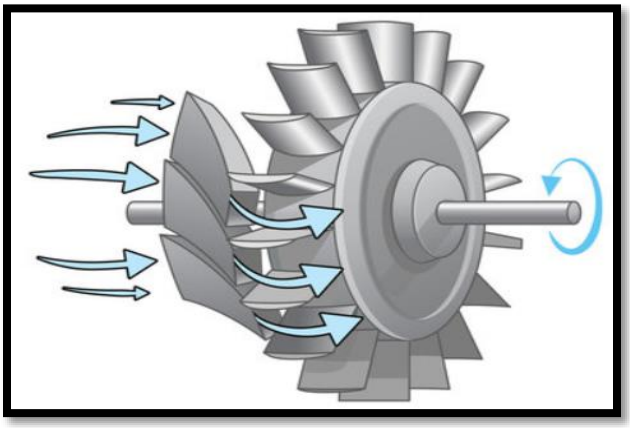

Figure I.12: Steam turbine mechanism

I.5.6. Types of steam turbines

Steam turbines may be classified into different categories depending on their construction, working pressures, size, and many other elements. but there are two basic types of steam turbines which are called impulse and reaction turbines. there are other types of steam turbines that are actually derivatives of these two main types.

1. Impulse Turbine

In this type of turbine, the superheated steam is projected at high velocity from fixed nozzles in the casing. when the steam strikes the blades (sometimes called buckets), it causes the turbine shaft to rotate. the high pressure and intermediate pressure stages of a steam turbine are usually impulse turbines. the entire pressure drops of steam take place in stationary nozzles only. Though the theoretical impulse blades have zero pressure drop in the moving blades, practically, for the flow to take place across the moving blades, there must be a small pressure drop across the moving blades also. in impulse turbines, the steam expands through the nozzle, where most of the pressure potential energy is converted to kinetic energy. The high-velocity steam from fixed nozzles impacts the blades changes its direction, which in turn applies a force. the resulting impulse drives the blades forward, causing the rotor to turn. The main feature of these turbines is that the pressure drop per single stage can be quite large, allowing for large blades and a smaller number of stages. Except for low-power applications, turbine blades are arranged in multiple stages in series, called compounding, which greatly improves efficiency at low speeds. Modern steam turbines frequently employ both reaction and impulse in the same unit, typically varying the degree of reaction and impulse from the blade root to its periphery. the rotor blades are usually designed like an impulse blade at the rot and like a reaction blade at the tip. Since the Curtis stages reduce the pressure and temperature of the fluid to a moderate level significantly with a high proportion of work per stage. a usual arrangement is to provide on the high-pressure side one or more curtis stages, followed by Rateau or reaction staging. In general, when friction is taken into account reaction stages the reaction stage is found to be the most efficient, followed by rateau and curtis in that order. Frictional losses are significant for curti's stages since these are proportional to steam velocity squared. The reason that frictional losses are less significant in the reaction stage lies in the fact that the steam expands continuously and therefore flow velocities are lower.

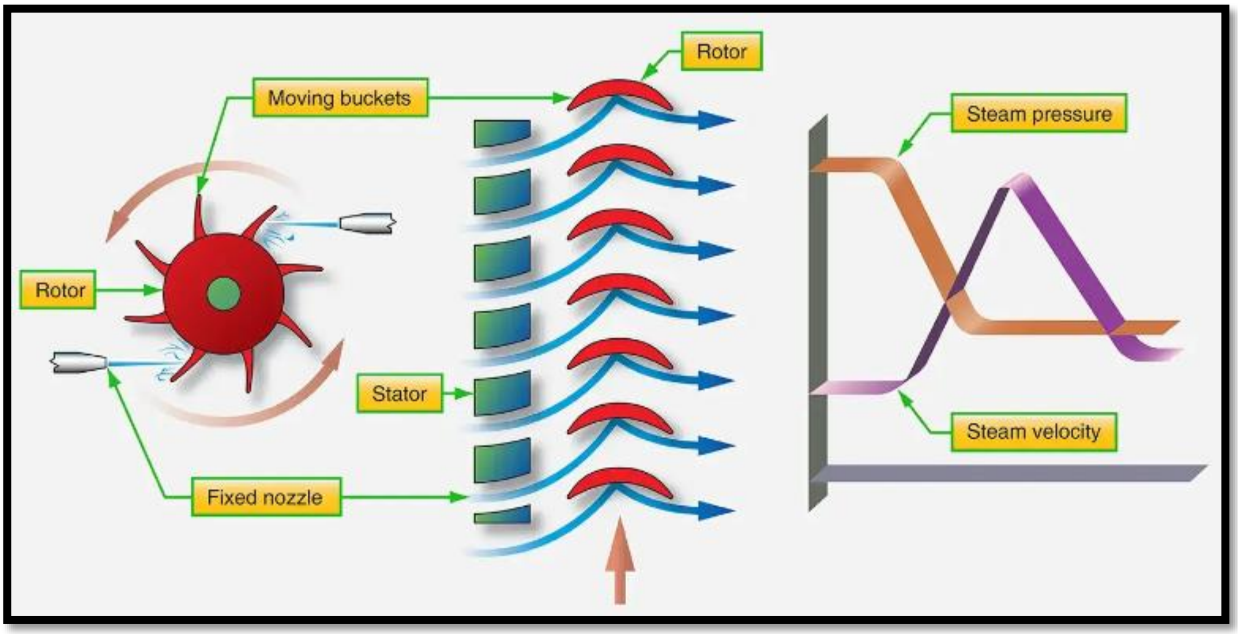

Figure I.13: Impulse turbine

2. Reaction turbine

In this type of steam turbine, the steam passes from fixed blades of the stator through the shaped rotor blades nozzles causing a reaction and rotating the turbine shaft. The low-pressure stage of a steam turbine is usually a reaction-type turbine. This steam having already expanded through the high and intermediate stages of the turbine is now of low pressure and temperature, ideally suited to a reaction turbine. In reaction turbines, the steam expands through the fixed nozzle, where the pressure potential energy is converted to kinetic energy. The high-velocity steam from fixed nozzles impacts the blades (nozzles), changes their direction, and undergoes further expansion. The change in its direction and the steam acceleration applies a force. The resulting impulse drives the blades forward, causing the rotor to turn. There is no net change in steam velocity across the stage but with a decrease in both pressure and temperature, reflecting the work performed in the driving of the rotor. In this type of turbine, the pressure drops take place in a number of stages, because the pressure drop in a single stage is limited. The main feature of this type of turbine is that in contrast to the impulse turbine, the pressure drop per stage is lower, so the blades become smaller, and the number of stages increases. On the other hand, reaction turbines are usually more efficient, i.e. they have higher "isentropic turbine efficiency". The reaction turbine was invented by Sir Charles Parsons and is known as the Parsons turbine. In the case of steam turbines, such as would be used for electricity generation, a reaction turbine would require approximately double the number of blade rows as an impulse turbine, for the same degree of thermal energy conversion. Whilst this makes the reaction turbine much longer and heavier, the overall efficiency of a reaction turbine is slightly higher than the equivalent impulse turbine for the same thermal energy conversion. Modern steam turbines frequently employ both reaction and impulse in the same unit, typically varying the degree of reaction and impulse from the blade root to its periphery. The rotor blades are usually designed like an impulse blade at the rot and like a reaction blade at the tip. You have to remember that although there only two types of steam turbine there are numerous mechanical arrangements of these, which include reheat steam turbines, cross compound steam turbines, single casing turbines, tandem steam turbines, condensing and exhaust steam turbines and, axial and radial flow steam turbines.

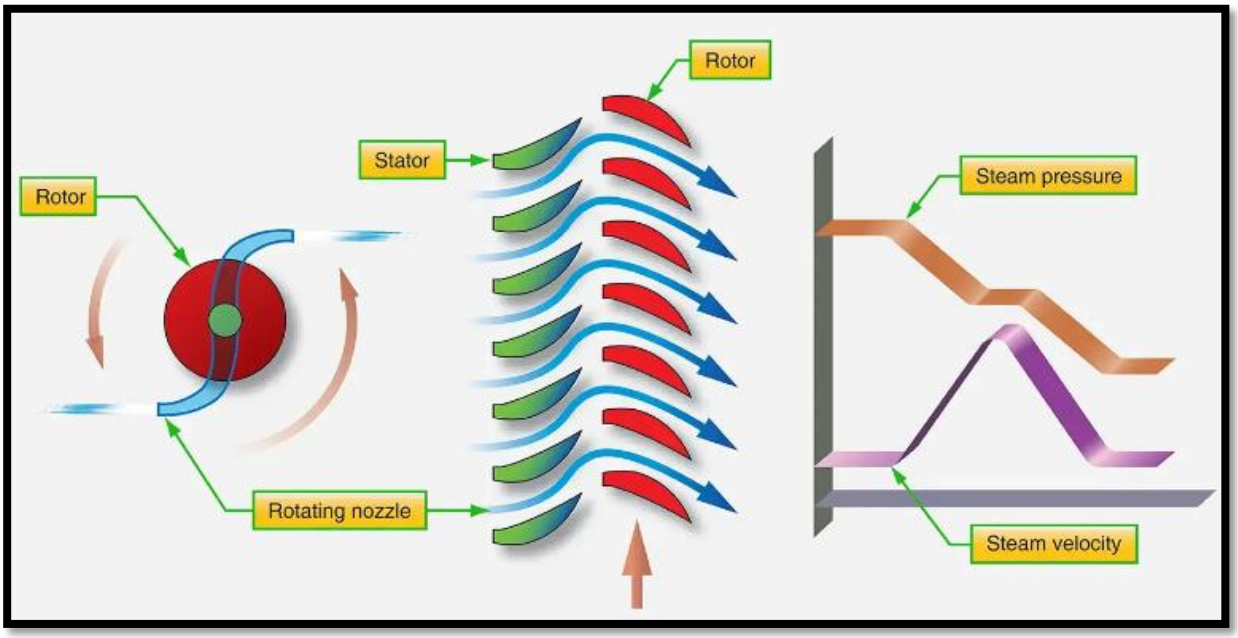

Figure I.14: Reaction turbine

❖ Other types of steam turbines

As we said before, there are only two main types of turbine. But there are other types of steam turbines that are actually the derivatives of those two main steam turbines with different arrangements that make a new way of working principle. now we have four main categories of steam turbines depending on their use:

a) **Condensing turbines:** in which the steam is completely expanded to a pressure of around 0.02 to 0.04 bar, then liquefied in a condenser cooled either by the ambient air or water. This type of turbine is mainly used power generation plants

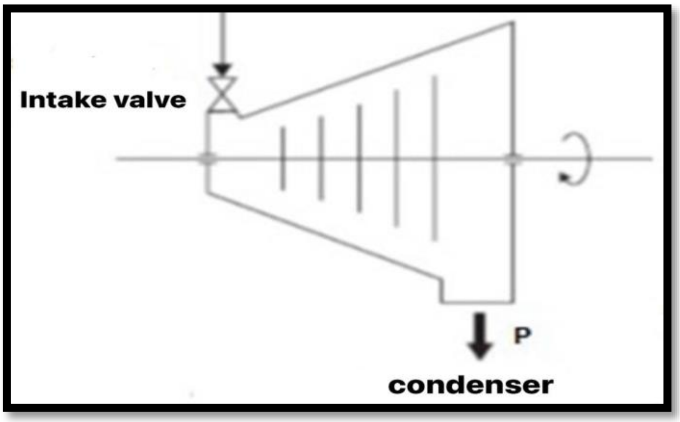

Figure I.15: Condensing turbines

b) **Back pressure turbines:** in which the steam is expanded from high pressure (> 40 bar) to low pressure (around 4 bar). This type of turbine produces mechanical power or electricity at the high temperatures and pressures obtainable in a boiler, while using the residual enthalpy for various processes

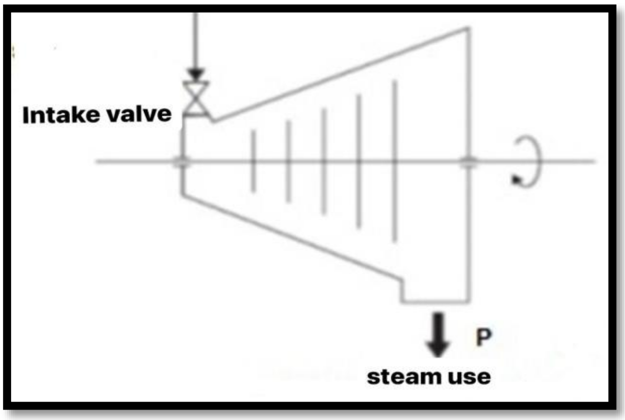

Figure I.16: Back pressure turbines

c) **Extraction and condensation turbines**: in which the steam undergoes partial expansion to a medium pressure (around 20 bar) in a high-pressure casing. some of the steam sent to a utility network, while the rest is expanded in a low-pressure body, as in a condensation turbine. This type of turbine is used extensively in cogeneration plants, where heat demand is likely to vary greatly over time

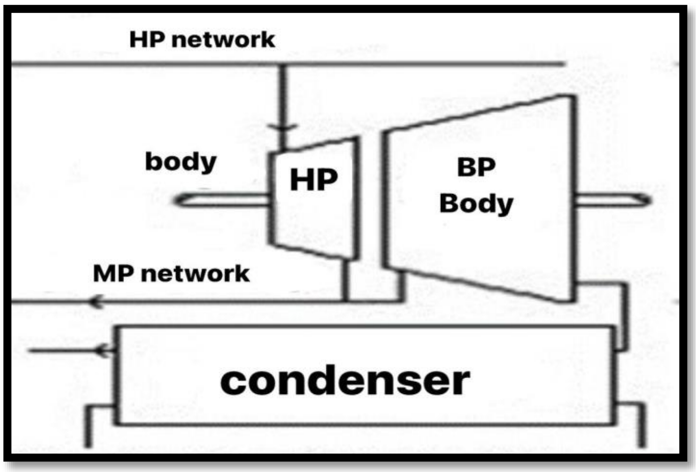

Figure I.17: Extraction and condensation turbines

d) **Back pressure extraction turbines:** whose steam escapes at low pressure into a LP network instead of being condensed.

