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-THEME-

Enhancement of gas turbine performance using renewable energies

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وما توفيقي إلا بالله

Thanks

With gratitude to God for guiding us on the path of knowledge, we have been able to complete this work.

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Dedication

بسم الله الرحمن الرحيم

أهدي هذا العمل إلى إلهي الحبيب الله رب العالمين، الذي كان توجيهه وبركاته قوتي وإلهامي طوال هذه الرحلة.

إلى سكان غزة و كتائب عز الدين القسام خاصة و إلى فلسطين عامة، الذين تلهمني مرونتهم وقوتهم كل يوم، مثابرتكم في مواجهة الشدائد هي شهادة على الروح البشرية.

لوالدي الأعزاء، الذين كان دعمهم الثابت وتضحياتهم التي لا نهاية لها وتشجيعهم المستمر أساس كل إنجازاتي. كان حبكم و دعائكم و صلواتكم قوتي الدافعة.

إلى أخواتي العزيزات، اللواتي لطالما رفع دعمهن وتفهمهن معنوياتي. لقد كانت و لا زلت رفقتكن ولطفكن لا تقدر بثمن بالنسبة لي.

إلى أصدقائي، الذين جعلت صداقتهم الحميمة وتشجيعهم في هذه الرحلة لا تُنسى ومرضية. لقد كانت صداقتكم مصدر فرح وتحفيز كبيرين.

هذا العمل هو شهادة على الحب والدعم والإيمان الذي وضعتموه فيّ جميعًا. شكرا لكونكم جزء لا يتجزأ من رحلتي.

العبد الضعيف. جمال الدين

Dedication

بسم الله الرحمان الرحيم

"وقل اعملوا فسيرى الله عملكم و المومنون"

الحمد لله الذي بنعمته تتم الصالحات. أشكر الله عز وجل على فضله وكرمه وعونه على التمام.

TO THE ONE WHO HAS GIVEN ME EVERYTHING HE HAS SO THAT I MAY ACHIEVE HIS HOPES, TO THE ONE WHO PUSHES ME FORWARD TO REACH MY GOALS, TO THE PERSON WHO EMBODIES HUMANITY WITH ALL ITS STRENGTH, TO THE ONE WHO DEDICATED HIMSELF TO MY EDUCATION WITH IMMENSE SACRIFICES, SANCTIFYING KNOWLEDGE, TO MY FIRST TEACHER IN LIFE, MY DEAR FATHER, MAY GOD PROLONG HIS LIFE;

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TO MY ONLY BROTHER, MY SUPPORT AND STRENGTH IN LIFE, I WISH YOU SUCCESS AND PROSPERITY.

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WITH ALL MY LOVE,
HITA HOUSSAM EDDINE.

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Nomenclature

Symbol	Description	Unit
C_p	Heat capacity	J/kg °C
h	Convective heat transfer coefficient	W/m² °C
m	Mass	kg
q	Heat transfer rate	W
R	thermal resistance	m.°C/W
r_1	Inner radius of the tube	m
r_2	Outer radius of tube	m
r_3	Radius of the soil adiabatic layer	m
s	internal section of the tube	m^2
T	Temperature	°C
u	air flow rate	m/s
W	Power capacity	W
x	Pipe length	m

Greek symbols

λ	thermal conductivity	W/m °C
γ	Specific heat ratio (Cp/Cv)	-
ρ	Density	kg/m³
η	Efficiency	-

Subscripts

a	Air
c	Compressor
f	Fuel
g	Flue gases
i	Tube inside
in	Input

p	Pipe
t	Turbine
th	Thermal efficiency

Abbreviations

EAHE	Earth to air heat exchanger
N_u	Nusselt number
P_r	Prandtl number
R_e	Reynolds number

General introduction

Gas turbines are a cornerstone of modern internal combustion engine technology, essential in various applications such as power generation, aviation, and industrial processes. These engines operate by transforming thermal energy into mechanical energy, typically driving a shaft connected to an industrial machine or converting gas expansion into kinetic energy through a nozzle, as seen in turbojet engines. The evolution of gas turbine technology is rich and multifaceted, dating back to Giovanni Branca's initial patent in 1629. Over the centuries, many inventors and engineers, including notable figures like John Barber, Claude Bourdin, and Henri Coanda, have contributed significant advancements that have shaped the current landscape of gas turbines. A major milestone was achieved in 1950 with the introduction of the first efficient gas turbine for electricity production, setting the stage for widespread adoption and further innovation.

Gas turbines offer numerous advantages, including high power output relative to their size and weight, which makes them highly desirable for applications where space and weight are critical constraints, such as in aircraft and ships. Their ability to generate substantial power from compact installations also makes them suitable for peak power plants and emergency power supplies. Additionally, gas turbines are capable of operating on a variety of fuels, ranging from natural gas to kerosene, providing flexibility in fuel choice based on availability and economic considerations.

Despite these benefits, gas turbines face several significant challenges, particularly concerning efficiency and operational costs. One of the primary issues is that gas turbines typically have lower thermal efficiency compared to other types of internal combustion engines, such as diesel engines. This efficiency gap is more pronounced in smaller installations, where the advantages of scale are less apparent. Furthermore, the initial capital costs for gas turbines are often high, which can be a barrier to their adoption, especially in cost-sensitive projects. Operational efficiency can also be adversely affected by environmental conditions, such as ambient air temperature, which impacts the density of the air and consequently the performance of the turbine.

Another critical challenge is the longer startup time required for gas turbines compared to diesel engines. This characteristic limits their use in applications where immediate power availability is crucial, such as backup power systems for hospitals or data centers. The need for longer startup times can also complicate their integration into power grids that require quick response times to fluctuations in demand. Moreover, gas turbines require sophisticated maintenance regimes to ensure their reliable operation, which can add to the operational costs over their lifespan.

The objective of this study is to enhance the performance of gas turbines by systematically addressing these challenges through a comprehensive and methodologically sound approach. This research aims to provide a detailed understanding of the fundamental concepts and principles underlying gas turbine technology, which is essential for identifying and implementing improvements. The study begins with a thorough review of the historical development and key components of gas turbines, setting the stage for more in-depth discussions on their operational mechanisms and performance characteristics.

Building on this foundation, the research progresses to a bibliographic synthesis that examines theoretical models and practical experiments related to gas turbines. This synthesis aims to consolidate existing knowledge and highlight gaps in the current understanding, paving the way for innovative solutions. A significant focus of the study is on mathematical modeling and the validation of these models using real-world data. Accurate simulations of thermodynamic behavior are crucial for improving gas turbine design and operation, and the validation process ensures the reliability and applicability of these models.

By addressing the challenges associated with gas turbines in a structured and systematic manner, this study seeks to contribute to the advancement of gas turbine technology. Through detailed analysis and validation, the research aims to provide solutions that enhance the efficiency, reliability, and operational effectiveness of gas turbines in various applications. This comprehensive approach not only aims to improve the performance of existing gas turbine installations but also to inform the development of next-generation technologies that can overcome current limitations and meet future energy demands.

Chapter I: Generalities

I.1 Introduction

Chapter I introduces the fundamental concepts and principles underlying gas turbine technology. This chapter aims to provide a foundational understanding of gas turbines, covering their historical evolution, key components, and operational mechanisms. We begin with a brief history of gas turbine development, tracing its advancements from early prototypes to modern high-efficiency systems. Following this, we delve into the anatomy of gas turbines, detailing the roles and functions of essential components such as compressors, combustion chambers, and turbines. This chapter also addresses the thermodynamic cycles that govern gas turbine operations, laying the groundwork for more advanced discussions in subsequent chapters. By establishing a solid knowledge base, Chapter I prepares the reader for a deeper exploration of strategies to enhance gas turbine performance using renewable energy sources.

I.2 Historical development

The first gas machine was patented in 1629 by an Italian mechanic Giovanni Branca, a machine in which a jet was directed towards a horizontal wheel connected to a gear system to actuate a press. Apres Branca several mathematicians have contributed to the improvement of this technology.

In 1791, the Englishman John Barber patented a hybrid device since this gas turbine had an alternative compressor. In the years 1820-1833 Claude Bourdin, a French professor, made several installations of hydraulic machines which named them Turbine, word deriving from the Latin Turbines'' meaning which turns, but he did not succeed in passing to the stage of industrially stable machines.

In 1844 the Fourneyron turbines were installed in Europe and the United States where improvements were made. Gas turbines began to materialize between the late nineteenth century and the early twentieth century

It is mentioned that a first gas turbine capable of providing work was built in 1903 by mechanical engineer Elling in Norway.

During 1906, the research of the French Armengaud and Le Male resulted in the first autonomous turboengine with an overall efficiency of 3%.

In 1910 the engineer Henri Coanda tried an airplane whose engine was an elementary gas turbine composed of a compressor, a combustion chamber and a nozzle.

But it is that in 1930 that the idea of gas turbine was really presented in the United States, France, Great Britain, Italy and Germany

The first use of turbines with an efficiency of 30% for electricity production was in 1950.

To these inventions were added those developed by the team of Secundo Compiniqui built a turboprop in 1940, and the contribution Frank Whittle of England after which the practical creation of the modern gas turbine was attributed.[1], [2]

I.3 Definition

The gas turbines are part of the turbomachinery defined as devices in which an energy exchange takes place between a rotor rotating around a constant speed axis and a permanently flowing fluid. A gas turbine (abbreviated as a TAG), also known as a combustion turbine, is the seat of the transformation assembly constituting the thermal cycle described by the fluid.

The word «gas» in the name «gas turbine» refers to the gaseous character of the fluid circulating along the turbine and not to the fuel used, which can be either gaseous (natural gas, butane or propane), or liquid (from the most volatile such as naphtha, alcohol, kerosene or domestic fuel oil) to the most viscous fuels (heavy or residual fuel oils or even crude oil).

An example Figure 1

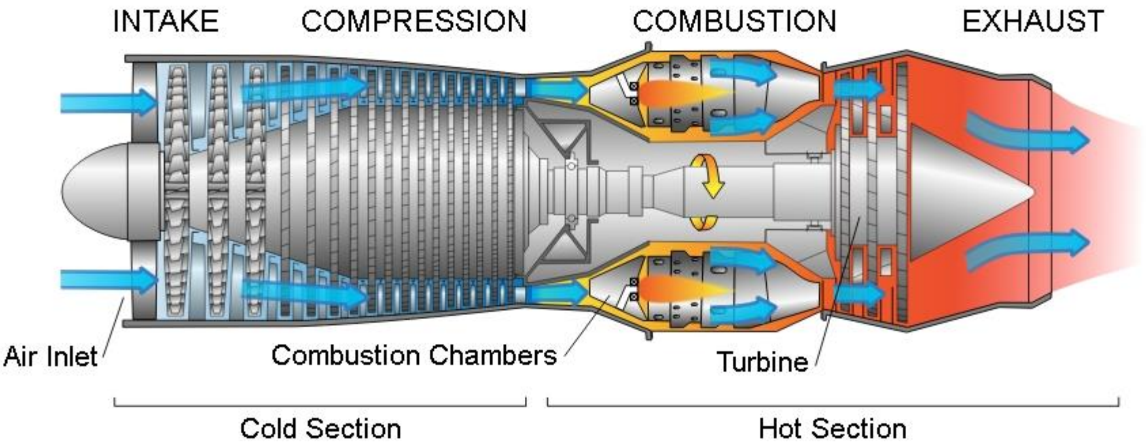

Figure 1. A diagram of a gas turbine engine[3].

I.4 Fundamentals of a gas turbine

The entire gas turbine consists of three essential components:

- The axial or centrifugal flow compressor.
- The chamber of combustion.
- The turbine.

I.4.1 Compressor

The role of the compressor is to suck and compress the air to bring it to optimal speeds, pressure and temperature at the entrance of the combustion chamber. It uses more than half the power produced by the expansion turbine, taking into account the air samples at the intermediate stages to cool the hot parts. There are two main kinds of compressors, centrifugal and axial.

Figure 2. Compresseur de type BCL.

I.4.2 Combustion chamber

The combustion chamber between the compressor and the turbine consists of a flame tube or hearth generally in the form of a torus. It is enclosed in a case, also of toric shape.