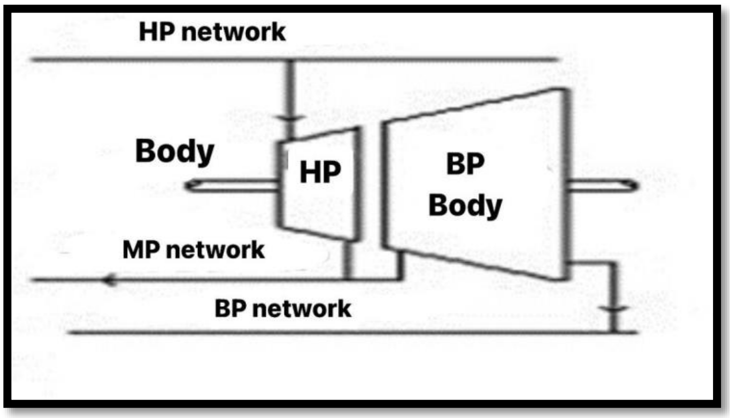

Figure I.18: Back pressure extraction turbines

I.5.7. Advantages

The advantages of steam turbines include the following.

- These turbines work at high speed and operating speed is also wide range.
- There is no balancing problem in this turbine as there are no reciprocating parts.
- Moving parts are very less
- These turbines generate continuous output power.
- Efficiency is high
- They use high vacuum very usefully
- There is no loss because of the initial condensation of steam
- These are used for higher output.

I.5.8. Disadvantages

The disadvantages of steam turbines include the following

- These are expensive
- Less efficient compared with responding engines.
- Less responsive as compared with other turbines and engines
- They need heat-resisting materials
- A gear for reduction is necessary
- The rotor bearings function under harsh temperature conditions
- Experts attention is mandatory while draining, shutting down or warming up

I.5.9. Applications

The applications of steam turbines range from medium to large scale industries like the following.

- Pharmaceutical and chemical industries
- Lube oil systems
- Control & flow measurement
- Condensers & heat exchangers
- Forgings, Machinings & Large Component Fabrications,
- Fabrications of steel Pipe, Spools
- Deaerators
- Waste plants
- Gas and oil industries
- Sugar Mills

I.6. Conclusion

In conclusion, this chapter presented the theoretical foundations of turbomachinery, with a particular focus on gas and steam turbines in terms of their principles, classifications, and applications. It also included a comprehensive overview of the Fertial industrial complex and its role in energy and chemical production. This theoretical and practical framework serves as a fundamental introduction to the more detailed study of steam turbines in the subsequent chapters.

Chapter II

Evaluation of the energy performance of a steam turbine installation

II.1. Introduction

The steam turbine is an external combustion heat engine that operates according to the Clausius-Rankine thermodynamic cycle. This cycle is distinguished by the change of state affecting the driving fluid, which is generally steam. It transforms the thermal energy of the water vapor during expansion into the mechanical energy of shaft rotation to drive a rotating mechanical device. The role of the steam turbine is to transform the energy contained in the steam into mechanical energy in the form of thermal energy and pressure energy. The sum of these two forms energy, expressed in kcal per kg of fluid, is characterized by the enthalpy of steam, which is a function of pressure and temperature.

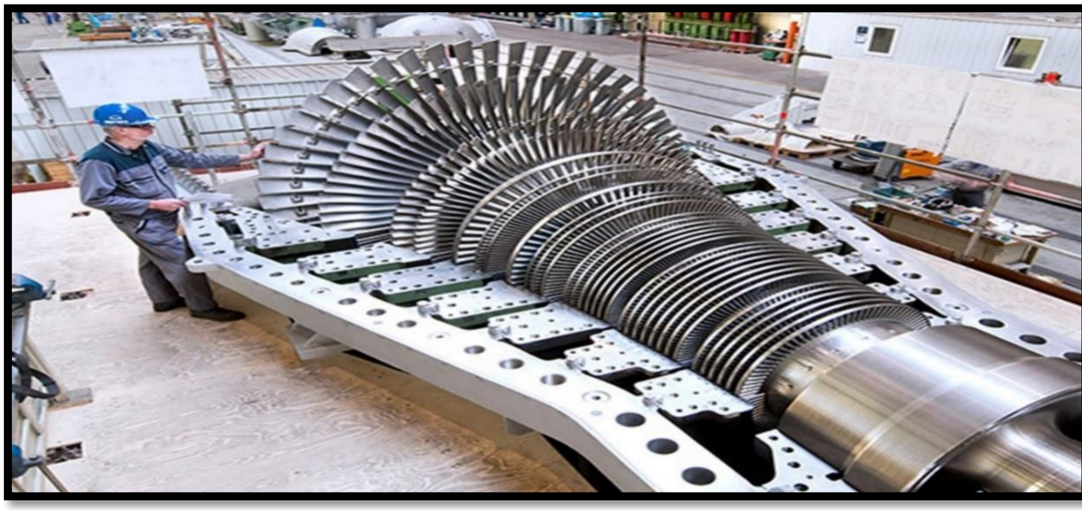

Figure II.1: Steam turbine

By creating a pressure difference and a temperature drop, a drop in enthalpy is produced between the hot source (steam generator) and the cold source (condenser, atmosphere). The turbine placed between these two sources ensures the transformation into mechanical rotational energy with the minimum possible losses. A steam turbine comprises one or more stages, each of which performs two functions:

- The expansion of steam, which corresponds to the conversion of potential energy into kinetic energy.
- The conversion of kinetic energy into torque by means of the moving blades.

The water delivered by the pump passes through the economizer, where it is heated to boiling temperature at constant pressure. It is then vaporized in the boiler and superheated in the superheater. These three elements (economizer, boiler and superheater) form a single unit known as the steam generator, and the outgoing steam is expanded in the turbine, where the thermal energy is transformed into mechanical work. The steam is then condensed in the condenser. The water obtained is then drawn off by the pump to describe another cycle. As shown in the (figure II.2).

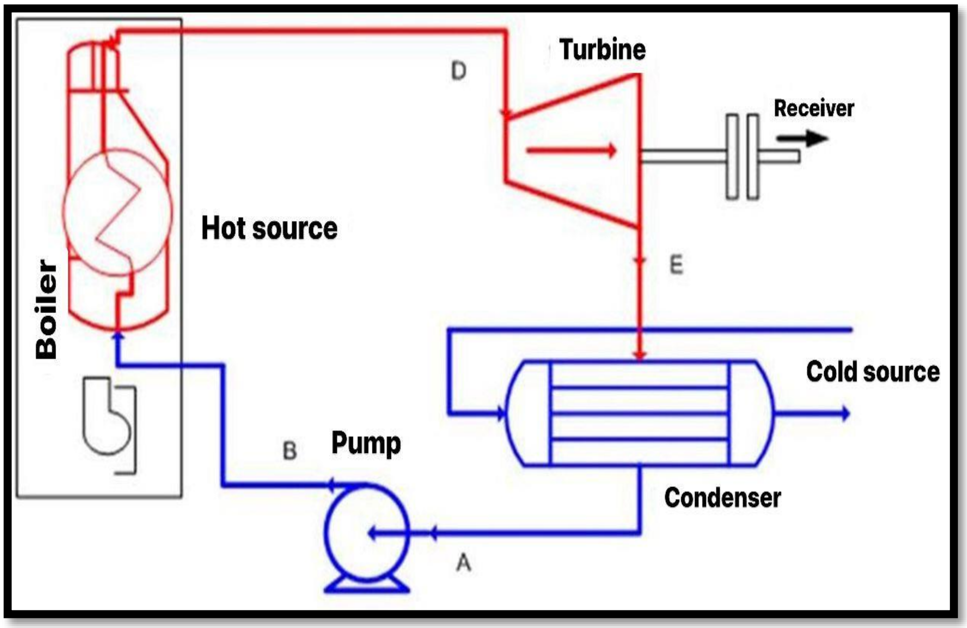

Figure II.2: Schematic diagram of an energy production facility

II.2. The different components of steam turbine

II.2.1. Turbine

The high-pressure steam from the boilers is directed into a turbine. The turbine is designed with blades that are turned by the force of the steam’s high-speed flow. As the steam flows through the turbine, its high-pressure energy is converted into rotational mechanical energy.

II.2.1.1. Construction of turbine

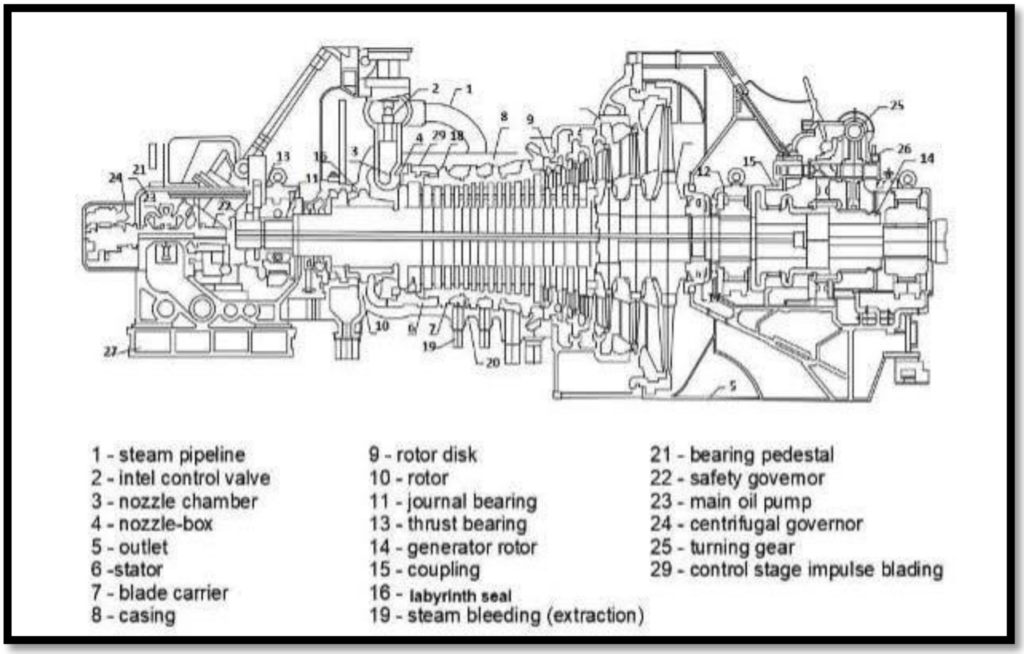

Figure II.3: Construction of turbine

1 - Steam Pipeline:

Carries high-pressure steam from the boiler to the turbine.

2 - Inlet Control Valve:

Regulates the amount of steam entering the turbine. It controls start/stop and speed.

3 - Nozzle Chamber:

Directs steam toward the nozzles, converting pressure energy into kinetic energy.

4 - Nozzle-Box:

Contains the nozzles that guide steam precisely onto the turbine blades.

5 - Outlet:

The exit point for steam after it has passed through the turbine and given up its energy.

6 - Stator:

Stationary blades that direct steam flow to the moving blades efficiently.

7 - Blade Carrier:

Holds and supports the moving blades (rotor blades).

8 - Casing:

Encloses the entire turbine, contains the steam, and ensures safety.

9 - Rotor Disc:

Discs mounted on the rotor shaft that hold the rotating blades.

10 - Rotor:

Main shaft that rotates due to steam force, transmitting mechanical energy to the generator.

11 - Journal Bearing:

Supports the rotor and allows it to spin smoothly with minimal friction.

12 - Thrust Bearing:

Absorbs axial forces to prevent the rotor from moving lengthwise due to steam pressure.

13 - Generator Rotor:

Part of the electrical generator; it turns with the turbine to generate electricity.

14 - Coupling:

Connects the turbine shaft to the generator shaft to transfer rotation.

15 - Labyrinth Packing:

Non-contact seals that minimize steam leakage between stationary and rotating parts.

19 - Steam Bleeding (Extraction):

Draws off some steam partway through the turbine for use in heating or industrial processes.

21 - Bearing Pedestal:

Structure that holds and supports the bearings for the rotor shaft.

22 - Safety Governor:

An emergency device that shuts down the turbine if it overspeeds.

23 - Main Oil Pump:

Provides oil for lubrication and cooling to the turbine bearings and other moving parts.