The combustion chamber is intended to heat the air coming out of the top decompression stage in order to provide the necessary energy to move the turbine or turbines and to give sufficient thrust to the nozzle in the case of aircraft. This heat input was reduced by the combustion of oxygen from the air with a fuel

It must be as complete as possible and the distribution of gas temperatures as homogeneous as possible. It is obvious that the principle of operation varies from one gas machine to another but the general principle of operation remains relatively identical.

The air entering the combustion chamber is divided into several circuits. One part goes directly into the flame tube and into the injector to contribute to the combustion. Another part bypasses the flame tube and is used both to cool the walls and to dilute and mix the air flow in the fireplace (see Figure 3 and 4).

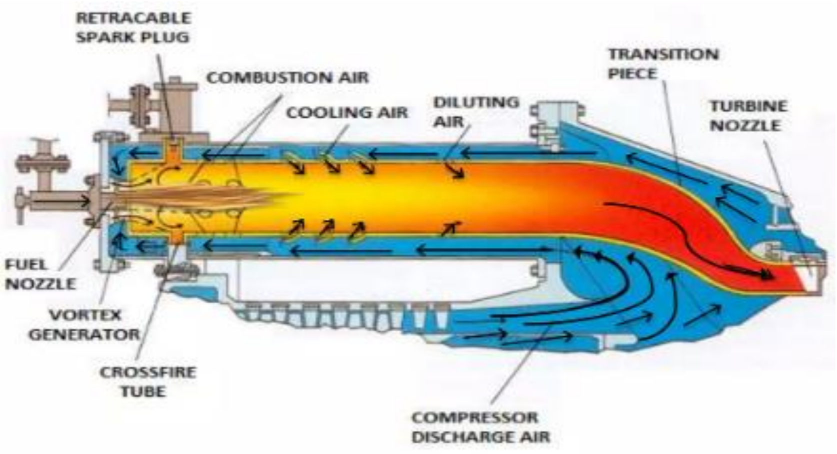

Figure 3. Diagram of the operation of a combustion chamber.

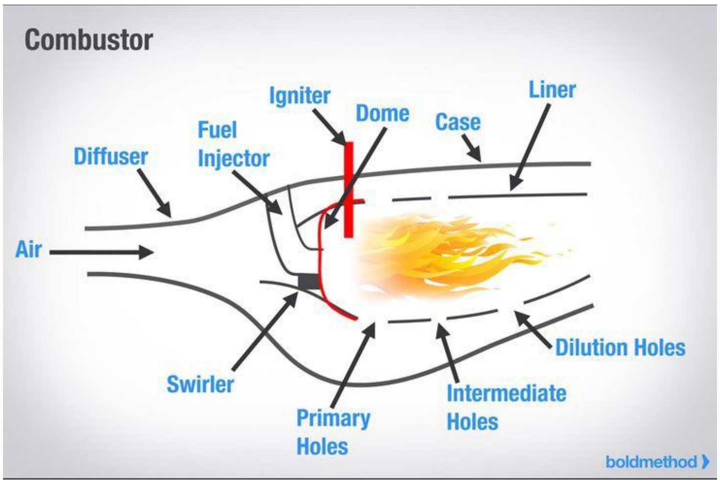

Figure 4. Simplified chart showing combustion chamber.[4]

Two types of combustion chambers are mainly encountered for gas turbines:

separate or tubular chambers and annular chambers

I.4.3 Turbine

The turbine recovers part of the energy from the combustion of gases for the operation of the compressor and accessories, and the other part to ensure the thrust in the case of a turbojet engine or drive the transmission shaft of a connected load (propeller, blower, pump, compressor, etc.).

The axial turbine is the solution used on most gas turbines. Exiting the combustion chamber, the gases will relax in the distributor or stator, which will accelerate the flow by deflecting it. Under the effect of this flow the rotor also having deflection profiles rotates. Therefore, a turbine stage consists of a fixed vane distributor or stator, followed by a moving vane or rotor as shown in Figure 5. The turbine can be single-stage, two-stage or multi-stage. In most cases, the number of rows of a turbine does not exceed three stages.

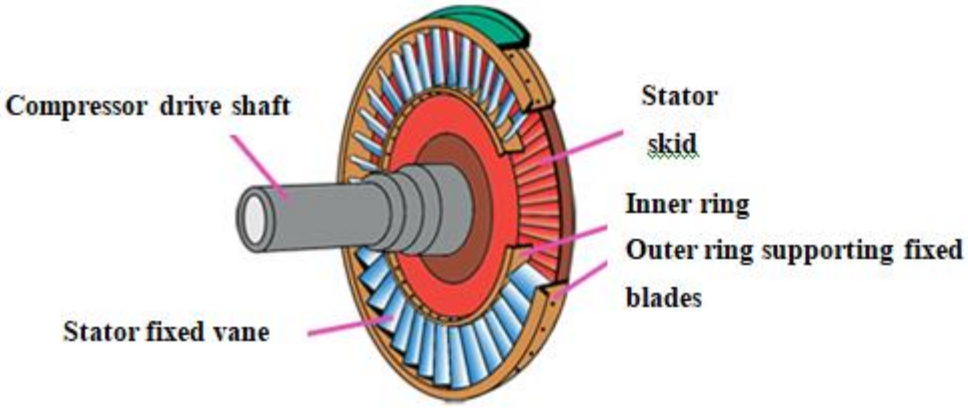

Figure 5. Schematic of a turbine stage.

I.5 principle of operation

A gas turbine operates as follows:

a) It extracts air from the surrounding environment (suction)

b) It compresses it to a higher pressure by the compressor (compression)

c) Increases the energy level of compressed air by adding and burning fuel in a combustion chamber (hot gas)

d) It carries high pressure and high temperature air to the section of the turbine that converts thermal energy into mechanical energy to rotate the shaft (expansion); this serves, on the one hand, to provide the necessary energy for air compression, which takes place in a compressor connected directly to the turbine section and, on the other side to provide the useful energy to the driven machine, coupled with the machine by means of a coupling such as an alternator or a centrifugal compressor

e) Discharges low pressure and temperature gases from the above-mentioned transformation (exhaust) to the atmosphere. [1]

The adjustment of the power and the speed of rotation is possible by acting on the flow of the air at the entrance and on the injection of the fuel.

I.6 Thermodynamic cycle of the gas turbine (Brayton cycle)

The basic thermodynamic cycle describing the operation of a gas turbine is called the "Brayton cycle." It is an open thermodynamic cycle because the exhaust gases are released directly into the atmosphere without any recovery (non-regenerative, non-combined cycle). It essentially consists of four transformations, which are represented on the (P - V) and (T - S) diagrams in Figures (6 and 7).

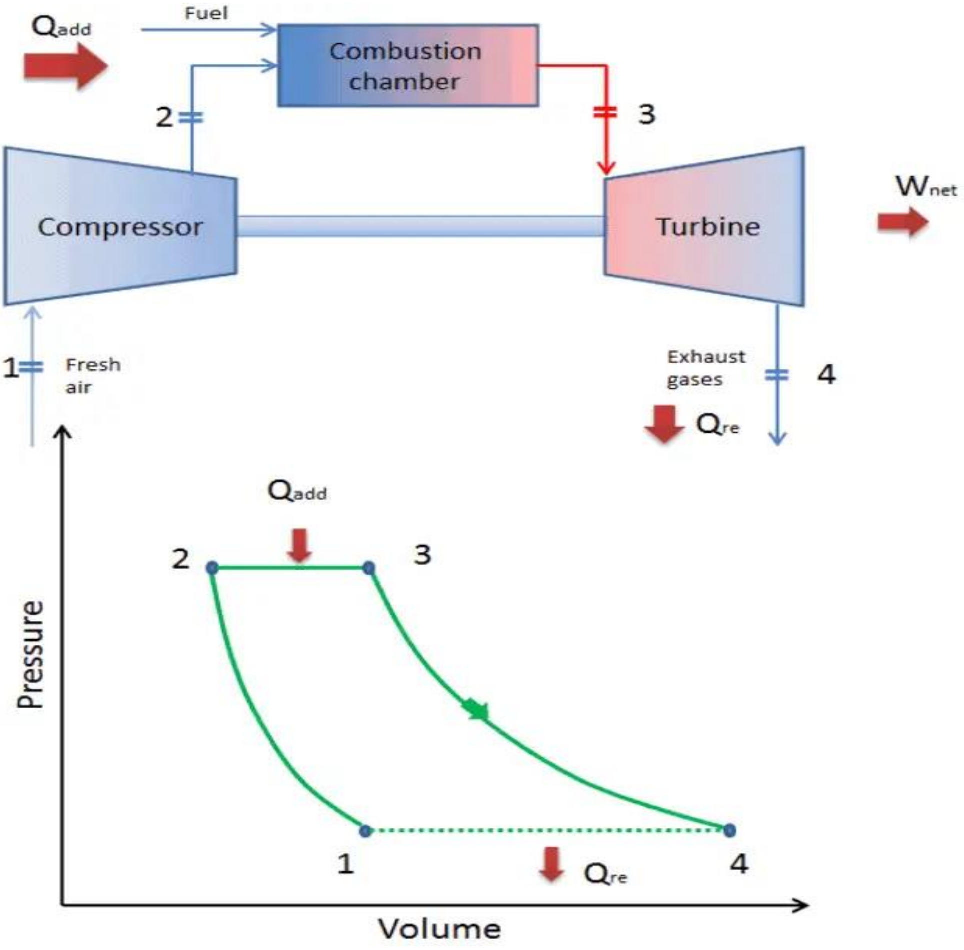

Figure 6. Cycle de Brayton – diagramme (P-V).[5]

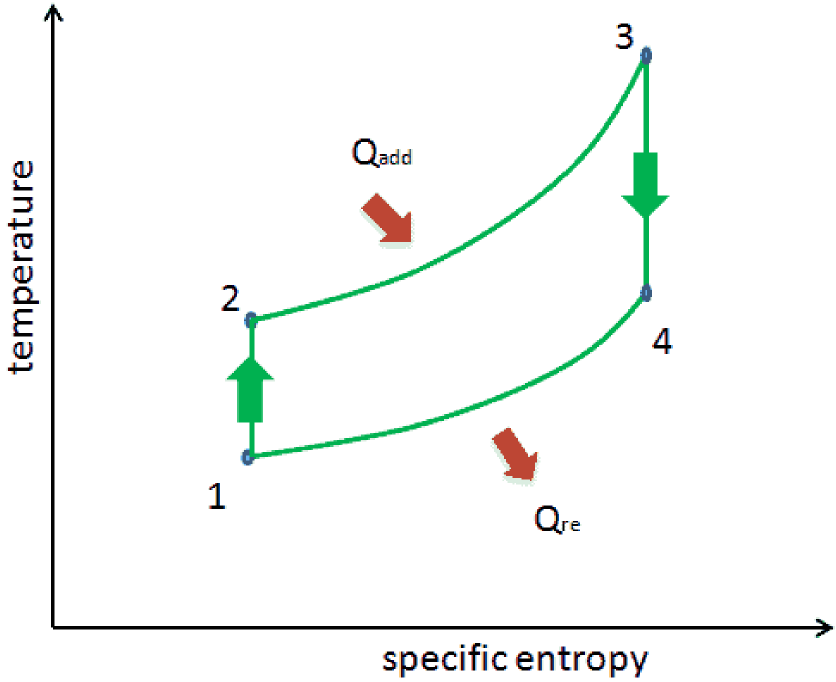

Figure 7. Cycle de Brayton – diagramme (T-S).[5]

With:

(1-2): Isentropic compression

(2-3): Heat addition at constant pressure in the combustion chamber

(3-4): Isentropic expansion

(4-1): Exhaust to the atmosphere

I.7 Classification of gas turbines

The turbines can be classified according to different points: as a type of work performed, the arrangement of the shaft, mode of action of the gas, thermodynamic operation, etc. These classes are arranged in the flow chart in Figure 8.

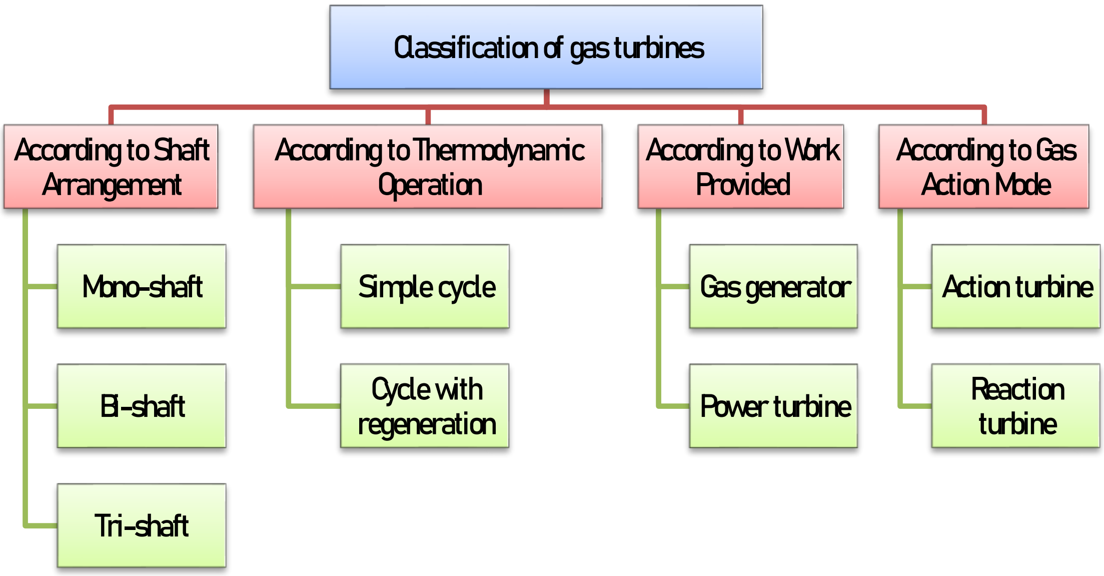

Figure 8. Diagram classifying types of gas turbines.

I.7.1 Thermodynamic mode of operation

The open-cycle gas turbine with direct suction and exhaust in the most widespread atmosphere is divided into two classes:

I.7.1.A Single cycle turbine

It is a turbine that uses only once the circulating fluid for power production. After the relaxation of the gases, they still have an energy potential that is lost in the atmosphere through the nozzle or chimney.

I.7.1.B Cycle turbine with regeneration

Heat losses caused by hot exhaust gases are the most important in the gas turbine installation.

For this, the efficiency of gas turbine installations can be increased by driving the exhaust gases into a heat exchanger where they heat the air coming out of the compressor before it enters the combustion chamber (Figure 10), some of the sensitive heat of these gases is recovered.

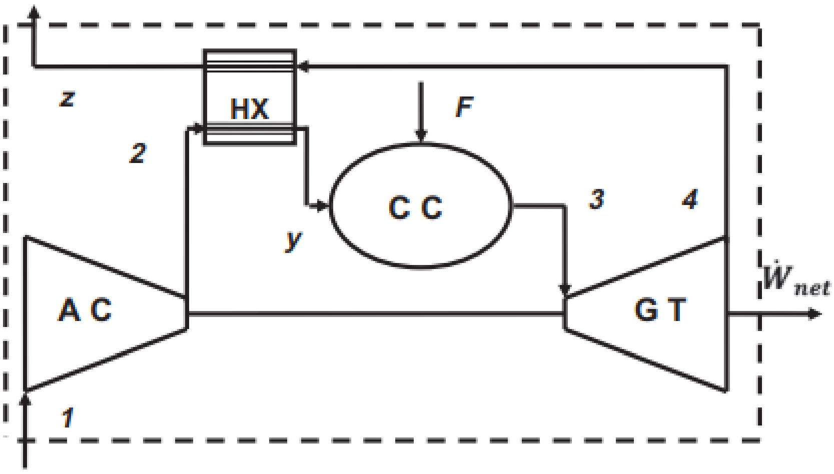

Figure 9. Schematic of regenerative gas turbine cycle.[6]

I.7.2 Tree Layout Mode

According to the tree layout, there are three types they are:

I.7.2.A Single-shaft turbine

The compressor and turbine sections are mounted on the same shaft which allows to turn at the same speed, this type is used for applications that do not require speed variations such as propeller drive for propulsion or generators for power generation.

I.7.2.B Twin-shaft turbine

It is a gas turbine consisting of a compressor, a combustion chamber and a turbine, the set is mounted on a common shaft and on the other hand a power or work turbine is mounted on another independent shaft with the receiver device. Another type of machine with two shafts, is the double-body gas turbine whose compressor and turbine are in two parts: the high-pressure part and the low-pressure part. Each part is mounted on the same tree (Figure 9).

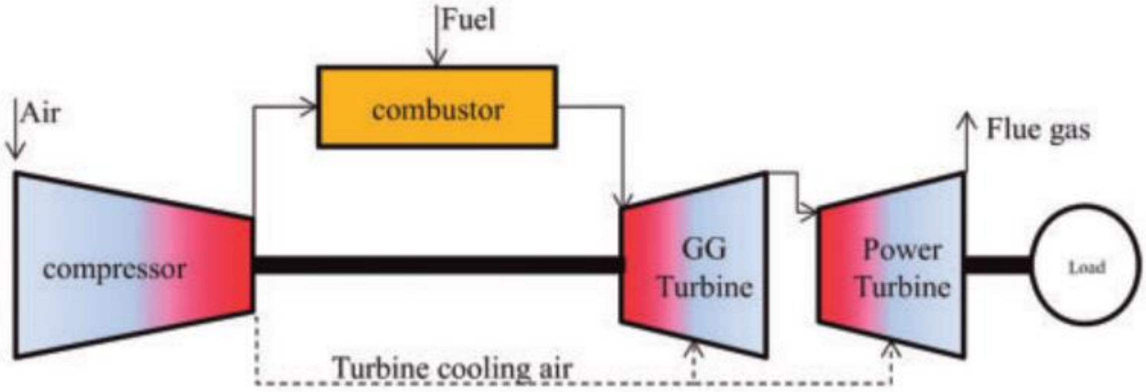

Figure 10. Twin shaft gas turbine.[7]

I.1.1.A Tri-shaft turbine

It is a turbine in which the rotors of the mechanical elements are mounted on three rotating shafts. These trees may or may not rotate between them with a speed ratio determined between these trees, they are called floating tree. This turbine is purely aeronautical

I.7.3 Mode of action of gas

Gas turbines fall into two broad categories, often combined in one machine:

I.7.3.A Action turbine

In which the relaxation is done only in the fixed blades. They are well suited to high pressure stages and are better suited for flow control. Their construction is more expensive and reserves their use for the first stages of the turbine.

I.7.3.B Jet turbine

In which the relaxation is divided between fixed and mobile blades. The degree of reaction is defined by the distribution of the relaxation between the blades. They are better suited to low pressure floors and have lower cost. When the degree of reaction of a stage is 50%, the shape of the fixed and movable blades is the same which decreases the number of molds necessary for the manufacture.

However, to achieve the same expansion, the reaction turbine will require more stages, which increases the length of the shaft line

I.7.4 Mode of work provided

Two types of gas turbine can be distinguished, depending on the nature of the work provided: power turbine and gas generator turbine.

I.7.4.A Power turbine

is a thermal machine where part of the energy of the active element is converted into mechanical energy and used to drive a load connected to it.

I.7.4.B Gas generator turbine

It is a gas turbine that produces hot exhaust gases for propulsion, but no mechanical work.

I.8 Areas of application

Gas turbines more used in the field of industry, because they are devices for the production of mechanical energy. It can also be used for training:

- Fixed Appliances:

These devices are intended for the following industrial services:

- Electrical transmission, for electrical power generation.
- Drive compressors.
- Drive the pumps.
- Specific industrial processes

- Mobile devices:

The applications of gas turbines derive directly from their specific advantages. Thus, the high mass power lends itself well to aircraft propulsion especially on helicopters. Naval propulsion is also increasingly using gas turbines, particularly for high-speed ships. There are also examples of applications for rail propulsion and military vehicles such as tanks (XM-1 Abrams or Leclerc)

On the other hand, the gas turbine is poorly adapted to road vehicles. Indeed, the variations in load and speed are too large and too fast to be achievable with a correct yield. In addition, the efficiency hardly reaches 30% for compact and low-power engines. The other major area of employment for gas turbines is power generation.

Indeed, these are constant-speed and relatively constant-load applications for which the efficiency of these machines is best. The power varies from a few hundred 60 kW to nearly 300MW. The most powerful machines are generally associated with steam turbines in combined cycles whose overall efficiency currently tends towards 60%.

In simple cycle, the yield is of the order of 30 to 35%. In low power plants, the debt is even less than 30%, but the suitability of combustion turbines for heat recovery in cogeneration applications (simultaneous production of electricity and heat) is used.

I.9 Advantages and disadvantages of gas turbines

advantages	disadvantages
High power in a limited space in which a diesel unit of the same power could not be housed. With the exception of start and stop, power is produced continuously. Easy start even in cold weather. Fuel diversity for operation. Possibility of low load operation.	Below about 3000 KW, the installation price is higher than that of a diesel generator. Launch time much longer than that of a diesel group, as an indication: 30 to 120s for a turbine, 8 to 20s for a diesel group. Less efficient than a diesel engine (single cycle). For information: 28 to 33% for a 3000 KW turbine, 32 to 38% for a diesel group.

I.10 Conclusion

In conclusion, Chapter I has provided a comprehensive overview of gas turbine technology, highlighting its historical development, core components, and operational principles. This foundational knowledge is crucial for understanding the complexities and challenges involved in optimizing gas turbine performance. The detailed examination of thermodynamic cycles and key components serves as a stepping stone for the more specialized and technical discussions presented in later chapters. With this groundwork laid, we are well-prepared to explore innovative approaches to enhancing gas turbine efficiency and integrating renewable energy solutions, as discussed in the subsequent chapters.

Chapter II: Bibliographic synthesis

II.1 Introduction

Chapter II focuses on a comprehensive review of the existing literature concerning gas turbine performance and the integration of renewable energy sources. This chapter aims to establish a theoretical foundation by examining prior research, theoretical models, and empirical studies that have explored various strategies to enhance gas turbine efficiency. It begins with an overview of the fundamental principles of gas turbine operation and progresses to more advanced topics, including the role of renewable energy in improving thermal efficiency and reducing emissions. By synthesizing the current state of knowledge, this chapter sets the stage for the subsequent development of mathematical models and simulations presented in Chapter III.

II.2 Bibliographic synthesis

Clara Peretti and al. [8], They conducted a comprehensive literature review was conducted to explore EAHE design and characteristics, as well as their potential integration with HVAC systems. A comparative analysis of various projects was undertaken to gather and synthesize design recommendations.

This paper focuses on a specific type of earth-coupled heat exchanger known as the earth-to-air heat exchanger (EAHE). Benefiting from the high thermal inertia of soil, temperature fluctuations are significantly reduced below ground compared to surface levels. At adequate depths, soil temperature remains lower than outdoor temperatures in summer and higher in winter. By drawing ambient air through buried pipes, the air undergoes cooling in summer and heating in winter before being utilized for ventilation. An EAHE system comprises a network of buried pipes through which air is conveyed by a fan. During summer, the air supplied to buildings is cooled and dehumidified, leveraging the lower soil temperature surrounding the heat exchanger. Conversely, in winter, when ambient temperatures drop below soil temperature, the process reverses, pre-heating the air. This paper delves into the primary advantages of EAHE systems.

Earth-to-air heat exchangers (EAHE) exhibit versatility in installation across various climate types, including hot desert, Mediterranean, humid subtropical, and oceanic climates. They can be tailored for both cool climates like those in Western Europe (e.g., Germany, Switzerland) and warmer regions such as India and Kuwait.

Numerous building typologies integrate ventilation systems with EAHE. For residential structures, an optimal pairing involves greenhouses and EAHE. Furthermore, when combined with other low-energy cooling techniques such as night cooling and sound thermal building design, EAHE systems have the potential to obviate the necessity for traditional air conditioning systems in many instances.