24 - Centrifugal Governor:

Uses centrifugal force to regulate turbine speed by controlling steam flow.

25 - Turning Gear:

Slowly rotates the turbine during shutdown or startup to prevent rotor warping due to temperature differences.

29 - Control Stage Impulse Blading:

Initial blade stage designed to precisely direct and control steam as it enters the turbine.

II.2.1.2. the different categories of steam turbine

The turbine is a machine which, thanks to the speed acquired by the fluid engine, turns a shaft which in turn drives another machine from an operational point of view, there are two classes of turbine:

1. Action (impulse) turbine: In the action turbine, expansion takes place only in the fixed blades. This is because the first stage of a turbine is exposed to large pressure differences and high temperatures.

2. Reaction turbine: In the reaction turbine, the expansion is distributed between the fixed and moving blades .The degree of reaction is defined by the distribution of the expansion between the blades.

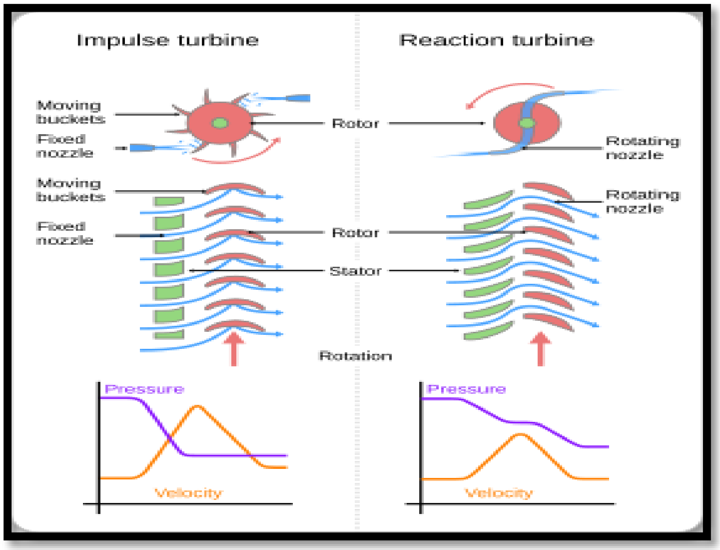

Figure II.4: Comparison of action and reaction turbines

II.2.2. Boiler

II.2.2.1. What is a Boiler?

A boiler is a closed vessel where water is heated and converted into steam using heat generated from burning fuel (coal, oil, gas, or even nuclear energy). The high-pressure steam produced is then used to drive a steam turbine, which generates electricity.

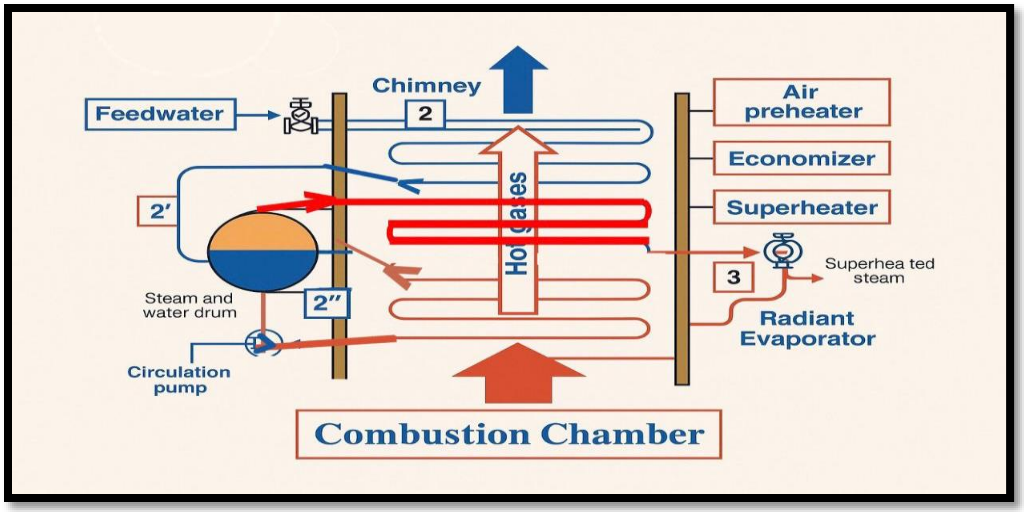

Figure II.5: Boiler system diagram

In (figure II.5) Feedwater enters the system at Point 2, flows through the Economizer, and enters the Steam Drum. From the Steam Drum, water is drawn by the Circulation Pump and directed to the Radiant Evaporator, where it absorbs radiant heat and evaporates into steam. The generated saturated steam returns to the Steam Drum. Steam then flows to the Superheater, where it is converted into superheated steam. The superheated steam exits the boiler system at Point 3 and proceeds to the turbine.

II.2.2.2. Main components of the boiler

- Feedwater line: water enters the boiler system through this line (Point 2).
- Air rreheater: recovers heat from exhaust gases to preheat the air for combustion, improving combustion efficiency.
- Economizer: preheats the feedwater using residual heat from exhaust gases before entering the steam drum, thus saving fuel.
- Steam and water drum: separates steam from water. Acts as a reservoir for both water and generated steam.
- Circulation pump: circulates water from the steam drum through the evaporator pipes to ensure uniform heating and boiling.
- Radiant evaporator: receives radiant heat from the combustion chamber and converts water into saturated steam.
- Superheater: heats the saturated steam to superheated steam before it exits the boiler at Point 3, increasing thermal efficiency.
- Combustion chamber: burns fuel to generate hot gases that transfer heat to the water/steam tubes.
- Chimney: releases exhaust gases into the atmosphere after heat recovery in the preheater and economizer.

II.2.3. Condenser

II.2.3.1.What is a condenser

A condenser is a heat exchange device used in steam power plants to condense exhaust steam from the steam turbine into liquid water (called condensate). This water is then reused in the boiler, making the process a closed-loop system.

II.2.3.2. Functions of the condenser

- Condenses steam: converts exhaust steam from the turbine back into water by removing heat.
- Maintains vacuum: creates a vacuum at the turbine's outlet to increase the pressure difference across the turbine, improving efficiency.
- Recycles water: returns the condensed water (condensate) to the boiler feed system.
- Improves efficiency: reducing the turbine exhaust pressure increases the work output and overall thermal efficiency of the Rankine cycle.

II.2.3.3. types of condensers

	Surface condenser	Jet (or mixing) condenser
Description	The most commonly used condenser in thermal power plants.	Steam is directly mixed with cooling water.
Operation	Cooling water flows through tubes, while exhaust steam from the turbine passes over the tubes and condenses without mixing with the cooling water.	Steam condenses upon direct contact with cold water.
Advantages	Allows reuse of boiler feedwater; maintains water purity.	Simple design, low initial cost.
Disadvantages	Large in size and expensive to build and maintain.	The condensed water is mixed with cooling water and cannot be reused without treatment.

Table II.1: Types of condensers

II.2.3.4. Main components of a surface condenser

- Steam inlet: entry point for low-pressure exhaust steam from the turbine.
- Tube bundle: tubes where cooling water flows to absorb heat from the steam.
- Cooling water inlet/outlet: Brings in cold water and removes warm water.
- Vacuum pump: maintains a low pressure by removing non-condensable gases.

- Condensate Pump: Pumps the condensed water (condensate) back to the boiler feed system.
- Air Extraction System: Removes trapped air to maintain condenser efficiency.

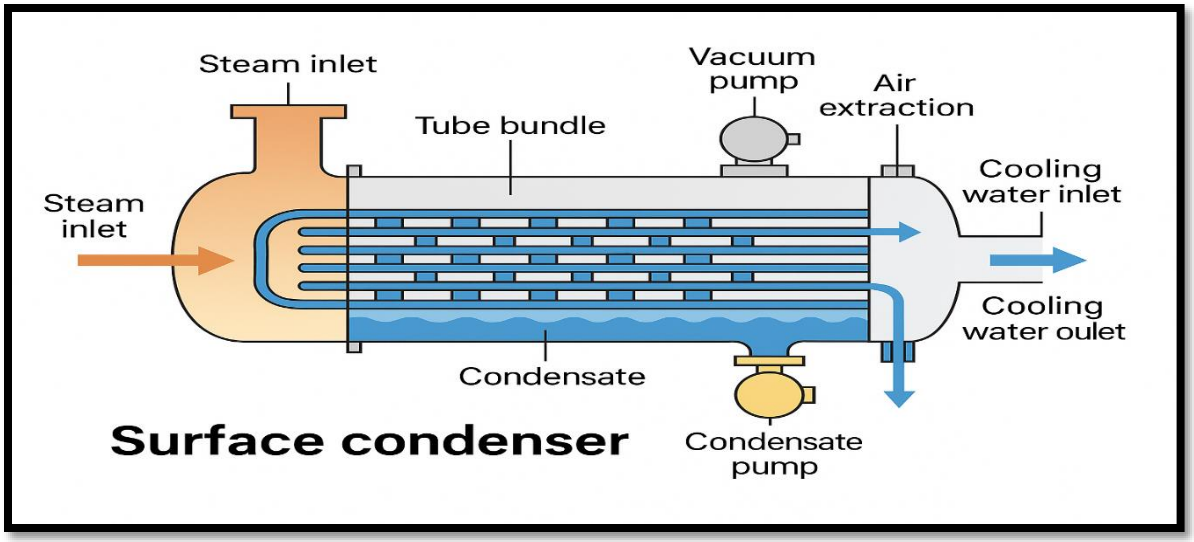

Figure II.6: Condenser

II.2.4. Pump

II.2.4.1. Concept of the pump in the Rankine cycle

- The pump increases the pressure of the working fluid (usually water) after it exits the condenser and before entering the boiler.
- Since the fluid is in a liquid state, the pump work required is relatively small compared to the work produced by the turbine.
- This process ensures that water enters the boiler at the required high pressure for efficient steam generation.

II.2.4.2. Basic components of a pump

As shown in the (Figure II.7):

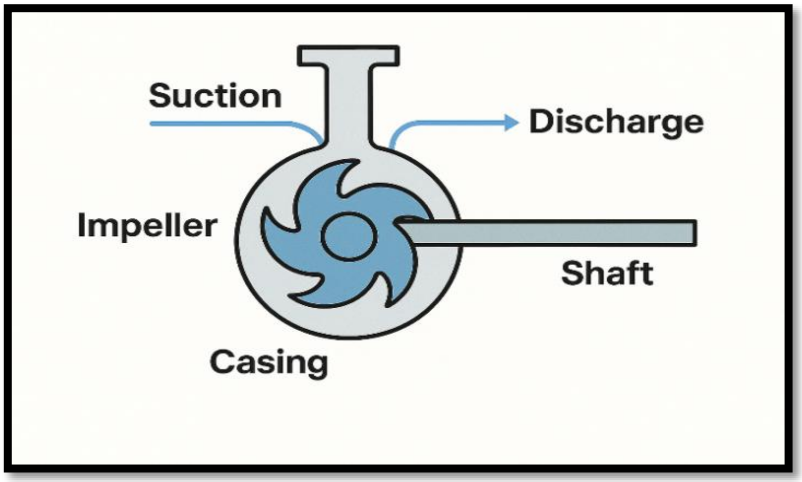

Figure II.7: basic components of a pump

- Suction: Where the fluid enters the pump (from the condenser).
- Impeller: Rotating component that adds energy to the fluid.
- Casing: Encloses the impeller and guides the fluid.
- Shaft: Connects the impeller to the driving motor.
- Discharge: Where high-pressure fluid exits the pump (to the boiler)

II.3. Evolution of steam turbine cycle

II.3.1. Wet steam Rankine cycle

The basic cycle (theoretical cycle) of a steam turbine involving a change of state is a wet Rankine cycle (Carnot cycle) which takes place entirely in wet steam. This cycle comprises:

1. Two isobars (isothermal change of state).
2. Two adiabatic cycles.

In (Figure II.9) is a Carnot cycle (rectangular in the (T -S) diagram), applied to condensable vapors

In practice, this cycle is difficult to achieve because:

- It is difficult to isentropically compress a mixture with two phases (1→ 2liq)
- It is difficult to control condensation (3 →1) to reach precisely point 1
- The turbine blades risk being rapidly eroded by the liquid droplets which appear during expansion.