Combining simulation with data measurement interpretation represents the most effective approach for analyzing the actual performance of an earth-to-air heat exchanger (EAHE) system. However, this analysis must be contextualized within the specific characteristics of the building and its management practices.

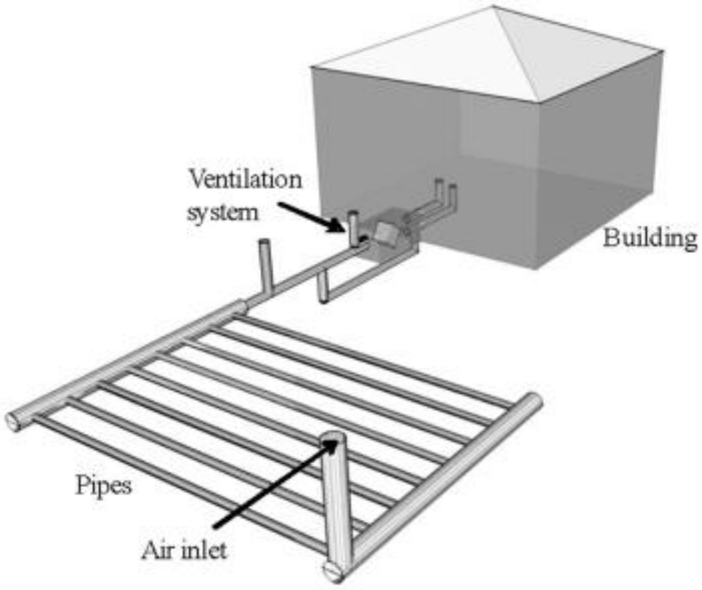

Figure 11. Example of an EAHE.[8]

Trilok Singh_Bisoniya and al. [9], in this paper aimed at reviewing the current status of geothermal and air exchange systems, synthesizing findings from scientific journals and conferences. It begins with an introduction, followed by a global overview of EAHE systems. Subsequent sections delve into experimental and analytical studies worldwide, with a specific focus on research conducted at Indian universities. Finally, the paper concludes, highlighting key insights and potential avenues for future research and application. However, the focus predominantly lies on scrutinizing EAHE systems within Indian universities, as of June 2012.

These systems leverage underground soil as a heat source and utilize air as the medium for transferring heat, particularly beneficial for space heating during winter.

This paper presents an exploration into the remarkable property of Earth: its ability to maintain a consistent temperature at a depth of approximately 1.5 to 2 meters throughout the year. Termed as Earth’s undisturbed temperature, this phenomenon sees the ground retaining warmth exceeding surface temperatures during winter and offering a refreshing coolness amidst summer's heat. Leveraging this stable reservoir of thermal energy, the Earth–Air Heat

Exchanger (EAHE) emerges as a strategic tool for passive heating and cooling within buildings. Comprising a network of metallic, plastic, or concrete pipes buried at specific depths underground, the EAHE facilitates the flow of fresh atmospheric air. In winter, this air is warmed as it passes through, contributing to the building's heating requirements, while in summer, it undergoes cooling, offering a reprieve from the sweltering heat. This paper delves into an extensive review of both experimental and analytical investigations of EAHE systems worldwide.

Categorizing sites based on geological availability is crucial for optimizing EAHE system design. Understanding soil properties, depth to bedrock, and groundwater levels informs the selection and design of the appropriate EAHE system type. Two main categories exist: 'open-loop' and 'closed-loop' systems. While open-loop systems draw outside air for ventilation, closed-loop systems recirculate air from the building through earth tubes. However, closed-loop systems have drawbacks, such as insufficient heating capacity and limitations in meeting fresh air requirements.

Despite initial popularity, EAHE systems faced obstacles like poor performance and disadvantages such as higher initial costs and decreased air quality over time. However, the imperative for renewable and sustainable energy technologies has reignited interest in EAHE systems.

In light of the significant benefits offered by EAHE systems, their design optimization, modeling, and testing are crucial endeavors. Various calculation models in the literature simulate the thermo-physical behavior of earth–air heat exchangers, enabling the development of well-designed systems. Remarkably, a properly designed EAHE has the potential to reduce electricity consumption in a typical house by up to 30%.

These systems not only reduce the heating and cooling loads of buildings but also cut down on power consumption, CFC and HCFC usage, and greenhouse gas emissions. With extensive use over the years, the United States and Europe stand as global leaders in implementing EAHE systems. Additionally, integrating EAHE systems with renewable energy sources such as solar and wind energy can further enhance their performance.

It becomes evident that the efficient utilization of EAHE systems, coupled with sustainable energy sources and advanced technology, will significantly contribute to energy conservation and environmental protection, not only in India but on a global scale. This review paper is anticipated to serve as a valuable resource for researchers and scientists engaged in the field of passive heating and cooling of buildings, particularly with the utilization of EAHE systems.

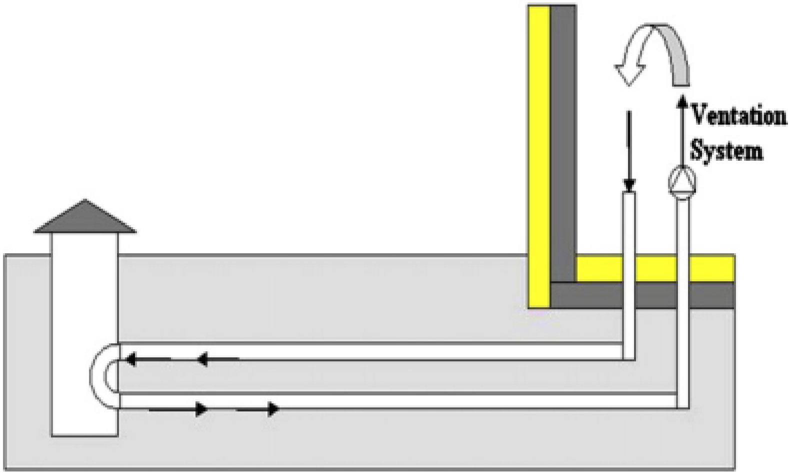

Figure 12. Earth–air heat exchanger (closed loop mode).[9]

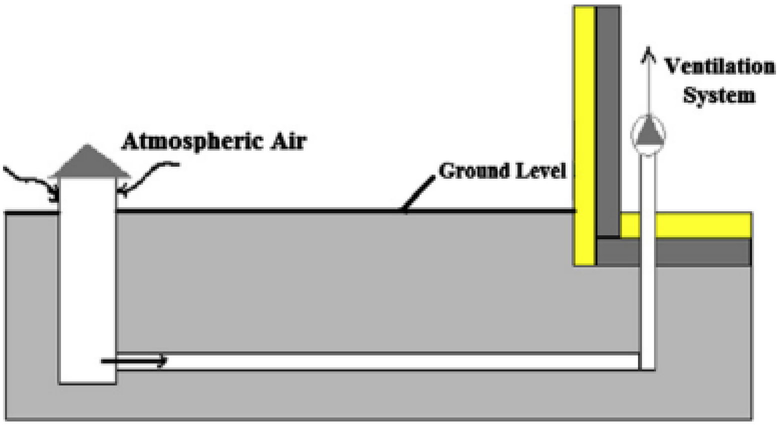

Figure 13. Earth–air heat exchanger (open loop mode).[9]

Namrata_Bordoloi and al. [10], studied in this article a comprehensive review of various combinations of EAHE systems, offering an accessible summary of previous research endeavors in this domain.

The review meticulously examines analytical and experimental studies on different configurations of EAHE systems, analyzing their thermal performance and considering environmental implications in the realm of energy conservation. Through this examination, it becomes apparent that design parameters directly or inversely influence the outlet temperature of EAHE systems. Interestingly, the choice of pipe materials does not significantly impact the outlet temperature.

Furthermore, the study underscores the substantial energy-saving potential of EAHE technology, which can surpass traditional air conditioning systems in efficiency. By leveraging EAHE systems, significant reductions in greenhouse gas emissions can be achieved, consequently contributing to environmental improvement. In essence, EAHE technology emerges as a viable solution for enhancing energy efficiency, reducing environmental impact, and fostering sustainable development.

Utilizing computational software like FLUENT, EnergyPlus, and TRANSYS aids in predicting the thermal performance of EAHE systems. Research indicates that beyond a certain depth, soil temperature remains lower in summers and higher than outside air in winters, with a recommended depth of 2.5–3 meters for maintaining constant soil temperature. Factors such as soil properties (moisture content, soil type) and design parameters (pipe diameter, material, length, air velocity) significantly influence EAHE performance, necessitating their careful consideration during system design.

This paper offers a comprehensive analysis of EAHE system advancements, providing valuable insights for future designers and researchers. EAHE systems have been implemented across diverse climatic zones worldwide, from the hot Sahara to the cold Australian regions, demonstrating their adaptability and feasibility. Integrating EAHE with ventilation and other cooling techniques optimizes indoor temperatures, reducing reliance on energy-intensive air conditioning systems. Hybrid EAHE systems, in particular, show promising energy-saving potential, outperforming conventional systems by approximately 5%.

However, despite substantial literature on EAHE systems, further investigation is warranted to elucidate the negligible temperature drop concerning pipe material variability. Future research endeavors should focus on understanding and optimizing the parameters influencing EAHE performance through careful investigation and selection. Through simulation and data interpretation, a deeper understanding of EAHE behavior can be attained, facilitating the realization of optimal temperature differentials and enhancing energy efficiency. In conclusion, EAHE emerges as a promising and efficient energy technology capable of addressing contemporary energy challenges and promoting sustainable development.

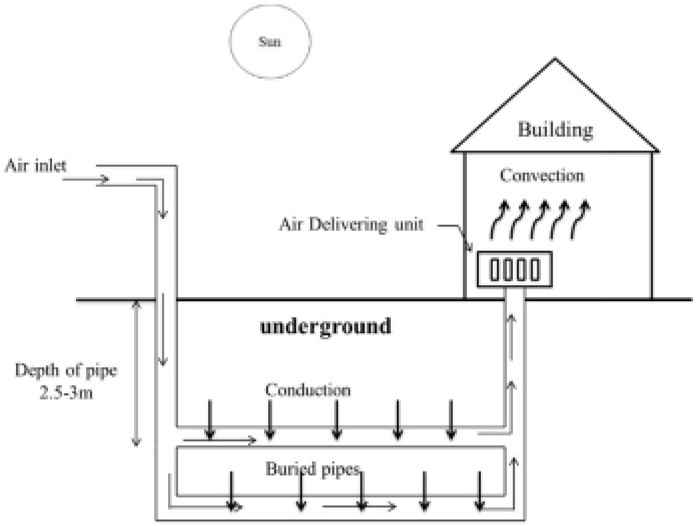

Figure 14. Working principle of EAHE.[10]

Vaz, Joaquim and al. [11], they researched on Earth-Air Heat Exchangers (EAHE) in Viamão, Brazil, explores their thermal potential. In this study, three ducts, labeled A, B, and C, are buried at varying depths in the soil, with ducts A and B positioned 1.60 meters apart and duct C at 0.50 meters depth. Casa Ventura, a building in the area, benefits from the EAHE system, which enhances its thermal conditions. Temperature data from soil, external air, and buried ducts are collected throughout 2007 to understand the transient temperature behavior and identify optimal periods for device utilization.

Results indicate that May and February offer prime conditions for heating and cooling air within Casa Ventura, respectively. Additionally, a comprehensive database detailing the transient temperatures of soil, external air, and indoor spaces is developed, providing valuable insights for future research and practical applications.

Bansal, Vikas and al [12], In this study they conducted a transient analysis of the Earth's heat exchange and air pipe (EPAHE) using FLUENT software to assess its cooling performance during the summer. The developed model is accurately validated against empirical data obtained from a setup located in Ajmer, western India. The investigation deepens the impact of pipe material and air flow speed on EPAHE performance, shedding light on the key factors that affect its effectiveness in providing cooling solutions.