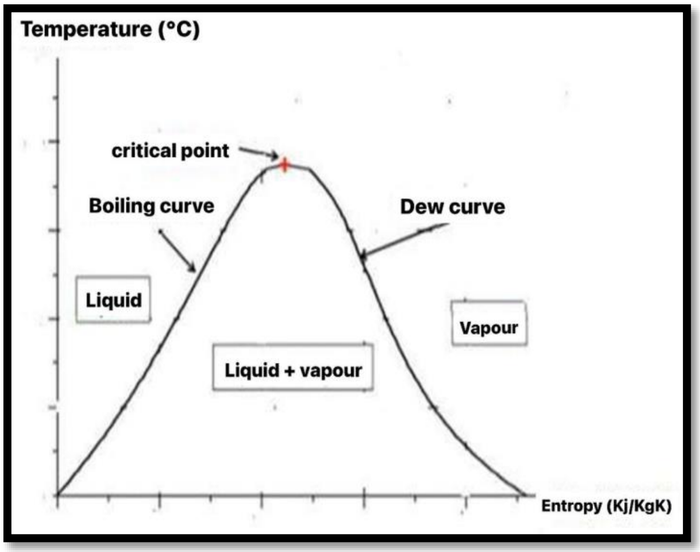

Figure II.8: Entropy diagram for water

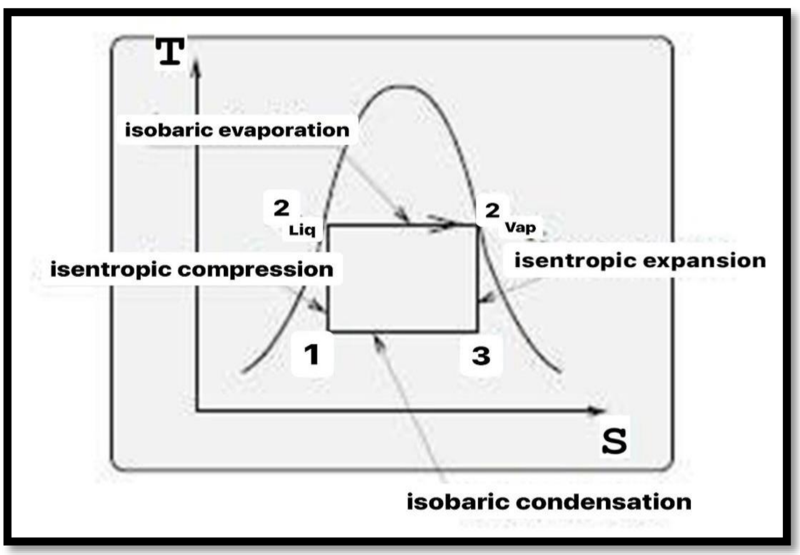

Figure II.9: Wet steam Rankine cycle (Carnot cycle)

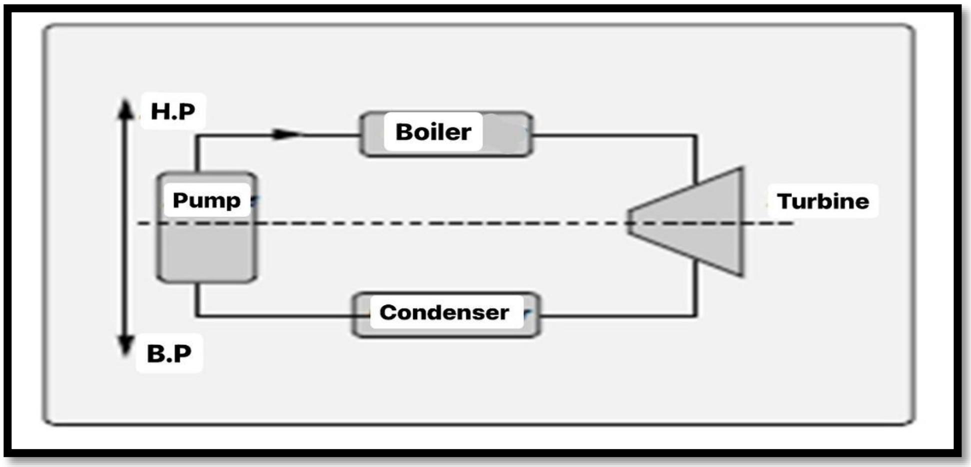

Figure II.10: Steam turbine cycle

Note:

- The real cycle must have the following properties:
  1. The area of the cycle in the diagram (T - S) must be as large as possible. This area represents the balance of heat exchanged, i.e. the total work : Wdet +Wcomp,
  2. The work of compression must be minimal.

- **Many of the difficulties associated with this cycle can be eliminated through these changes**

  a) Condensing it completely in the condenser

  In the actual cycle, the wet steam from the turbine is completely condensed displacement of point 1 to 1_{liq} (figure II.11)

  b) Isentropic compression in the pump and constant pressure heat addition in the boiler

  The liquid undergoes isentropic compression to vaporization pressure (point 2), and is then vaporized at constant pressure to point 2_{vap} (Figure II.11)

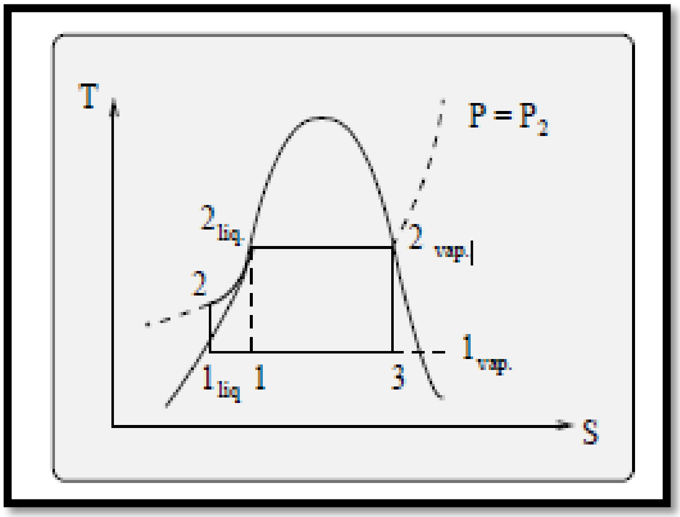

Figure II.11: Rankine cycle

- 1_{liq} - 2 : Isentropic compression (compression in centrifugal pumps)
- 2 – 2_{liq} -2_{vap} : Isobaric heat input (in the boiler)
- 2_{vap} – 3 : Isentropic expansion (in steam turbine)
- 3– 1_{liq}: Isobaric heat rejection (condensation in condenser).

❖ **Note**

Now, after making these two changes, we have a Rankine cycle as shown in the (figureII.10) but we still face the problem of the turbine blades being exposed to the risk of rapid erosion due to the liquid droplets that appear during expansion, which makes it difficult to apply this cycle practically. Therefore, let us learn about the Erin cycle.

II.3.2. Hirn cycle

The Hirn cycle is a Rankine cycle in which the steam leaving the boiler is superheated to a temperature above the critical temperature (Figure II.13)

❖ This cycle has two advantages:

1. superheating increases the temperature (energy) of the steam at start of expansion
2. expansion takes place in a dry state

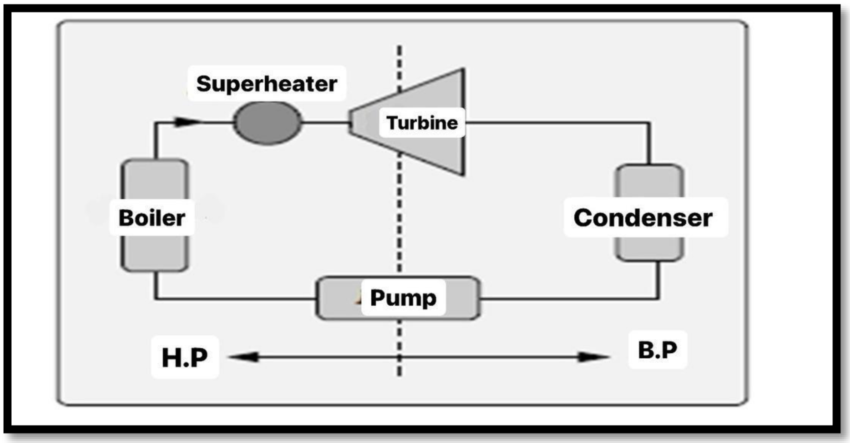

Figure II.12: Turbine installation with steam superheating

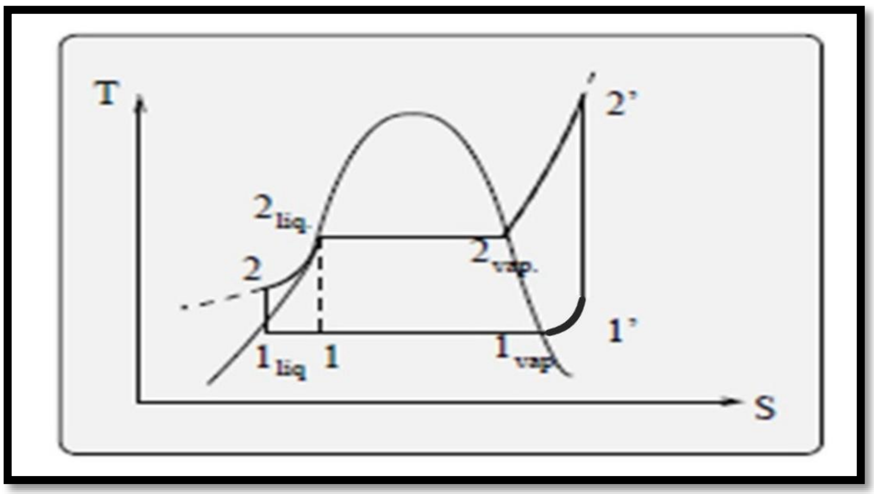

Figure II.13: Hirn cycle

In an ideal superheated Hirn cycle, the system running the cycle undergoes a series of four processes: two isentropic (reversible adiabatic) processes alternating with two isobaric processes

- 1_{liq}-2 : Isentropic compression in a pump
- 2-2' : Heat addition at constant pressure (isobaric) in a boiler
- 2'-1' : Isentropic expansion in a turbine
- 1'-1_{vap} -1_{liq} : Constant pressure (isobaric) heat rejection in a condenser

II.4. Evaluation of the energy performance of a steam turbine

The four components associated with the Rankine cycle (pump, boiler, turbine and condenser) are constant flow devices, and therefore the four processes that make up the Rankine cycle can be analyzed as constant flow processes. The changes in kinetic and potential energy of the steam are generally small compared to the working and heat transfer conditions and are therefore generally neglected. Then, the constant flow energy equation per unit mass of steam reduces to

$$(q_i - q_o) + (W_i - W_o) = h_o - h_i \qquad \text{(II.1)}$$

II.4.1. Operating parameters of a fertial steam turbine

❖ **The main operating parameters of the steam turbine are as follows:**

Item	Symbol	Value	Unit	Notes
Boiler pressure (high pressure)	P_b	42	bar	Pressure at turbine inlet
Steam temperature at turbine inlet	$T_{2'}$	420	°C	Superheated steam
Condenser pressure (low Pressure)	P_C	0.068	bar	Pressure at turbine outlet
Turbine efficiency	η_t	88%	-	
Pump efficiency	η_p	88%	-	
Vapor mass flow rate	$\dot{m}_{vap}$	37.44	$kg.s^{-1}$	
Fuel mass flow rate (natural gas)	$\dot{m}_f$	2.636	$kg.s^{-1}$	
Low heat value (natural gas)	LHV	48500	$kJ.kg^{-1}$	

Table II.2: The main operating parameters of a fertial steam turbine

II.4.2. Calculation of steam turbine performance

The values of pressure, temperature and enthalpy of the main states of water in liquid form and in the form of steam in the recovery boiler and in the turbine are given in Table II.3.

Point	P (bar)	T (°C)	$h (kJ.kg^{-1})$
1_{liq}	0.068	38.6	161.0
2	42	38.6	165.8
2_{liq}	42	253.3	1087.4
2_{vap}	42	253.3	2800.8
2′	42	420	3250.9
1′	0.068	38.6	2278.8
1_{vap}	0.068	38.6	2570.1

Table II.3: Temperature-pressure-enthalpy characteristics of the different states thermodynamics of water for a fertial steam turbine

II.4.2.1. Determination of enthalpy of different state point of the steam turbine cycle

- State (point 1_{liq})

$h_{1liq} = h_{sat}(P_c)$

$$\mathbf{h_{1liq} = 161.0\ kJ.kg^{-1}}$$

$v_{1liq} = v_{sat}(P_c)$

$$\mathbf{v_{1liq} = 0.001006\ m^3.kg^{-1}}$$

- State (point 2)

$$W_{p(ideal)} = v_1 (P_b - P_c) \quad (II.2)$$

$W_{p(ideal)} = 0.001006 * (42 - 0.0068)*10^2$

$$\mathbf{W_{p(ideal)} = 4.22\ kJ.kg^{-1}}$$

$$W_{p(actual)} = \frac{W_{P(ideal)}}{\eta_p} \quad (II.3)$$

$W_{p(actual)} = \frac{4.22}{0.88}$

$$\mathbf{W_{p(actual)} = 4.80\ kJ.kg^{-1}}$$

$$h_2 = h_{1liq} + W_{p(actual)} \quad (II.4)$$

$h_2 = 161 + 4.8$

h_2 = 165.8 kJ.kg^{-1}

- State (point 2_{liq})

$h_{2liq} = h_{sat}(P_b)$

h_{2liq} = 1087.4 kJ.kg^{-1}

- State (point 2_{vap})

$h_{2vap} = h_{sat}(P_b)$

h_{2vap} = 2800.8 kJ.kg^{-1}

- State (point 2')

$h_{2'}$ is determined in the superheated zone of the water diagram

$h_{2'}$ = 3250.9 kJ.kg^{-1}

$S_{2'}$ = 6.919 kJ.kg^{-1}.K^{-1}

- State (point 1')

for an isentropic process

$S_{1'} = S_{2'}$ = 6.919 kJ.kg^{-1}.K^{-1}

$S_{sat,vap}(P_c)$ = 8.275 kJ.kg^{-1}.K^{-1}

$S_{1'} < S_{sat,vap}(P_c)$

then the vapour is wet at the turbine outlet

So we have to find $x_{1's}$

$$x_{1's} = \frac{S_{2'} - S_{liq}}{S_{liq} - S_{vap}} \quad \text{(II.5)}$$

$$x_{1's} = \frac{6.919 - 0.559}{7.718}$$

$x_{1's}$ = 0.824

$$h_{1's} = h_{liq} + x_{1's}\,(h_{liq} - h_{vap}) \quad \text{(II.6)}$$

$h_{1's}$ = 161 + 0.824 * 2409.1

$h_{1's}$ = 2146.1 kJ.kg^{-1}

$$h_{1'} = h_{2'} - \eta_T(h_{2'} - h_{1's}) \quad \text{(II.7)}$$

$h_{1'}$ = 3250.9 – 0.88 (3250.9 – 2146.1)

$h_{1'}$ = 2278.8 kJ.kg^{-1}

- State (point 1_{vap})

$h_{1vap} = h_{sat}(p_c)$

$$\mathbf{h_{1vap} = 2570.1\ kJ.kg^{-1}}$$

II.4.2.2. Calculation of the performance characteristics of the steam turbine installation.

a) Pump work calculation (W_p):

Calculating the work input required by the pump

- $W_p = h_2 - h_{1liq}$ (II.8)

  $W_p = 165.8 - 161.0$

  $$\mathbf{W_p = 4.8\ kJ.kg^{-1}}$$

b) Turbine work output (W_T):

Determining the total work produced by the turbine in both stages.

- $W_T = h_{2'} - h_{1'}$ (II.9)

  $W_T = 3250.9 - 2278.8$

  $$\mathbf{W_T = 972.1\ kJ.kg^{-1}}$$

c) Boiler heat input (q_b):

Calculating the total heat added to the working fluid in the boiler

- $q_b = h_{2'} - h_2$ (II.10)

  $q_b = 3250.9 - 165.8$

  $$\mathbf{q_b = 3085.1\ kJ.kg^{-1}}$$

d) Net work output (W_{net}):

Finding the net useful work by subtracting pump work from turbine work

- $W_{net} = W_T - W_p$ (II.11)

  $W_{net} = 972.1 - 4.8$

  $$\mathbf{W_{net} = 967.3\ kJ.kg^{-1}}$$

e) Thermal efficiency (ηt):
Evaluating the thermal efficiency of the cycle

- $\eta_t = \frac{W_{net}}{q_b}$ (II.12)

$$\eta_t = \frac{967.3}{3085.1}$$

η_t = 31.3 %

II.4.2.3. Calculation of the steam turbine power

The power of the steam turbine is given by the following relationship:

$$P = \dot{m}_{vap}.W_T \quad \text{(II.13)}$$

P = 37.44 * 972.1

P = 36395.42 kW = 36.395 MW

II.4.3. Calculation of boiler thermal efficiency

The thermal efficiency of the boiler is given by the following relationship:

$$\eta_b = \frac{\dot{Q}_b}{\dot{Q}_f} \quad \text{(II.14)}$$

$$\eta_b = \frac{\dot{m}_{vap}.(h_{2\prime} - h_2)}{\dot{m}_f.\ LHV} \quad \text{(II.15)}$$

$$\eta_b = \frac{37.44\ (3250.9 - 165.8)}{2.636 * 48500}$$

η_b = 90.34 %

II.4.4. Calculation of total efficiency

The global efficiency of the steam turbine is given by the following relationship:

$$\eta_{tot} = \frac{\dot{m}_{vap}\, W_{net}}{\dot{m}_f\, LHV} \qquad (II.16)$$

$$\eta_{tot} = \frac{\dot{m}_{vap}\, W_{net}}{\dot{m}_f\, LHV} * \frac{h_{2\prime} - h_2}{h_{2\prime} - h_2}$$

$$\eta_{tot} = \frac{\dot{m}_{vap}.(h_{2\prime} - h_2)}{\dot{m}_f.\ LHV} * \frac{W_{net}}{h_{2\prime} - h_2} \qquad (II.17)$$

$$\eta_{tot} = \eta_b \,.\, \eta_t \qquad (II.18)$$

$$\eta_{tot} = 90.34\ \% * 31.3\ \%$$

$$\boldsymbol{\eta_{tot} = 28.27\ \%}$$

II.5. conclusion

In this chapter, we conducted a comprehensive evaluation of the energy performance of a steam turbine installation operating according to the Rankine and Hirn cycles. We began by exploring the fundamental components of the system—namely the turbine, boiler, condenser, and pump—highlighting their construction, function, and interdependence. We then discussed the thermodynamic principles governing the operation of steam turbines and examined various configurations, including the ideal and actual Rankine cycle, and the improvements introduced by the Hirn cycle through superheating.

Through a detailed thermodynamic analysis, we calculated the enthalpies at key state points and evaluated the performance indicators such as turbine work, pump work, net work output, and overall cycle efficiency. The results demonstrate a net specific work of 967.3 kJ/kg, a thermal efficiency of 31.3% for the turbine, and a global system efficiency of 28.2%, reflecting the impact of irreversibilities and energy losses.

These findings underscore the importance of optimizing steam conditions, component efficiency, and system integration to enhance the overall performance of steam turbine installations. This analysis sets the foundation for the next phase of the study, where we will explore strategies for improving energy efficiency and reducing operational losses in steam power system.

Chapter III

Study of Different Techniques for Increasing the Thermal Efficiency of Steam Turbines

III.1. Introduction

Although the Hirn cycle with superheating offers a marked improvement over the basic steam cycle mainly by increasing thermal efficiency and reducing moisture at the turbine outlet steam turbines still suffer from considerable thermal losses and limited energy recovery during expansion. These limitations, combined with the growing demand for higher performance in thermal power plants, highlight the need for further cycle enhancements.

This chapter explores two proven methods for improving the thermodynamic performance of steam turbines: reheating and extraction-condensing cycles. These techniques aim to optimise heat input conditions, increase the average temperature of heat addition, and reduce irreversibilities within the expansion process.

Each method will be examined in terms of operating principles, thermal benefits, implementation challenges, and impact on overall cycle efficiency. The analysis will be supported by numerical simulations using the baseline data introduced in the previous chapter, providing a practical context for applying these enhancements in modern power generation systems.

III.2. Reheating technique

III.2.1. Principle of operation

The reheating technique enhances steam turbine efficiency by employing multi-stage expansion. In this method, steam is partially expanded in the high-pressure turbine, then reheated before entering the low-pressure turbine for further expansion. This intermediate reheating process helps to prevent significant temperature drops and reduces moisture formation during expansion, thereby improving the overall thermal efficiency of the cycle.

This approach allows the steam to remain at a higher average temperature throughout the turbine stages, thus maximizing energy extraction and improving efficiency while minimizing the risk of turbine blade erosion due to moisture content

(Figure III.1) shows the reheating Hirn cycle, a modified version of the basic steam cycle designed to enhance thermal efficiency and reduce moisture in the steam at the turbine exhaust.

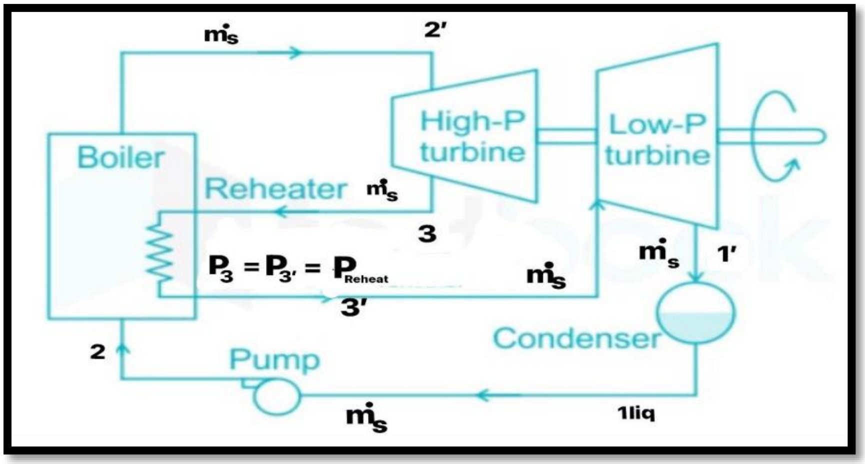

Figure III.1: Schematic diagram of reheating Hirn cycle

The working fluid (water/steam) undergoes the following main processes:

- Pump process (1liq → 2):

The saturated liquid from the condenser is compressed by a feedwater pump to a pressure in preparation for heat addition in the boiler.

- Heat addition (2 → 2′):

In the boiler, the pressurized liquid absorbs heat and turns into superheated steam (state 2′). This steam is then directed to the high-pressure turbine.

- First Expansion (2′ → 3):

The steam expands through the high-pressure turbine, converting thermal energy into mechanical work. As it expands, its pressure and temperature decrease.

- Reheating Process (3 → 3′):

The partially expanded steam is sent to a reheater, where it is reheated at a constant pressure.

This reheating process increases the temperature again before further expansion.

- Second expansion (3′ → 1′):

The reheated steam expands in the low-pressure turbine, producing additional mechanical work and reducing its pressure and enthalpy further.

- Condensation (1′ → 1liq):

The steam leaves the turbine and enters the condenser, where it cools and condenses back into saturated liquid, thus completing the cycle.

III.2.2. Evolution of the reheating Hirn cycle

The development of the Hirn cycle with reheating resulted from a series of gradual improvements that began with the simple Hirn cycle. These enhancements were driven by the need to improve the thermal performance of steam power plants and to address operational challenges caused by high steam moisture content in turbines

- To improve the efficiency of the Hirn cycle, we try to increase the pressure P2.
- This increase in pressure runs the risk of displacing the expansion into a wet environment (figure III.2)

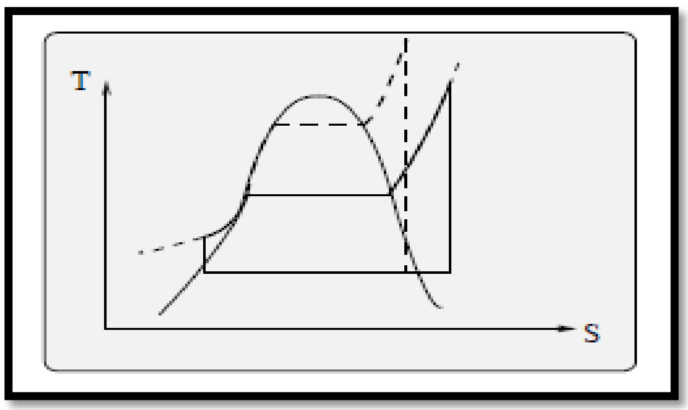

Figure III.2: Hirn cycle with pressure increase

- In order to maintain a dry steam expansion, the expansion is fractionated, allowing the steam to be reheated after a partial expansion (figure III.3)

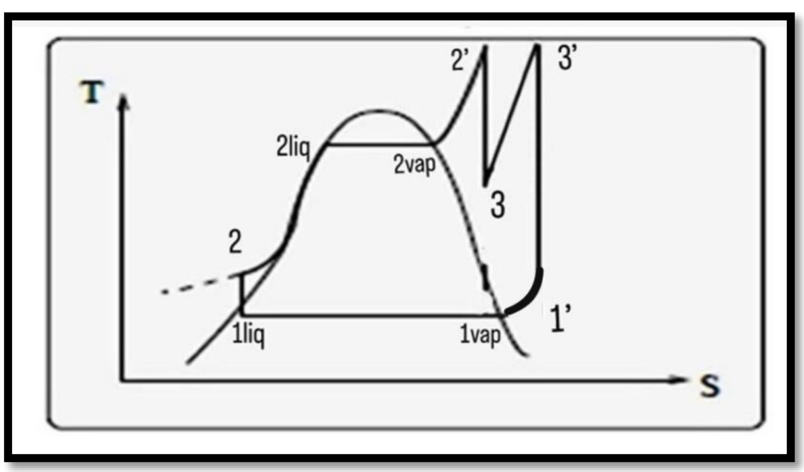

Figure III.3: Reheating Hirn cycle

In a reheating Hirn cycle, the system undergoes a series of six processes, comprising three isentropic (reversible adiabatic) processes. alternating with three isobaric processes.