The Earth–Pipe–Air Heat Exchanger (EPAHE) illustrated in Fig. 4 consists of two horizontal cylindrical pipes, each with an inner diameter of 0.15 meters and a buried length of 23.42 meters. These pipes are constructed from PVC and mild steel and are buried at a depth of 2.7 meters in flat, dry soil. Both PVC and steel pipes are connected to a common intake and outlet manifold to facilitate airflow. Globe valves are installed in each pipe assembly to regulate the flow of air.

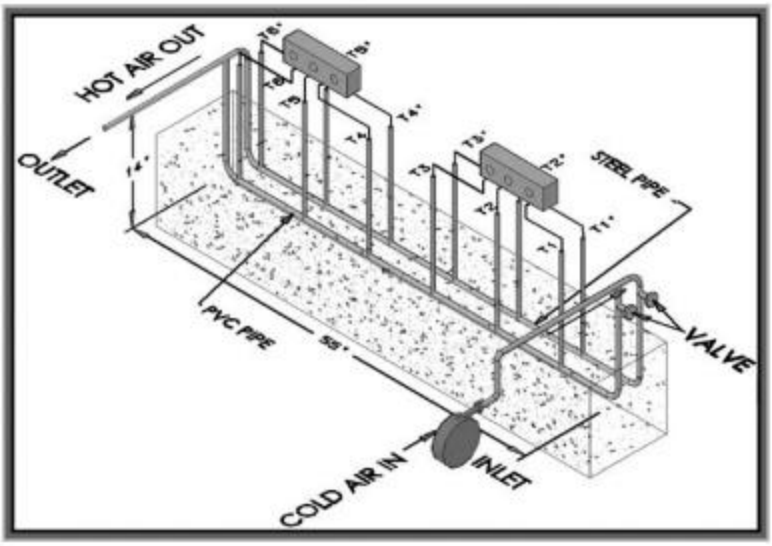

Figure 15. Experimental set-up of EPAHE.[11]

At the inlet, the open end of a single pipe is connected via a vertical pipe to a 1 HP, single-phase motorized blower operating at 2800 RPM and delivering 0.033 m^3/s of air. The blower facilitates the movement of ambient air through the earth–air–pipe system. The velocity of the air passing through the pipes can be adjusted by varying the RPM of the blower using an autotransformer with a range of 0–270 V and a maximum current of 2 A (type: 2D-1PHASE), with a precision of 1 V.

Six thermocouples, denoted as T1 to T6, are strategically inserted at fixed intervals along the length of each pipe to measure the temperature of the air. These thermocouples are of the K-type and feature temperature indicators with a precision of 0.1°C. The flow of air through each individual pipe can be controlled using valves, with only one valve being kept open at any given time to facilitate the flow of air through one pipe. Observations are recorded for various velocities and airflow rates through both pipes independently. Airflow velocities are measured using a vane probe-type anemometer, offering a range of 0.4–30.0 m/s with a precision of 0.1 m/s.

The experimental and simulation results for modeling the Earth–Pipe–Air Heat Exchanger (EPAHE) system exhibit a fair agreement, with a maximum deviation of 11.4%. It's noted that the drop in air temperature decreases with an increase in flow velocity. Based on this analysis, it can be inferred that the performance of the EPAHE system remains unaffected by the material of the buried pipe, allowing for the utilization of more economical pipe materials.

For a pipe measuring 23.42 meters in length and 0.15 meters in diameter, a temperature rise of 8.0–12.7°C is observed across flow velocities ranging from 2 to 5 m/s. The hourly cooling capacity of the system falls within the range of 1.2–3.1 MW h. Additionally,

The coefficient of Performance (COP) of the EPAHE system discussed in this study varies from 1.9 to 2.9 with an increase in velocity from 2.0 to 5.0 m/s, indicating its efficiency across varying operational conditions.

Barakat and al. [13], studied one of the passive cooling strategy for air cooling in gas turbine through the Eairth Air Heat Exchanger (EAHE) cooling system. The Earth-to-Air Heat Exchanger (EAHE) or Earth Air Tunnel (EAT) systems harness the earth's heat storage capability by utilizing the ground as a source or sink for heat exchange. This process allows for the transfer of heat to or from the ground to provide either full or partial heating and cooling for buildings. The majority of these researches concentrated on the impact of EAHE parameters on the performance, such as pipe length, inner pipe diameter, inlet air velocity, depth of the buried pipe, the physical and thermal properties of the soil, and the material of the pipe employed. Based on a physical model of the proposed system and then a mathematical model to simplify the analysis Then an economic assessment. With the help of the PC program in MATLAB, the mathematical model was solved. The results obtained from this study can be summarized as follows:

The outlet air temperature is reduced when longer and deeper earth tubes with smaller diameters and lower inlet air velocity are used.

The case study results indicate that the EAHE system can increase output power production and thermal efficiency by 9% and 4.8%, respectively.

By adding the EAHE, the annual net electricity power production rises to 12991 MW with a pay pack period of 1.2 years.

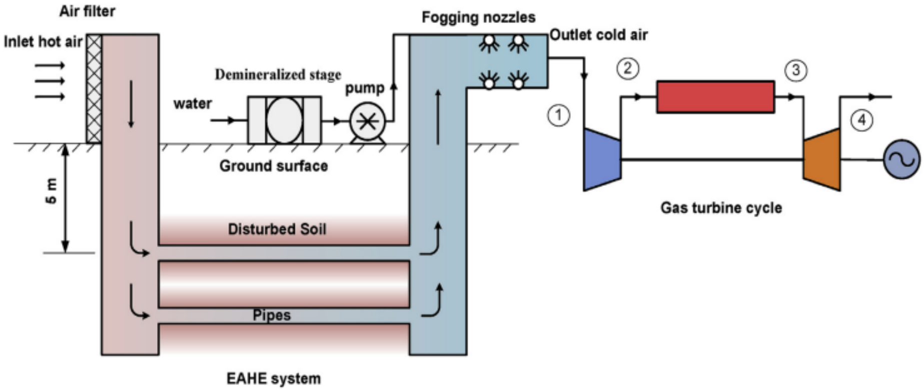

Figure 16. Schematic diagram of EAHE system installed in gas turbine power plant.[13]

Alhazmy, M. M.and al. [14], In this study they investigated the efficacy of enhancing gas turbine power plant performance through air cooling at the plant intake. It compares two distinct air cooling methods: water spraying systems and cooling coils. The evaluation encompasses plant efficiency, net power output, and the potential for reusing condensed water from exhaust gases after appropriate recycling. Various design and operational parameters are scrutinized, including ambient temperature, relative humidity, turbine inlet temperature, and pressure ratio. The findings indicate that spray coolers can augment power and improve efficiency more affordably than cooling coils, particularly in hot and arid climates. Although condensing water from exhaust gases may partially supplement water needs in dry climates, cooling coils afford precise control over compressor inlet conditions at the expense of significant power consumption, leading to a notable decline in overall plant performance.

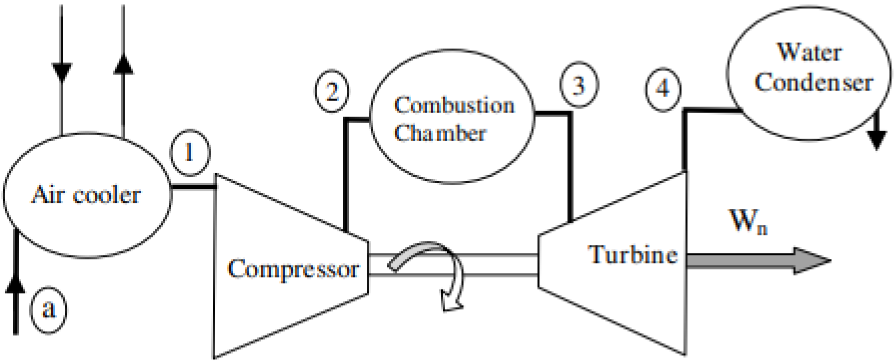

Figure 17. Schematic of the gas turbine cycle.

Q.M. Jaber a and al. [15], they looked at the impact of air cooling intake on gas turbine performance, focusing on a comparison between different cooling systems: evaporative and cooling coil. A computer simulation model is developed to assess the performance of the gas turbine unit at Marka Power Station in Amman, Jordan. Performance characteristics are analyzed across various operational parameters, such as ambient temperature, relative humidity, turbine inlet temperature, and pressure ratio. The results demonstrate that the evaporative cooling system effectively enhances power output and efficiency of the gas turbine unit at a lower cost compared to the cooling coil system, which demands high power consumption for the operation of the vapor-compression refrigeration unit. Despite this, the evaporative system affords complete control over inlet temperature conditions regardless of relative humidity levels.

The study assesses the effects of two methods of air cooling: fumigation systems and coil cooling. Each air temperature and humidity cooling system changes differently, with varying cooling capacities imposing limits on the minimum achievable temperature at the compressor entrance. The aim of this paper is not to delve into other issues related to off-design operation, compressor or turbine design, and cooling systems. Instead, it aims to provide guidance on proposed cooling systems for comparative assessment with underlying condition conditions, without cooling the air in the entrance, thus providing insights into general differences in performance.

Results indicate that the evaporative cooling system can increase generated power by approximately 5% and enhance the efficiency of the gas turbine unit, all at a lower cost compared to cooling coils. However, supplying the necessary water for such coolers may pose challenges in certain regions, including Jordan.

Cooling coils offer complete control over compressor inlet conditions regardless of ambient factors, albeit at a significant operational power requirement. During hot and dry conditions, the net power output from the gas turbine unit can increase by approximately 1.0-1.5 MW when utilizing a cooling system compared to base-case conditions under similar operating conditions. Coil cooling also boosts power plant efficiency by about 1% or more depending on operating conditions and the selected chiller system, although the power extracted for refrigeration must be factored in. This extraction of power from the gas turbine output diminishes overall plant performance, particularly evident in high-temperature scenarios due to increased cooling loads. Increasing the coefficient of performance (COP) can lead to augmented power and net power output from the plant. Alternatively, absorption cooling systems are anticipated to yield more power, as the energy required to operate the absorption cycle is sourced freely from the turbine's exhaust, albeit at a higher initial capital cost.

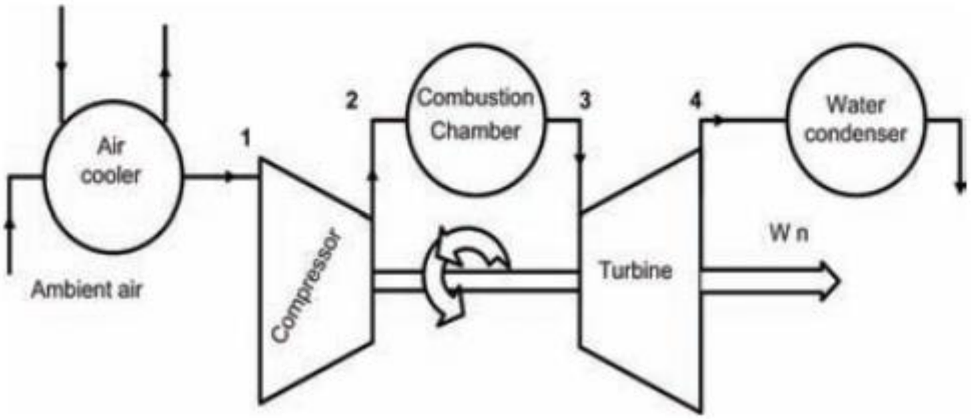

Figure 18. Simple sketch of gas turbine cycle with air cooler.

Cyrus B. Meher-Homji and al. [16], they provided a brief review of refrigeration techniques, with particular emphasis on the direct water fog of the gas turbine inlet air. Provides a comprehensive overview of the latest current fog systems and their applications on gas turbines. By examining these techniques, the paper enables readers to assess the benefits derived from the implementation of this technology in gas turbine operations.

Alaa A. El-Shazly and al. [17], They researched the recent study, the thermodynamic performance of a natural gas-operated gas turbine was simulated. The performance was evaluated for three scenarios: the base case without any turbine inlet cooling (TIC) systems, with an evaporative cooler, and with an absorption chiller. Various performance metrics were compared, including output power, thermal efficiency, heat rate, specific fuel consumption, consumed fuel mass flow rate, and economics.