$1_{liq} \rightarrow 2$: Isentropic Compression in a Pump
$2 \rightarrow 2'$: Isobaric Heat Addition in the Boiler
$2' \rightarrow 3$: Isentropic Expansion in the High-Pressure Turbine
$3 \rightarrow 3'$: Isobaric Reheating Process
$3' \rightarrow 1'$: Isentropic Expansion in the Low-Pressure Turbine
$1' \rightarrow 1_{vap} \rightarrow 1_{liq}$: Isobaric Heat Rejection in the Condenser

III.2.3. Evaluation of the energy performance of the steam turbine

We are still with the same four components of the Rankine cycle but with some modifications in the boiler and these components are considered to have a constant flow if we neglect the kinetic energy which is small compared to the working conditions and heat transfer With this concept, the system is subject to a series of six processes, consisting of three isentropic (isothermal reversible) processes alternating with three isobaric processes We can analyze these processes in detail in this paragraph

II.2.3.1. Operating parameters of the steam turbine

- **The main operating parameters of the steam turbine are as follows:**

Item	Symbol	Value	Unit
Boiler pressure (High pressure)	P_b	42	bar
Steam temperature at turbine inlet	$T_{2'}$	420	°C
Reheating pressure (Intermediate pressure)	P_3	10	bar
Reheating temperature	$T_{3'}$	420	°C
Condenser pressure (Low pressure)	P_C	0.068	bar
High turbine efficiency	η_t	88%	-
Low turbine efficiency	η_t	88%	-
Pump efficiency	η_p	88%	-
Vapor mass flow rate	$\dot{m}_{vap}$	37.44	$kg.s^{-1}$
Low heat value (natural gas)	LHV	48500	$kJ.kg^{-1}$

Table III.1: Main operating parameters of the reheating steam turbine

❖ **Criteria for Selecting the optimal reheat pressure:**

- Pressure should be between 20–25% of the boiler pressure (to balance efficiency and cost).
- Avoid very low pressures that lead to high moisture content in the low-pressure turbine.
- Verify the T–S diagram to ensure that the steam remains superheated.
- Consider the economic cost of materials and equipment.

So we chose P = 10 bar, which is equal to 23.8% of the boiler pressure

❖ Criteria for selecting the reheat temperature

- It should be equal or close to the main turbine inlet temperature but not higher.
- Steam must remain superheated after reheating to avoid condensation.
- Material heat resistance must be considered.
- The goal is to improve efficiency without significantly increasing costs.

So we chose $T_{reheat} = T_{2'} = 420$ °C

III.2.3.2 Calculation of steam turbine performance

The values of pressure, temperature and enthalpy of the main states of water in liquid form and in the form of steam in the recovery boiler and in the turbine are given in Table III.2.

Point	P (bar)	T (°C)	h(kJ.kg^{-1})
1_{liq}	0.068	38.6	161.0
2	42	38.6	165.8
2_{liq}	42	253.3	1087.4
2_{vap}	42	253.3	2800.8
2′	42	420	3250.9
3	10	249	2940.78
3’	10	420	3475.3
1′	0.068	38.6	2536.60
1_{vap}	0.068	38.6	2570.1

Table III.2: Temperature-pressure-enthalpy characteristics of the different states thermodynamics of water for the reheating steam turbine

II.2.3.2.1 Determination of enthalpy of different state point of the steam turbine cycle

- State (point 1_{liq})

$h_{1liq} = h_{sat}(P_c)$

$$\mathbf{h_{1liq} = 161.0\ kJ.kg^{-1}}$$

$v_{1liq} = v_{sat}(P_c) = 0.001006$

$$\mathbf{v_{1liq} = 0.001006\ m^3.kg^{-1}}$$

- State (point 2)

$$W_{p(ideal)} = v_1\,(P_b - P_C) \qquad (III.1)$$

$= 0.001006 * (42 – 0.0068)*10^2$

$$\mathbf{W_{p(ideal)} = 4.22\ kJ.kg^{-1}}$$

$$W_{p(actual)} = \frac{W_{P(ideal)}}{\eta_p} \qquad (III.2)$$

$$W_{p(actual)} = \frac{4.22}{0.88}$$

$$\mathbf{W_{p(actual)} = 4.80\ kJ.kg^{-1}}$$

$$h_2 = h_{1liq} + W_{p(actual)} \qquad (III.3)$$

$h_2 = 161 + 4.8$

$$\mathbf{h_2 = 165.8\ kJ.kg^{-1}}$$

- State (point 2_{liq})

$h_{2liq} = h_{sat}(P_b)$

$$\mathbf{h_{1liq} = 1087.4\ kJ.kg^{-1}}$$

- State (point 2_{vap})

$h_{2vap} = h_{sat}(P_b)$

$$\mathbf{h_{2vap} = 2800.8\ kJ.kg^{-1}}$$

- State (point 2’)

$h_{2'}$ is determined in the superheated zone of the water diagram

$h_{2'} = 3250.9\ kJ.kg^{-1}$

$S_{2'} = 6.919\ kJ.kg^{-1}.K^{-1}$

- State (point 3)

for an isentropic process

$S_3 = S_{2'} = 6.919\ kJ.kg^{-1}.K^{-1}$

$S_{sat,vap}(P_{reheat}) = 6.586\ kJ.kg^{-1}.K^{-1}$

$S_3 > S_{sat,vap}(P_{reheat})$

The vapour is still dry at the outlet of the high-pressure turbine

So h_3 is determined in the superheated zone of the water diagram

$h_{3s} = 2898.5\ kJ.kg^{-1}$

$h_3 = h_{2'} - \eta_T(h_{2'} - h_{3s})$ (III.4)

$h_3 = 3250.9 - 0.88\ (3250.9 - 2898.5)$

$h_3 = 3250.9 - 310.112$

$h_3 = 2940.788\ kJ.kg^{-1}$

- State (point 3')

$h_{3'}$ is determined in the superheated zone of the water diagram

$h_{3'} = 3475.3\ kJ.kg^{-1}$

$S_{3'} = 7.762\ kJ.kg^{-1}.K^{-1}$

- State (point 1')

for an isentropic process

$S_{1'} = S_{3'} = 7.762\ kJ.kg^{-1}.K^{-1}$

$S_{sat,vap}(P_c) = 8.275\ kJ.kg^{-1}.K^{-1}$

$S_{1'} < S_{sat,vap}(P_c)$

then the vapour is wet at the turbine outlet

So we have to find $x_{1's}$

$$x_{1's} = \frac{S_{1'} - S_{liq}}{S_{vap} - S_{liq}} \quad \text{(III.5)}$$

$$x_{1's} = \frac{7.762 - 0.559}{7.718} = 0.933$$

$h_{1's} = h_{1liq} + x_{1's} (h_{liq} - h_{vap})$ (III.6)

$h_{1's} = 161 + 0.933 * 2409.1$

$\mathbf{h_{1's} = 2408.6\ kJ.kg^{-1}}$

$h_{1'} = h_{3'} - \eta_T(h_{3'} - h_{1's})$ (III.7)

$h_{1'} = 3475.3 - 0.88(3475.3 - 2408.6)$

$h_{1'} = 3475.3 - 938.696$

$\mathbf{h_{1'} = 2536.60\ kJ.kg^{-1}}$

- State (point 1_{vap})

$h_{1vap} = h_{vap,f} (P_c)$

$\mathbf{h_{1vap} = 2570.1\ kJ.kg^{-1}}$

II.2.3.2.2. Calculation of the performance characteristics of the steam turbine installation

a) Pump Work Calculation (W_p):

Calculating the work input required by the pump

- $W_p = h_2 - h_{1liq}$ (II.8)

$W_p = 165.8 - 161.0$

$\mathbf{W_p = 4.8\ kJ.kg^{-1}}$

The pump work remains the same in both cycles, as the fluid is compressed from the same initial pressure to the same boiler pressure. This part of the cycle is not affected by the reheating process.

b) Turbine Work Output (W_T):

Determining the total work produced by the turbine in both stages.

- $W_T = (h_{2'} - h_3) + (h_{3'} - h_{1'})$ (III.9)

$W_T = (3250.9 - 2940.788) + (3475.3 - 2536.60)$

$\mathbf{W_T = 1248.81\ kJ.kg^{-1}}$

With reheating, the turbine produces significantly more work. This is because steam is expanded in two stages, with reheating in between, which increases the total enthalpy drop across the turbine.

This also reduces the moisture content at the turbine exhaust, protecting the blades and enhancing efficiency.

c) Boiler Heat Input (q_b):
Calculating the total heat added to the working fluid in the boiler

- $q_b = (h_{2'} - h_2) + (h_{3'} - h_3)$ (III.10)

  $q_b = (3250.9 - 165.8) + (3475.3 - 2940.788)$

  $\boldsymbol{q_b = 3619.612\ kJ.kg^{-1}}$

The heat input increases in the reheated cycle due to the additional fuel burned during the second heating phase. Although this raises the fuel demand, it leads to more efficient work extraction from the steam.

d) Net Work Output (W_{net}):
Finding the net useful work by subtracting pump work from turbine work

- $W_{net} = W_T - W_P$ (III.11)

  $W_{net} = 1248.81 - 4.8$

  $\boldsymbol{W_{net} = 1244.01\ kJ.kg^{-1}}$

The reheated turbine delivers around **276.71 kJ.kg^{-1}** more net work, which is a substantial gain for the same steam flow rate.

e) Thermal Efficiency (ηt):
Evaluating the thermal efficiency of the cycle

- $\eta_t = \frac{W_{net}}{q_b}$ (III.12)

  $\eta_t = \frac{1244.01}{3619.61}$

  $\boldsymbol{\cdot\ \eta_t = 34.3\ \%}$

This clear efficiency improvement is one of the most important benefits of reheating. It means we get more work output per unit of heat added, making the cycle more energy-efficient.

- Efficiency Gain from Reheating:

34.3 % - 31.3 % = 3 %

Reheating technology improves steam turbine energy efficiency by 3%

II.2.3.3 Calculation of the steam turbine power

The power of the steam turbine is given by the following relationship:

- $P = \dot{m}_s.W_T$ (III.13)

$P = 37.44 * 1248.81$

P = 46755.44 kW = 46.75MW

The calculations clearly demonstrate that incorporating a reheating stage significantly enhances the performance of the steam turbine. While the mass flow rate remains constant, the specific work output increases from 972.1 $kJ.kg^{-1}$ to 1244.01 $kJ.kg^{-1}$, resulting in a substantial rise in turbine power from 36.4 MW to 46.75 MW. This increase is primarily due to the reheating process, which raises the average temperature of heat addition, reduces moisture content at later expansion stages, and consequently improves thermal efficiency and mechanical reliability of the turbine.

II.2.3.4 Calculation of boiler thermal efficiency

In order to calculate the boiler's efficiency, the mass of the added fuel and the total fuel flow must be determined

We can calculate the increase in fuel mass flowing ($\dot{m}_{fs}$) from this relationship.

$\dot{m}_{vap}.(h_{3'} - h_3) = \dot{m}_{fs}.LHV$ (III.14)

$$\dot{m}_{fs} = \frac{\dot{m}_{vap}.(h_{3'} - h_3)}{LHV}$$

$$\dot{m}_{fs} = \frac{\mathbf{37.44\ (3475.3 - 2940.788)}}{48500}$$

$\dot{m}_{fs} = 0.412\ kg.s^{-1}$

We can calculate the total mass of fuel flowing ($\dot{m}_{f,re}$) using this relationship.

$$\dot{m}_{f,re} = \dot{m}_f(\text{superheat}) + \dot{m}_{fs} \quad \text{(III.15)}$$

$$\dot{m}_{f,re} = 2.636 + 0.412$$

$$\dot{m}_{f,re} = 3.048 \text{ kg.s}^{-1}$$

To enable reheating, more fuel is required an increase of around 0.412 kg.s^{-1}. However, this increase is justified by the extra work and higher efficiency obtained.

The thermal efficiency of the boiler is given by the following relationship:

$$\eta_b = \frac{\dot{Q}_b}{\dot{Q}_f} \quad \text{(III.16)}$$

$$\eta_b = \frac{\dot{m}_{vap}.[(h_{2'} - h_2) + (h_{3'} - h_3)]}{\dot{m}_{f,re}.\ LHV} \quad \text{(III.17)}$$

$$\eta_b = \frac{37.44\ (3250.9 - 165.8) + (3475.3 - 2940.788)}{3.048 * 48500}$$

$$\boldsymbol{\eta_b = 91.67\ \%}$$

The boiler performs slightly better in the reheated case. This is because heat is added in stages, which reduces thermal losses and improves heat exchange effectiveness.

II.2.3.5 Calculation of total efficiency

The global efficiency of the steam turbine is given by the following relationship:

$$\eta_{tot} = \frac{\dot{m}_{vap}\, W_{net}}{\dot{m}_f\, LHV} \quad \text{(III.18)}$$

$$\eta_{tot} = \frac{\dot{m}_{vap}\, W_{net}}{\dot{m}_f\, LHV} * \frac{h_{2'} - h_2}{h_{2'} - h_2}$$

$$\eta_{tot} = \frac{\dot{m}_{vap}.(h_{2'} - h_2)}{\dot{m}_f.\ LHV} * \frac{W_{net}}{h_{2'} - h_2}$$

$$\eta_{tot} = \eta_b\,.\,\eta_t \quad \text{(III.19)}$$

η_{tot} = 91.67% * 34.3 %

η_{tot} = 31.47%

III.3. extraction technique

Extraction steam turbines are a type of steam turbine designed to allow a portion of the steam to be extracted at an intermediate stage of expansion. The extracted steam is then used for external thermal applications, such as feedwater heating or industrial processes requiring thermal energy. This approach enhances the overall efficiency of the thermodynamic cycle by utilizing thermal energy that would otherwise be wasted in conventional systems.

III.3.1. Principle of operation

The main principle of extraction steam turbines lies in redistributing the available thermal energy in the steam so that it is not solely used for mechanical power generation, but also partially utilized for external thermal demands. this is achieved by extracting a specific portion of steam at an intermediate pressure and temperature from within the turbine, before the remaining steam continues expanding toward the condenser pressure

the extraction point is carefully selected to match thermal usage requirements—such as regenerative feedwater heating or industrial heating processes which leads to improved cycle efficiency and reduced thermal losses

We will use the extracted steam to heat the feed water. This process can be carried out with either a closed or an open feed water heater.

- **Exraction Hirn cycle with open feedwater heater**

This cycle represents an improved version of the basic Hirn cycle, where part of the steam is extracted from the turbine and used to heat the feedwater through an open feedwater heater. This enhancement improves the thermal efficiency of the cycle and reduces the required heat input from the boiler look at the figure III.4.

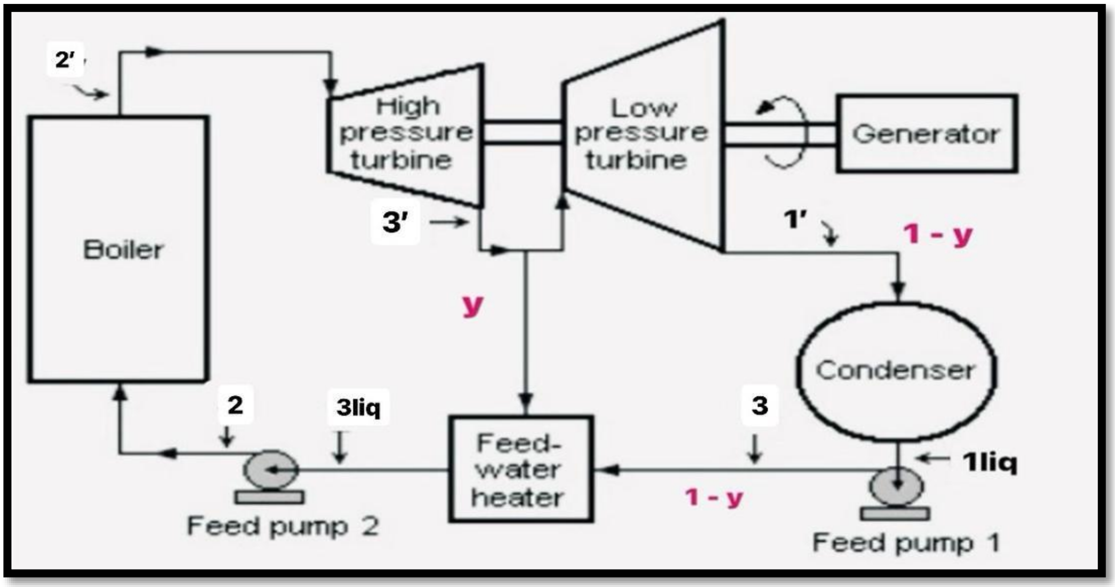

Figure III.4: Thermodynamic schematic of the exraction Hirn cycle with open feedwater heaters

❖ Cycle components and Thermodynamic Process

1. Boiler

- The feedwater enters the boiler at point (2) as a high-pressure liquid.
- It is heated and converted into superheated steam at point (2’).

2. Steam Turbine

- The steam expands through the turbine from point (2’) to point (3’).
- At (3’), a mass fraction y of the steam is extracted for feedwater heating.
- The remaining steam (fraction 1 - y) continues expanding to the low-pressure stage and exits at point (1′).

3. Condenser

- The steam exiting the turbine at (1′) is condensed into saturated liquid at low pressure, reaching point (1_{liq}).

4. Feed Pump 1

- This pump raises the pressure of the condensate from point (1_{liq}) to an intermediate pressure at point (3), suitable for mixing in the open feedwater heater.

5. Open Feedwater Heater

- In this direct-contact heat exchanger, the extracted steam (y) from point (3’) mixes directly with the compressed water (1 - y) from point (3).
- A single saturated liquid stream is produced at point (3_{liq}), which contains the combined thermal energy.

6. Feed Pump 2

- This pump raises the pressure of the mixed fluid from (3_{liq}) to boiler pressure, entering the boiler at point (2), thus closing the cycle.

III.3.2. Evolution of the extraction Hirn cycle with open feedwater heaters

As shown in the (figure III.5) Heat is transferred to the working fluid during process 2-2_{liq} at a relatively low temperature
This lowers the average heat-addition temperature and thus the cycle efficiency.

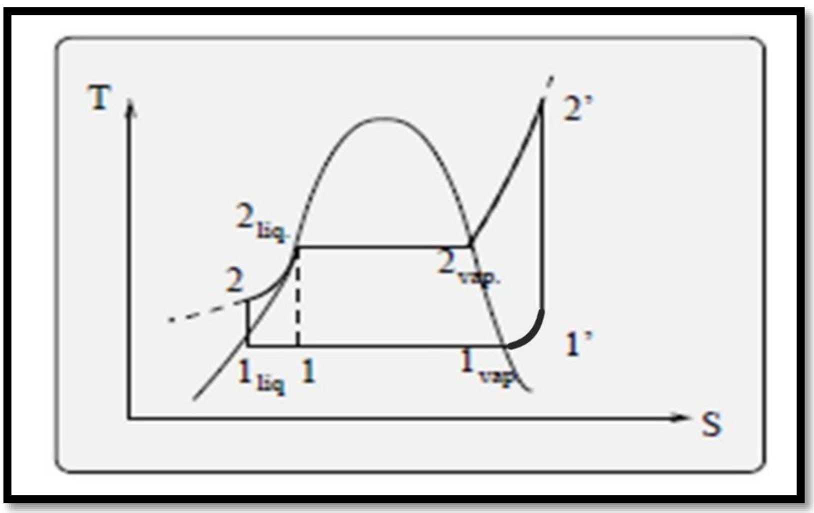

Figure III.5: Hirn cycle

We look for ways to raise the temperature of the liquid leaving the pump (called the feedwater) before it enters the boiler.

- A practical regeneration process in steam power plants is accomplished by extracting steam from the turbine at various points.

- This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead.
- The device where the feedwater is heated by regeneration is called a regenerator, or a feedwater heater.

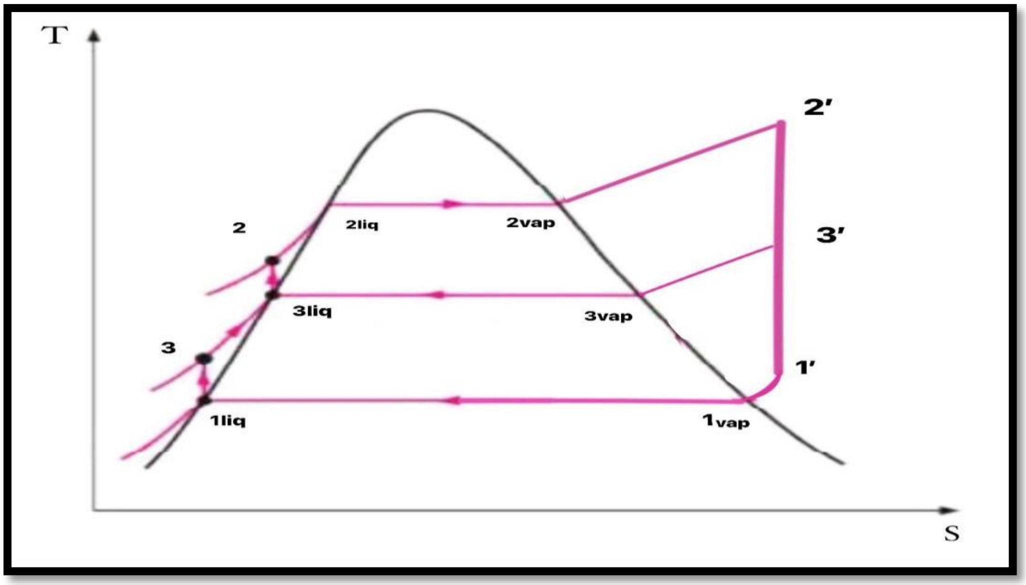

Figure III.6: Exraction Hirn cycle with open feedwater heaters

The extraction Hirn cycle using open feedwater heaters consists of multiple stages, including isentropic (reversible adiabatic) and isobaric (constant pressure) processes.

- **(1_{liq} → 3) and (3_{liq} → 2) : Isentropic compression in pumps**

Process: Pressurization of feedwater through one or more pumps

Description:

- The working fluid (saturated liquid) is compressed from low pressure (1liq) to higher pressures (up to 3) through intermediate stages (e.g., 3liq), corresponding to the pressure levels of the FWHs.
- No heat is added or removed; energy input comes in the form of shaft work.

- **2 → 2' : Isobaric heat addition in the boiler**

Process: Heat is added to the pressurized liquid until it becomes dry saturated or superheated vapor.
Description:

- Occurs at high pressure.

- The fluid absorbs heat and transitions from subcooled liquid → saturated liquid → saturated vapor (or superheated).

- **2' → 3' → 1' : Isentropic expansion in the turbine**

Process: Expansion of steam through the turbine stages
Description:

- Steam expands through high-pressure and low-pressure stages.
- At intermediate stages (3'), part of the steam is extracted for regenerative heating in FWHs.
- Produces mechanical work.

- **3' → 3 : Isobaric regenerative heating**

Process: Direct contact heat exchange (mixing) between extracted steam and feedwater
Description:

- Steam from turbine extraction is mixed with cooler feedwater at the same pressure.
- Resulting mixture is saturated liquid at the heater pressure.
- No external heat input is required.

- **1' → 1_{liq} : Isobaric heat rejection in the condenser**

Process: Condensation of low-pressure steam
Description:

- Steam releases latent heat and condenses into saturated liquid at low pressure.
- Heat is rejected to the environment.

III.3.3. Operating parameters of the steam turbine

- **The main operating parameters of the steam turbine are as follows:**

Item	Symbol	Value	Unit
Boiler pressure (high pressure)	P_b	42	bar
Steam temperature at turbine inlet	$T_{3'}$	420	°C
Extraction pressure	$P_{2'}$	10	bar
Condenser pressure (low pressure)	P_C	0.068	bar
Turbine efficiency	η_t	88%	-
Pump1 efficiency	η_p	88%	-
Pump2 efficiency	η_p	88%	-
Vapor mass flow rate	$\dot{m}_{vap}$	37.44	$kg.s^{-1}$
Low heat value (natural gas)	LHV	48500	$kJ.kg^{-1}$

Table II.3: The main operating parameters of the extraction steam turbine

III.3.4. Calculation of steam turbine performance

The values of pressure, temperature and enthalpy of the main states of water in liquid form and in the form of steam in the recovery boiler and in the turbine are given in Table II.4.

Point	P (bar)	T (°C)	h($kJ.kg^{-1}$)
1_{liq}	0.068	38.6	161.0
3	10	38.6	162.135
3_{liq}	10	179.9	762.8
2	42	181.2	766.898
2_{liq}	42	253.2	1087.4
2_{vap}	42	253.2	2800.8
2’	42	420	3250.9
3’	10	299	3074.2
1′	0.068	38.6	2257.47
1_{vap}	0.068	38.6	2570.1

Table III.4: Temperature-pressure-enthalpy characteristics of the different states thermodynamics of water for the extraction steam turbine

III.3.4.1. Determination of enthalpy of different state point of the steam turbine cycle

- State (point 1_{liq})

$h_{1liq} = h_{sat}(P_c)$

$\mathbf{h_{1liq} = 161.0\ kJ.kg^{-1}}$

$v_{1liq} = v_{sat}(P_c)$

$\mathbf{v_{1liq} = 0.001006\ m^3.kg^{-1}}$

- State (point 3)

$$W_{p(ideal)} = v_1 (P_3 - P_c) \quad \text{(III.20)}$$

$W_{p(ideal)} = 0.001006 * (10 - 0.0068)*10^2$

$\mathbf{W_{p(ideal)} = 0.999\ kJ.kg^{-1}}$

$$W_{p(actual)} = \frac{W_{P(ideal)}}{\eta_p} \quad \text{(III.21)}$$

$W_{p(actual)} = \frac{0.999}{0.88}$

$\mathbf{W_{p(actual)} = 1.135 kJ.kg^{-1}}$

$$h_3 = h_1 + W_{p(actual)} \quad \text{(III.22)}$$

$h_3 = 161 + 1.135$

$\mathbf{h_3 = 162.135\ kJ.kg^{-1}}$

- State (point 3_{liq})

$h_{3liq} = h_{sat}(P_{3liq})$

$\mathbf{h_{3liq} = 762.8\ kJ.kg^{-1}}$

$V_{3liq} = v_{sat}(P_{3liq})$

$\mathbf{v_{3liqs} = 0.001127\ m^3.kg^{-1}}$

- State (point 2)

$$W_{p(ideal)} = v_1 (P_b - P_{3liq}) \quad \text{(III.23)}$$

$W_{p(ideal)} = 0.001127 * (42 - 10)*10^2$

$\mathbf{W_{p(ideal)} = 3.606\ kJ.kg^{-1}}$

$$W_{p(actual)} = \frac{W_{P(ideal)}}{\eta_p} \quad \text{(III.24)}$$

$W_{p(actual)} = \frac{3.606}{0.88}$

$\mathbf{W_{p(actual)} = 4.098\ kJ.kg^{-1}}$

$h_2 = h_{3liq} + W_{p(actual)}$ (III.25)