Results indicated that at an ambient air temperature of 37°C, after accounting for all associated auxiliary power consumption, the absorption chiller with a regenerator achieved a remarkable augmentation of 25.47% in power and 33.66% in efficiency. This led to an average power price saving of about 13%. In contrast, the evaporative cooler provided a more modest increase of 5.56% in power and 1.55% in efficiency, resulting in a saving of 3% in average power price.

These findings underscore the effectiveness of absorption chillers, particularly with a regenerator, in significantly enhancing both power output and efficiency of gas turbines in high ambient temperature conditions.

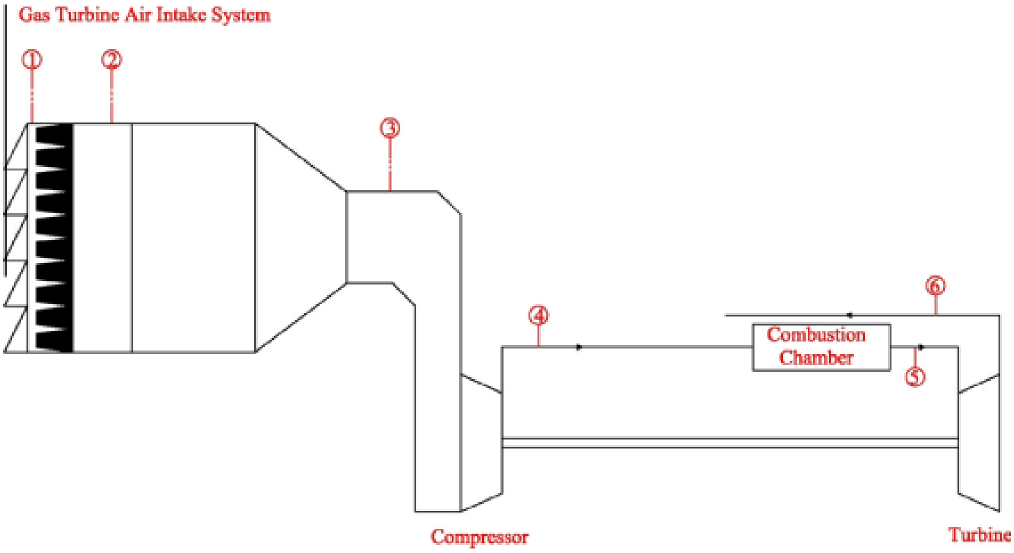

Figure 19. Schematic of simple gas turbine cycle.

Thamir K. Ibrahim and al. [18], they summarized a thermodynamic analysis of the composite cycle gas turbines, exploring the different configurations of the gas turbines and their effects. The study examines the effects of ambient temperature and pressure ratio on the selection of the optimal composition of the gas turbine and its subsequent impact on the performance of the combined cycle gas turbine (CCGT). Using MATLAB software, performance analysis codes were used to simulate different gas turbine configurations. Results indicate that the composition of simple gas turbines shows a higher energy output, while the composition of renewable gas turbines shows greater efficiency, especially with regard to changes in ambient temperatures. Moreover, the composition of simple gas turbines shows an increase in power production with higher pressure ratios, while regenerative composition shows higher efficiency at lower pressure ratios. Thus, total variability in power output is considered insignificant at low pressure ratios. Comprehensive modeling of the study confirms the significant impact of ambient temperatures and pressure ratios on CCGT performance. It indicates that the integration of regenerative cycles into export cycles can lead to higher overall efficiency in joint cycles.

Advancements have continuously improved gas turbine power plant performance, primarily by increasing turbine inlet temperature.

The present analysis focuses on the impact of ambient temperature, compression ratio, and gas turbine configuration on achieving not only high-efficiency CCGT power plants but also enhancing operational flexibility.

The study examines various cycles within combined cycle gas turbine power plants, including simple gas turbines, two-shaft gas turbines, intercooler gas turbines, and regenerative gas turbines. Modeling results indicate that ambient temperature and compression ratio significantly impact the performance of these power plants across different gas turbine configurations. The key findings are:

1. Ambient temperature and compression ratios have a substantial influence on the overall thermal efficiency of combined cycle gas turbine power plants across different gas turbine configurations.

2. Combined cycle gas turbines with regenerative gas turbine configurations exhibit higher overall thermal efficiency, reaching about 64.5%, particularly with low compression ratios.

3. As ambient temperature increases, the overall thermal efficiency of combined cycle gas turbines decreases, while total power output increases linearly for most gas turbine configurations except for regenerative gas turbines, where total power output decreases.

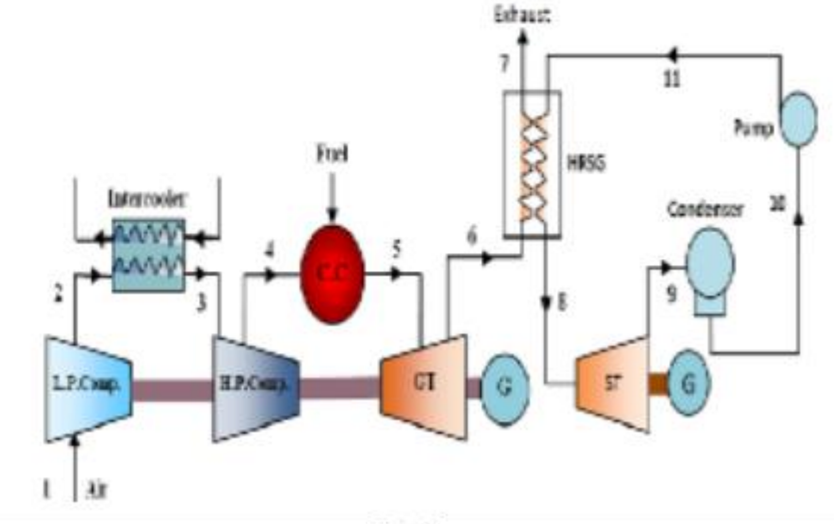

Figure 20. The schematic diagram: Intercooler combined cycle gas turbine powerplant.[18]

Sahil Popli and al. [19], It studies the use of gas turbine exhaust gas waste-heat powered single-effect water-lithium bromide (H2O eLiBr) absorption chillers for cooling gas turbine compressor inlet air in energy-intensive industrial facilities like oil refineries and natural gas processing plants (NGPPs) in hot climates. In comparison to conventional methods like evaporative coolers and mechanical vapor-compression chillers, the proposed scheme demonstrates superior performance in extreme ambient conditions, such as those in the Persian Gulf during summer. The results indicate that three steam-fired, single-effect H2O eLiBr absorption chillers utilizing gas turbine exhaust heat could provide significantly more cooling capacity compared to evaporative coolers or mechanical vapor-compression chillers, while also generating additional electricity. The economic analysis suggests a short payback period for implementing the waste heat recovery scheme, making it an attractive option for enhancing electrical power generation in NGPPs in the Middle East. Additionally, this approach could reduce plant natural gas consumption for power generation, leading to cost savings and emissions reduction.

In this context, this study focuses on assessing the feasibility of using heat-sucking cooling to cool the inlet air of the gas turbine compressor in NG factories, especially in hot climates such as the Arabian Gulf. Before going into this waste heat use strategy, the air cooling techniques found in the gas turbine compressor entrance are reviewed.

The study evaluated the thermodynamic and economic feasibility of utilizing waste heat-powered absorption refrigeration for cooling gas turbine compressor inlet air in natural gas processing plants (NGPPs) operating in hot and humid climates like the Persian Gulf.

The study suggests that waste heat-powered absorption refrigeration could find broader applications in oil and gas plants, including propane chillers in NGPPs, light end recovery in oil refineries, sea water desalination, and more. Future research avenues could explore gas turbine part load operation, exergy analysis, environmental impact assessment, and the design of ARS condenser water-cooling systems tailored for hot climates like the Middle East.

Popov and al. [20], summarized in this paper the concept of a joint solar-assisted cycle plant, which aims at hybridizing gas turbine composite cycle stations with solar energy systems. Two options have been proposed with the help of solar energy: one includes a mechanical electric chiller from a dedicated photovoltaic plant, and the other uses a steam-fueled absorption chiller generated in a solar field with Linear Fresnel reflectors. Software packages are used to estimate the efficiency and additional costs of these configurations, and to compare them to traditional integrated solar cycle factories. The results show that the composition with the absorption chiller has specific additional capital costs for the factory and requires less land area. This concept offers a promising approach to integrating Frennel inverter linear technology integrated into power generation.

The hybrid plant offers three advantages: higher solar energy conversion efficiency compared to Rankine cycle plants, cost-effectiveness of the larger steam turbine, and avoidance of thermal inefficiencies associated with daily start-up and shutdown of the steam turbine.

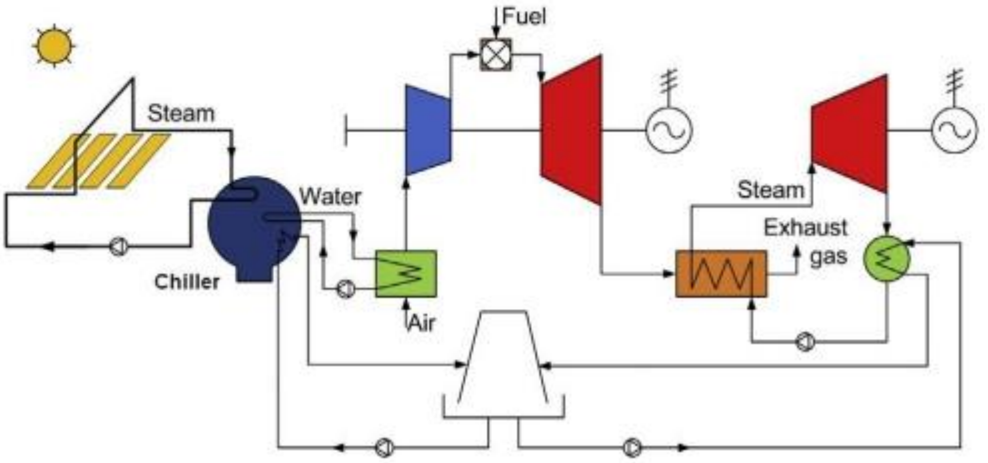

Figure 21. graphical abstract of solar thermal energy into gas turbine combined cycle plant.[20]

Shihong Cen and al. [21], Shihong Sen and AL [14], explore in this study how combining biomass and solar energies can ease their individual constraints, enhancing the provision of clean energy. The focus is on a new hybrid system where solar energy is harnessed to produce hydrogen, addressing its inherent volatility. Thermoelectric panels generate electricity used in an electrical analyzer of proton exchange membrane to produce hydrogen. The resulting hydrogen complements a biomass gas turbine plant, enhancing its efficiency in the post-launch phase. Through thermal economic analysis, system performance, and improvement are assessed based on the level cost of electricity. Comparison with the traditional biomass-powered composite cycle, which lacks hydrogen after shooting, reveals significant benefits. Hydrogen integration after fire reduces CO2 emissions by 22 .7% and increases power generation capacity by 24 .1% under optimal conditions. However, due to the additional costs of solar panels and electric analyzer, the cost of standard electricity of the proposed system exceeds the cost of the conventional system.

This study proposes an innovative solar mass and hybrid biomass system where hydrogen is used as a shared food in post-launch combustion to increase energy capacity and reduce CO2 emissions in a biomass-powered composite cycle. Hydrogen production is facilitated by solar energy by photovoltaic thermal panels (PVT) in an integrated configuration. A feasibility analysis of the proposed system is conducted through thermal economic investigations, taking into account the level cost of electricity (LCOE) as an economic indicator. Improvement is made to determine optimal operating conditions based on reducing input parameters.

G. Comodi and al. [22] , In this paper they demonstrate the development of a test seat specially designed to implement direct steam expansion technology on 100 kWMGT. By cooling the air temperature at the entrance to 15 ° C under specific operating conditions, the test seat aims to assess the impact on MGT performance, especially during hot summer days.

The results indicate notable improvements in electrical power production and efficiency in MGT. With the low air temperature in the entrance, MGT shows an increase in electrical power production of up to 8% compared to nominal power production under ISO conditions, accompanied by a 1.5% increase in electrical efficiency. Furthermore, the study notes an almost linear correlation between the increase in electrical power production and efficiency and the drop in entrance air temperature when the refrigerant operates within nominal working parameters. In general, these results emphasize the potential of inlet air cooling techniques to enhance the performance of MGTs, especially in difficult surroundings.

The paper underscores the potential of Microturbines (MGTs) in distributed generation, especially for cogeneration in various sectors, thanks to their power output range and favorable attributes such as high power density and low operational costs. However, MGTs face challenges in hot climates due to their sensitivity to ambient conditions, which hinder their full utilization.

While Gas Turbines (GTs) have been extensively studied regarding atmospheric condition impacts, research on MGT performance under varying conditions is limited. The paper discusses previous studies on MGT performance and introduces a test bench designed to assess MGT cogeneration performance.

Various Inlet Air Cooling (IAC) techniques have been explored to mitigate ambient temperature effects on GT performance. These include wetted media evaporative cooling, high-pressure fogging, absorption chiller cooling, and refrigerative vapor compression cooling. The paper focuses on direct expansion mechanical vapor compression technology to address MGT sensitivity to ambient conditions.

The paper concludes with a summary of the MGT, experimental setup, IAC system design, test campaign results, and remarks on the advantages of direct expansion vapor compression for MGTs.

Turbocharged air inlet cooling is a commercial way to enhance the efficiency of gas turbines, applicable to almost all installations. Mahmood_Farzaneh-Gord and al [23], compare in this paper two common and one new methods of air cooling at Khangiran refinery in Iran. Common methods include evaporation media and mechanical coolers. The new method replaces throttle valves with turbocharged extenders to take advantage of the cooling and power potential of the refinery's natural gas pressure landing plant. The study, aimed at improving the refinery's gas turbine performance, concluded that turbine extensions were the most economically feasible option and recommended their implementation.

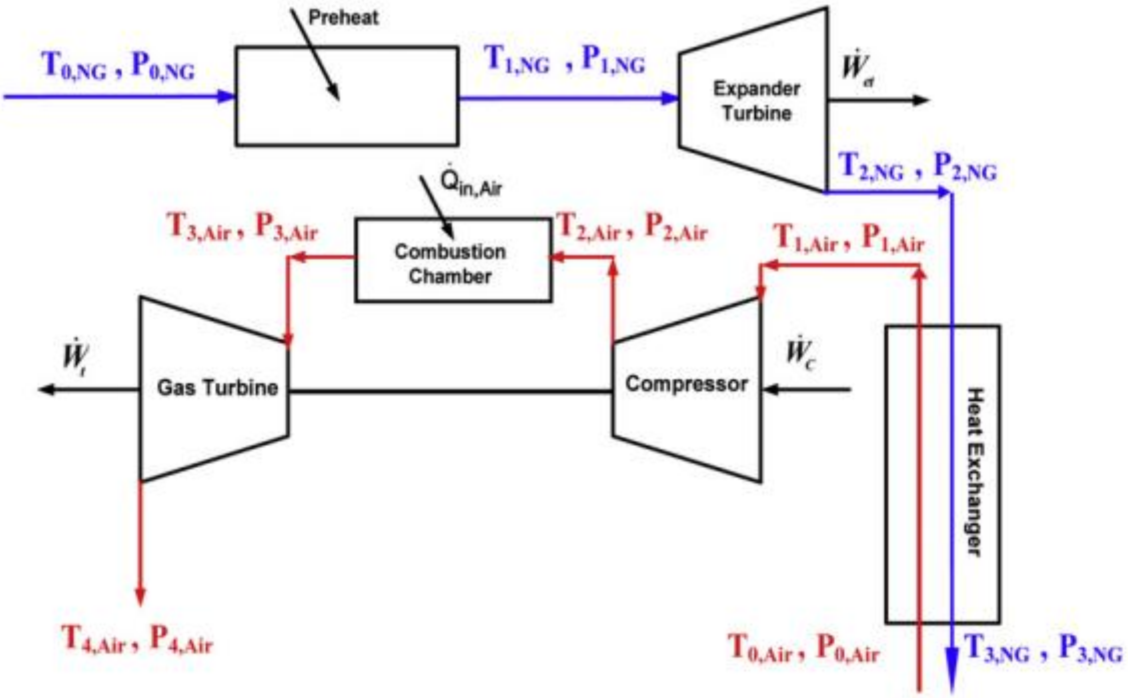

Figure 22. A schematic diagram of the proposed system (from Farzaneh-Gord et al.).[23]

In Saudi Arabia, the peak demand for electricity during the midday summer is almost double that of off-peak. However, combustion turbines, which generate about 42% of Saudi Electricity Company's (SEC) annual power, are experiencing a 24% drop in high temperatures up to 50 ° C. Enhancing energy contributions from existing stations through air cooling introduced can greatly help meet the additional peak demand of 35 GW projected for 2023. Ibrahim and al. [24], they conducted a comprehensive review of various air cooling options in the combustion turbine entrance (CTIAC) of SEC, to determine its main benefits and disadvantages in relation to Saudi Arabia's environmental conditions and energy requirements.

Najjar and al. [25], in this new work, they combined the use of wasted heat and air cooling inlet to boost the production of gas turbine energy. The system features a successive Rankin Organic Upper Propane Cycle (ORC) with a lower propane cycle. The study aims to demonstrate the advantages of this joint gas turbine system and includes an economic assessment to compare its benefits to other systems.

The use of wasted heat from gas turbine exhaust enhances energy and efficiency by reducing air temperature in the entrance. The system combines the upper organic rankin cycle of propane (ORC) with the lower propane gas cooling cycle. The upper cycle generates energy to partially power the lower cycle, which includes an extender that operates its compression and cools the air of the turbine entrance.

Key variables include ambient temperature, turbine exhaust temperature, pressure ratios and intense saturation pressure. In extreme conditions (45 ° C and 80% moisture), the system increased net energy and overall efficiency by 35% and 50% respectively, due to a drop in ambient temperature by 15 ° C.

This system is very possible in both relatively hot and cold conditions, acting as a common generation and cooling system suitable for different climates. Economically, it has a recovery period ranging from 1.5 to 2 years, outperforming other cooling systems, including absorption.

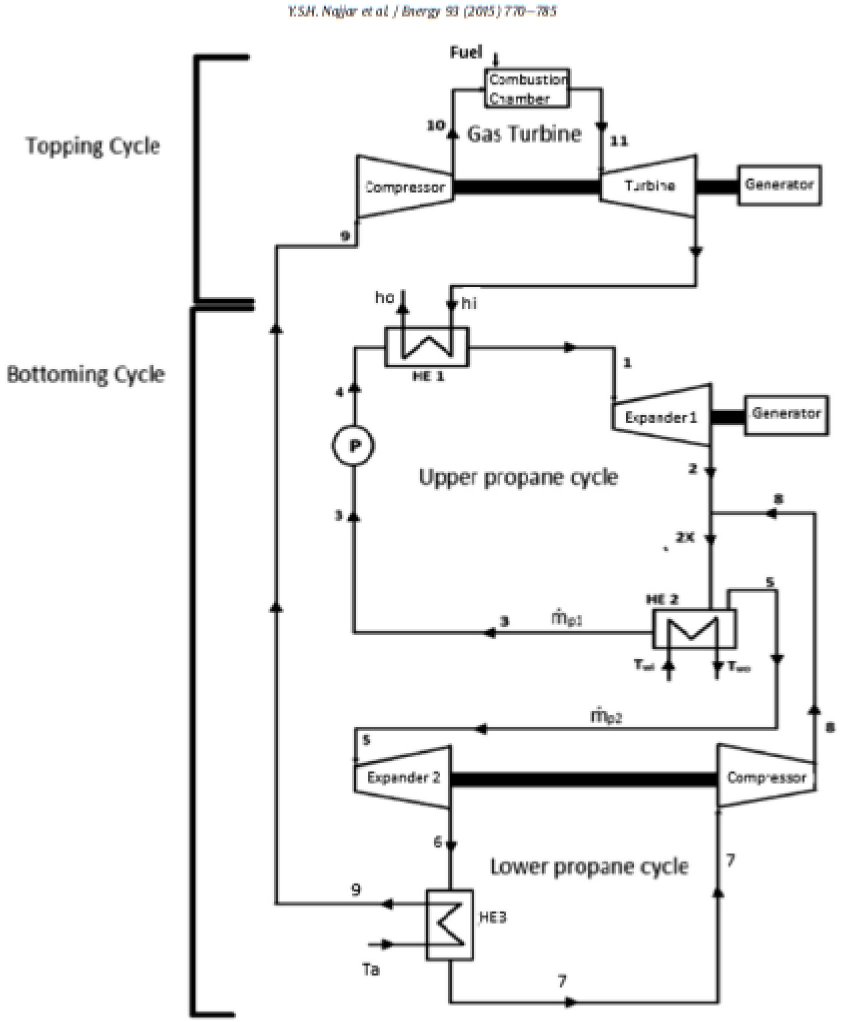

Figure 23. Schematic of Gas turbine Cascaded System.

Integrated Gasification Combined Cycles (IGCC) are energy systems consisting of a gasifier, a combined cycle power plant, and an Air Separation Unit (ASU) for oxygen supply. Morini and al. [26], inthis paper evaluated a power augmentation system for IGCC using gas turbine inlet air cooling via liquid nitrogen spray, a byproduct of the ASU. Unlike water evaporative cooling and refrigeration, this method avoids limitations related to air saturation and pressure drops in heat exchan.

A thermodynamic model was created using a commercial energy conversion simulation code, followed by a sensitivity analysis on key parameters. The model was then applied to real temperature profiles from various sites over a year, comparing the effectiveness of this system with traditional inlet air cooling methods.

Zhang and al. [27], in this study proposed a cold production process for inlet air cooling using cryogenic energy from liquefied natural gas (LNG). The process enhances the off-design performance of a gas turbine combined cycle under varying ambient conditions. The proposed method increases cold output by 38.1% to 42.5% compared to conventional LNG evaporation. For inlet air cooling, it boosts relative power by 2.2% to 14.4% and efficiency by 0.7% to 2.2%, depending on relative humidity, over cold production without air cooling. Additionally, compared to traditional air cooling, it increases relative power by 0.6% to 3.1% and efficiency by 0.3% to 0.5%.

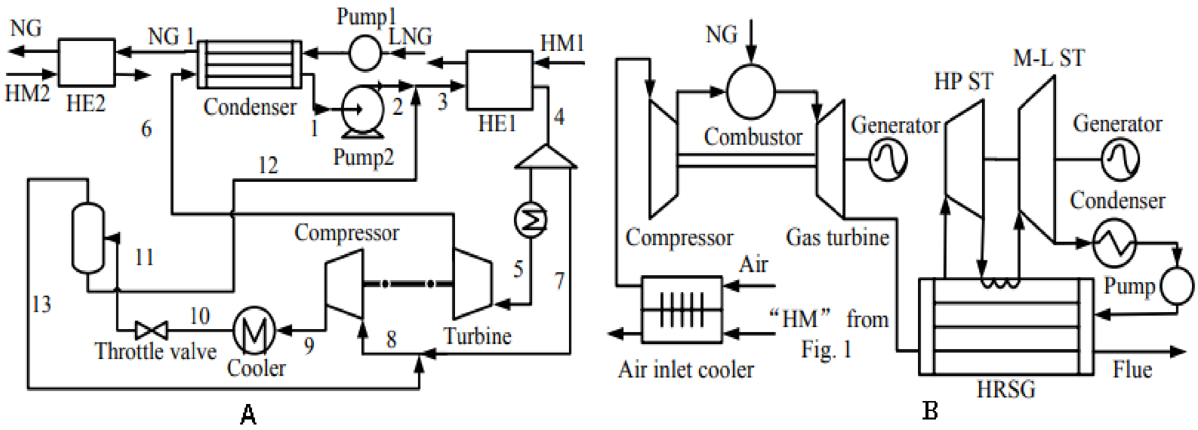

Figure 24. A: flow sheet diagram of the proposed cold, B : A simplified flow sheet diagram of the combined cycle for inlet air cooling.[27]

II.3 Conclusion

The bibliographic synthesis presented in Chapter II underscores the significant advancements and ongoing research efforts aimed at enhancing gas turbine performance through renewable energy integration. The reviewed literature highlights various innovative approaches, such as the incorporation of Earth-to-Air Heat Exchangers, which have shown promise in improving thermal efficiency and reducing environmental impact. This chapter has provided a detailed understanding of the theoretical underpinnings and practical applications of these technologies, thereby forming a robust basis for the modeling and simulation work that follows. The insights gained from this review are crucial for informing the development of more effective and sustainable gas turbine systems

Chapter III:

Mathematical modelling and results

III.1 Introduction

In this chapter, we delve into the mathematical modeling and simulation techniques essential for optimizing gas turbine performance. This section begins by presenting two critical models: the Earth-to-Air Heat Exchanger (EAHE) model and the Gas Turbine model. These models are integral to understanding the thermal dynamics and efficiency improvements possible through the integration of renewable energy sources. Following the model descriptions, we explore the numerical methods employed to solve these models and validate them with empirical data. The results and discussions section highlights the performance outcomes of both the EAHE and gas turbine systems, offering insights into their operational efficiencies and potential areas for enhancement.