$h_2 = 762.8 + 4.098$

$\mathbf{h_2 = 766.898\ kJ.kg^{-1}}$

- State (point 2_{liq})

$h_{2liq} = h_{sat}(P_b)$

$\mathbf{h_{2liq} = 1087.4\ kJ.kg^{-1}}$

- State (point 2_{vap})

$h_{2vap} = h_{sat}(P_b)$

$\mathbf{h_{2vap} = 2800.8\ kJ.kg^{-1}}$

- State (point 2')

$h_{2'}$ is determined in the superheated zone of the water diagram

$\mathbf{h_{2'} = 3250.9\ kJ.kg^{-1}}$

$\mathbf{S_{2'} = 6.919\ kJ.kg^{-1}.K^{-1}}$

- State (point 3')

for an isentropic process

$S_{3'} = S_{2'} = 6.919\ kJ.kg^{-1}.K^{-1}$

$S_{sat,vap}(P_{3'}) = 6.586\ kJ.kg^{-1}.K^{-1}$

$S_{3'} > S_{sat,vap}(P_{3'})$

The vapour is still dry at the outlet of the high-pressure turbine

So h_3 is determined in the superheated zone of the water diagram

$\mathbf{h_{3's} = 3050.1\ kJ.kg^{-1}}$

$h_{3'} = h_{2'} - \eta_T(h_{2'} - h_{3's})$ (III.26)

$h_{3'} = 3250.9 - 0.88\ (3250.9 - 3050.1)$

$h_{3'} = 3250.9 - 176.7$

$\mathbf{h_{3'} = 3074.2\ kJ.kg^{-1}}$

- State (point 1')

for an isentropic process

$S_{1'} = S_{2'} = S_{3'} = 6.919\ kJ.kg^{-1}.K^{-1}$

$S_{sat,vap}(P_c) = 8.275\ kJ.kg^{-1}.K^{-1}$

$S_{1'} < S_{sat,vap}(P_c)$

then the vapour is wet at the turbine outlet

So we have to find $x_{1's}$

$$x_{1's} = \frac{S_{1'} - S_{liq}}{S_{vap} - S_{liq}} \quad \text{(III.27)}$$

$$x_{1's} = \frac{6.919 - 0.559}{8.275 - 0.559}$$

$$\boldsymbol{x_{1's} = 0.824}$$

$$h_{1's} = h_{liq} + x_{1's}(h_{vap} - h_{liq}) \quad \text{(III.28)}$$

$$h_{1's} = 161 + 0.824 * 2409.1$$

$$\boldsymbol{h_{1's} = 2146.1\ kJ.kg^{-1}}$$

$$h_{1'} = h_{3'} - \eta_T(h_{3'} - h_{1's}) \quad \text{(III.29)}$$

$$h_{1'} = 3074.2 - 0.88\ (3074.2 - 2146.1)$$

$$\boldsymbol{h_{1'} = 2257.472\ kJ.kg^{-1}}$$

- State (point 1_{vap})

$h_{1vap} = h_{sat}(p_c)$

$$\boldsymbol{h_{1vap} = 2570.1\ kJ.kg^{-1}}$$

III.3.4.2. Calculation of the performance characteristics of the steam turbine installation.

1. Mass Fraction of Extracted Steam (y) in Open Feedwater Heater:

The energy balance equation for the open feedwater heater

➢ $y.h_{3'} + (1 - y).h_3 = h_{3liq}$ (III.30)

$3074.2y + (1 - y)\ 162.13 = 762.8$

$$y = \frac{762.8 - 162.13}{3050.1 - 162.13}$$

$$\boldsymbol{y = 0.208 = 20.8\ \%}$$

2. Pump Work Calculation (W_p):
Calculating the work input required by the pump
Pump 1 :

- $W_{p1} = (h_3 – h_{1liq})$ (III.31)

  $W_{p1} = (162.135 – 161.0)$

  $W_{p1} = 1.135$ kJ.kg^{-1}

Pump 2 :

- $W_{p2} = h_2 – h_{3liq}$ (III.32)

  $W_{p2} = 766.898 – 762.8$

  $W_{p2} = 4.098$ kJ.kg^{-1}

Compared to the basic Hirn cycle, the extraction Hirn cycle includes an additional pump (Pump 2), which increases the total pump work. However, this increase is relatively small and has a minor impact on the overall cycle performance, especially when compared to the gain in thermal efficiency due to feedwater heating.

3. Turbine Work Output (W_T):
Determining the total work produced by the turbine in both stages.

- $W_T = (h_{2'} – h_{3'}) + (1 - y)(h_{3'} – h_{1'})$ (III.33)

  $W_T = (3250.9 – 3074.2) + (1 – 0.208)(3074.2 – 2257.47)$

  $W_T = 823.6$ kJ.kg^{-1}

In the extraction Hirn cycle, the total turbine work is reduced compared to the basic Hirn cycle due to the diversion of a portion of the steam (y = 0.208) for feedwater heating. This reduction in work output is the cost paid for improving the thermal efficiency through regeneration

4. Boiler Heat Input (q_b):
Calculating the total heat added to the working fluid in the boiler

- $q_b = h_{2'} – h_2$ (III.34)

  $q_b = 3250.9 – 766.898$

q_b = 2484.002 kJ.kg^{-1}

The boiler heat input in the extraction Hirn cycle is slightly lower than in the basic Hirn cycle due to the preheating of feedwater by the extracted steam. This reduces the required energy input from the boiler, contributing to an improvement in thermal efficiency.

5. Net Work Output (W_{net}):

Finding the net useful work by subtracting pump work from turbine work

- $W_{net} = W_T - W_{p1} - W_{p2}$ (III.35)

$W_{net} = 823.6 - 1.135 - 4.098$

W_{net} = 818.372 kJ.kg^{-1}

Although the extraction Hirn cycle produces less turbine work than the basic cycle, the reduction in net work output is moderate. This is an expected consequence of diverting part of the steam for regeneration, which sacrifices some work to enhance thermal efficiency

6. Thermal Efficiency (ηt):

Evaluating the thermal efficiency of the cycle

- $$\eta_t = \frac{W_{net}}{q_b} \quad \text{(III.36)}$$

$$\eta_t = \frac{818.372}{2484.002}$$

η_t = 32.9 %

The thermal efficiency of the extraction Hirn cycle (32.9%) is higher than that of the basic Hirn cycle. This improvement is a direct result of feedwater heating by extracted steam, which raises the average temperature of heat addition and enhances cycle efficiency despite the slight loss in net work output.

III.3.4.3. Calculation of the steam turbine power

The power of the steam turbine is given by the following relationship:

- $P = \dot{m}_{vap}.W_T$ (III.37)

$P = 37.44 * 818.372$

P = 30639.84 kW = 30.63 MW

The power output of the steam turbine in the extraction Hirn cycle (30.63 MW) is slightly lower than in the basic Hirn cycle, primarily due to the reduced specific turbine work caused by steam extraction. However, this reduction is compensated by a more efficient use of heat input, reflecting the typical trade-off in regenerative cycles

III.3.5. Calculation of fuel mass flow rate

$$\dot{m}_{vap}.(h_{2'} - h_2) = \dot{m}_{f,ex}.LHV.\ \eta_b \quad \text{(III.38)}$$

$$\dot{m}_{f,ex} = \frac{\dot{m}_{vap}.(h_{2'} - h_2)}{LHV.\ \eta_b}$$

$$\dot{m}_{f,ex} = \frac{\mathbf{37.44\ (3250.9 - 766.898)}}{48500\ .0.903}$$

$\dot{m}_{f,ex} = 2.122\ kg.s^{-1}$

The fuel mass flow rate in the extraction Hirn cycle ($2.122\ kg.s^{-1}$) is lower than that in the basic Hirn cycle for the same steam mass flow rate. This reflects the improved thermal efficiency of the extraction cycle, as less fuel is needed to generate the required heat input due to preheating of the feedwater

III.3.6. Calculation of total efficiency

The global efficiency of the steam turbine is given by the following relationship:

- $$\eta_{tot} = \frac{\dot{m}_{vap}\ W_{net}}{\dot{m}_f\ LHV} \quad \text{(III.39)}$$

$$\eta_{tot} = \frac{\dot{m}_{vap}\ W_{net}}{\dot{m}_f\ LHV} * \frac{h_{2'} - h_2}{h_{2'} - h_2}$$

$$\eta_{tot} = \frac{\dot{m}_{vap}.(h_{2'} - h_2)}{\dot{m}_f.\ LHV} * \frac{W_{net}}{h_{2'} - h_2} \quad \text{(III.40)}$$

$\eta_{tot} = \eta_b \cdot \eta_t$ (III.41)

$\eta_{tot} = 90.34\ \% * 32.9\ \%$

$$\boldsymbol{\eta_{tot} = 29.72\ \%}$$

The total efficiency of the extraction Hirn cycle (29.72%) is higher than that of the basic Hirn cycle. This improvement is mainly due to the enhanced thermal efficiency resulting from feedwater preheating. Although part of the steam is diverted from producing mechanical work, the overall fuel-to-electricity conversion becomes more effective

III.4. Conclusion

In this chapter, we examined how the performance of the conventional steam turbine cycle (initially analyzed in Chapter II) can be enhanced through the application of two thermodynamic improvement strategies: reheating and steam extraction. The objective was to evaluate how these modifications impact key performance metrics such as thermal efficiency, specific work output, fuel consumption, and net power generation.

The analysis demonstrated that the reheating cycle provides the highest performance gains, achieving a thermal efficiency of 34.3% and a net power output of 46.75 MW. These improvements are attributed to increased average heat addition temperature and reduced steam moisture at the turbine's later stages. In contrast, the extraction cycle, while producing a lower net power output of 30.63 MW, offered a significant reduction in fuel mass flow rate, making it a more fuel-efficient and economically viable solution in scenarios where operational cost and fuel economy are prioritized.

Table III.5 presents a detailed comparison of the thermodynamic and operational parameters of the three configurations evaluated: the baseline cycle, the reheated cycle, and the extraction cycle.

Parameter	Baseline cycle	Reheating cycle	Extraction cycle
Boiler pressure (P_b)	42 bar	42 bar	42 bar
Steam inlet temperature	420 °C	420 °C	420 °C
Reheat / Extraction pressure	—	10 bar	10 bar
Turbine efficiency (η_T)	88%	88%	88%
Boiler efficiency (η_b)	90.34%	91.67%	90.34%
Thermal efficiency (η_t)	31.3%	34.3%	32.9%
Global efficiency (η_{tot})	28.27%	31.47%	29.72%
Fuel flow rate ($\dot{m}_f$)	2.636 $kg.s^{-1}$	3.048 $kg.s^{-1}$	2.122 $kg.s^{-1}$
Net specific work (W_{net})	967.3 $kJ.kg^{-1}$	1244.01 $kJ.kg^{-1}$	818.37 $kJ.kg^{-1}$
Power output (P)	36.4 MW	46.75 MW	30.63 MW

Table III.5: Comparative performance summary of the baseline, reheating, and extraction steam turbine cycles

Both enhancement techniques proved effective in improving the steam cycle's performance, but they serve different operational objectives. Reheating is ideal for scenarios where maximizing energy output is the primary goal, whereas extraction is more appropriate in systems where fuel savings, economic feasibility, and environmental impact are critical.

Ultimately, the choice of improvement strategy should be guided by a comprehensive assessment of the plant's operational conditions, economic targets, and sustainability requirements. This study highlights how integrating modern thermodynamic enhancements into conventional cycles can pave the way for more efficient, cost-effective, and environmentally conscious thermal power generation.

General Conclusion

This thesis has addressed the evaluation and enhancement of steam turbine performance through a structured approach combining theoretical knowledge, case study analysis, and thermodynamic modeling.

The first chapter introduced the fundamental principles of turbomachinery, with particular focus on gas and steam turbines, providing both theoretical clarity and practical context via the Fertial industrial complex. This framework established the relevance of the study and highlighted the industrial importance of improving turbine efficiency in Algeria and beyond.

Chapter II provided a comprehensive energy analysis of a steam turbine installation, operating under the Rankine and Hirn cycles. This included a thorough examination of each system component and the thermodynamic processes governing their interaction. Using real operational data, the performance metrics of a Fertial steam turbine were determined, revealing both the system's strengths and its limitations in terms of thermal and global efficiency.

In Chapter III, the core of this work, performance enhancement strategies were proposed and analyzed. The use of reheating and extraction-condensing configurations was shown to significantly improve thermal efficiency and power output. Through numerical simulations, it was demonstrated that the reheated cycle achieved a thermal efficiency of 34.3% and a power output of 46.75 MW, while the extraction method offered meaningful fuel savings, with an overall efficiency of 29.72%.

In conclusion, this study demonstrates that with appropriate thermodynamic modifications, steam turbines can achieve significantly higher performance. These improvements not only boost energy output but also contribute to fuel savings and system sustainability. Future work could extend this research by integrating economic analysis, real-time control strategies, and environmental assessments, paving the way for the next generation of intelligent and efficient power systems.

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