III.2 Mathematical models

The following assumptions have been considered To simplify the analysis calculation ([13], [28]):

- Thermo-physical properties of air and soil are constant.
- Air is incompressible and has constant thermal properties.
- Convective heat transfer coefficient along the buried pipe is constant.
- Ground surface temperature equals ambient air temperature.
- Inlet air temperature is fixed at 40°C.
- Air in the tube is well mixed with uniform temperature and flow along the length of the buried pipes.

III.2.1 Earth-to-air heat exchanger model

Schematic diagram of the proposed hybrid cooling system in a gas turbine in figure 25:

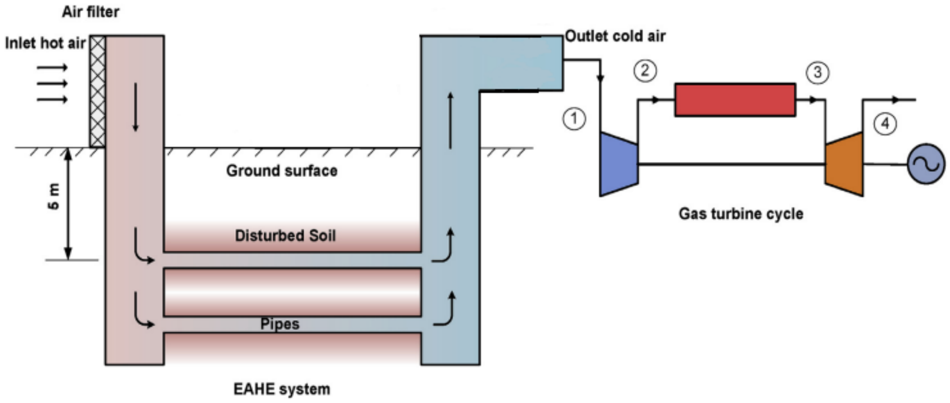

Figure 25. Schematic diagram of EAHE system installed in gas turbine power plant.

The energy balance between two tube sections distant from Δx (Figure 23) are written as follows:

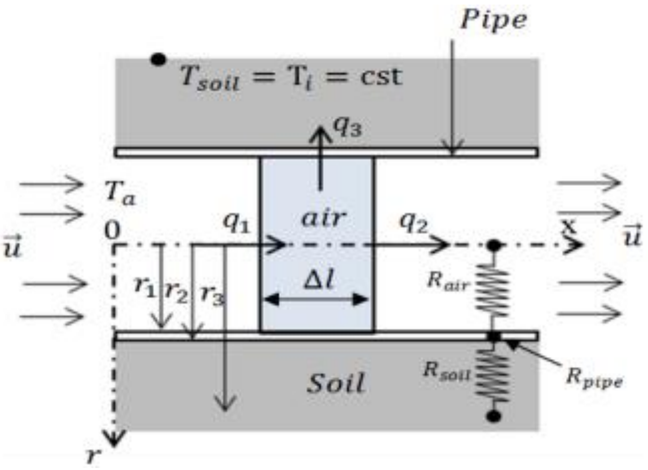

Figure 26. One-dimensional scheme of the EAHE.

$$\mathrm{m}c_{\mathrm{pair}}\,\frac{DT_a}{Dt} = q_1 - q_2 - q_3 \tag{1}$$

Equation 1 shows the energy balances for cooling where:

$$\mathrm{q}_3 = \frac{\mathrm{T}_{\mathrm{air}} - \mathrm{T}_{\mathrm{soil}}}{\mathrm{R}_{\mathrm{total}}} \tag{2}$$

Therefore, from Equation 2, the energy balance 1 is written as follows:

$$\mathrm{m}\ c_{\mathrm{pair}}\left(\frac{\partial T_a}{\partial t} + u\frac{\partial T_a}{\partial x}\right) = -\lambda.s.\frac{\partial T_a}{\partial x}\bigg|_x + \lambda.s.\frac{\partial T_a}{\partial x}\bigg|_{x+\Delta x} + \frac{(T_{\mathrm{soil}} - T_a)}{R_{\mathrm{totale}}} \tag{3}$$

Where u being the average air flow rate inside the EAHE.

The total thermal resistance (R_{total}) is composed of the soil conduction resistance (R_{soil}) and the tube conduction resistance (R_{tube}), and the convective air resistance (R_{air}).

$$R_{\mathrm{total}} = R_{\mathrm{soil}} + R_{\mathrm{tube}} + R_{air} \tag{4}$$

Where the tube resistance is written as follows

$$R_{\mathrm{tube}} = \frac{1}{\lambda_{\mathrm{tube}}\cdot 2\pi\cdot\Delta x}\,ln\left(\frac{r_2}{r_1}\right) \tag{5}$$

Soil resistance is given by the relation (46):

$$R_{\mathrm{soil}} = \frac{1}{\lambda_{\mathrm{soil}}\cdot 2\pi\cdot\Delta x}\,ln\left(\frac{r_3}{r_2}\right) \tag{6}$$

On the other hand that of the air is written in the form below

$$R_{\mathrm{air}} = \frac{1}{h_{cv}\cdot 2\pi\cdot r\cdot \Delta x} \tag{7}$$

By dividing equation 43 per unit of the differential element Δx, we obtain

$$\rho.\mathrm{s}\ c_{\mathrm{pair}} \cdot \left(\frac{\partial T_a}{\partial t} + u\frac{\partial T_a}{\partial x}\right) = \frac{-\lambda.s.\frac{\partial T_a}{\partial x}\Big|_{x} + \lambda.s.\frac{\partial T_a}{\partial x}\Big|_{x+\Delta x}}{\Delta x} + \frac{(T_{\mathrm{soil}} - T_a)}{R_{\mathrm{itotal}}} \tag{8}$$

Note by s, the internal section of the tube, s = π. r_1^2 et h = (Nu k)/2 r_1 [13],

the mean coefficient of heat transfer by convection.

Where the number of Nusselt, Nu = 0.023 $\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3}$ [13, 29, 30] and the number Reynolds, Re=ρv/μ [29].

Either: R_{itotal} the total thermal resistance per unit length.

$$\rho.s.c_{\mathrm{pair}} \cdot \left(\frac{\partial T_a}{\partial t} + u\frac{\partial T_a}{\partial x}\right) = \lambda.s \cdot \frac{\partial^2 T_a}{\partial x^2} + \frac{(T_{\mathrm{soil}} - T_a)}{R_{\mathrm{itotal}}} \tag{9}$$

If Δx tends towards 0 and taking into account that the transfer is permanent and convection dominates the conduction, equation (9) is reduced to:

$$\rho.\pi \cdot r_1^2 \cdot c_{\mathrm{pair}} \cdot u\frac{dT_a}{dx} = \frac{(T_{\mathrm{soil}} - T_a)}{R_{\mathrm{itotal}}} \tag{10}$$

We introduce integration into equation (10)

$$\int \frac{dT_a}{(T_{\mathrm{soil}} - T_a)} = \int \frac{1}{\rho.\pi\cdot r_1^2\cdot c_{\mathrm{pair}}\cdot u\cdot R_{\mathrm{itotal}}}dx \tag{11}$$

The relation (11) is written as follows.

$$ln(T_a - T_{\mathrm{soil}}) = -\left(\frac{1}{\rho\cdot\pi\cdot r_1^2\cdot c_{\mathrm{pair}}\cdot u\cdot R_{\mathrm{itotale}}}\right)x + C \tag{12}$$

Where T_i is the temperature at the inlet of the EAHE.

Therefore, the temperature profile is written as follows:

$$T_a(x) = T_{\mathrm{sol}} + exp\left[-\frac{1}{\rho\cdot\pi\cdot r_1^2\cdot c_{\mathrm{pair}}\cdot u\cdot R_{\mathrm{itotale}}}x\right]\cdot c_1 \tag{13}$$

With Ta(z=0)=T_{in} and from it $C_1 = T_{\mathrm{in}} - T_{\mathrm{soil}}$

Finally, it can obtain the temperature of the air along the EAHE as follows:

$$T_a(x) = T_{\text{sol}} + (T_i - T_{\text{sol}}) \cdot exp\left[-\frac{1}{\rho\cdot\pi\cdot r_1^2\cdot c_{\text{pair}}\cdot u\cdot R_{\text{itotale}}}x\right] \quad (14)$$

III.2.2 Gas turbine model

Basically, gas turbine power plants consist of four components, including the compressor, combustion chamber (CC), turbine, and generator, as given in the following.

A simplified analytical model for gas turbine cycles will be considered, based on the following assumptions [31].

- The air and combustion products are treated as ideal gases.
- The system assumes that the fuel supplied is natural gas.
- The temperature at the turbine inlet remains constant.

The outlet temperature T2 can be calculated by calculating the air entering the compressor at T1.

$$T_2 = T_1\left\{1+\left[\frac{1}{\eta_c}\left(r_c^{\frac{\gamma_a-1}{\gamma_a}}-1\right)\right]\right\} \quad (15)$$

where $\eta_c$is the isentropic efficiency of the compressor and rc is the compression ratio.

The power consumption of an adiabatic compressor can be estimated as follows:

$$W_c = \dot{m}_a Cp_{a,avg} T_1\left\{\left[\frac{1}{\eta_c}\left(r_c^{\frac{\eta_a-1}{\gamma_a}}-1\right)\right]\right\} \quad (16)$$

where $\dot{m}_a$ is the inlet air mass flow rate, $\text{Cp}_{a,avg}$ is the specific heat of dry air at average temperature across the compressor [14].

By knowing the temperature of combustion gas at turbine inlet T3, the heat delivered by the combustor can be estimated from the energy balance as follows [13]:

$$\dot{Q}_{\text{in}} = \dot{m}_a Cp_{\text{gavg}}(T_3 - T_2) \quad (17)$$

where Cp_{gavg} is the specific heat of flue gases at average temperature across the combustor [14].

The definition of mass flow rate for fuel used is [13]:

$$\dot{m}_f = \frac{\dot{Q}_{\mathrm{in}} / LHV}{\eta_{\mathrm{comb}}} \qquad (18)$$

where η_{comb} is the combustion efficiency.

The temperature of the flue gases that exit the turbine T4 can be measured [13].

$$T_4 = T_3 \left\{ 1 - \left[\eta_t \left(1 - r_e^{\frac{1-\gamma_g}{\gamma_g}} \right) \right] \right\} \qquad (19)$$

Turbine power is evaluated as [13]:

$$W_t = \left(\dot{m}_a + \dot{m}_f \right) Cp_{g.avg} T_3 \left\{ \eta_t \left(1 - r_e^{\frac{1-\gamma_g}{g}} \right) \right\} \qquad (20)$$

Hence, the net power output is [13]:

$$W_{net} = W_t - W_c \qquad (21)$$

The thermal efficiency is evaluated as [13]:

$$\eta_{th} = \frac{W_{net}}{\dot{Q}_{in}} \qquad (22)$$

The specific fuel consumption is given as [13]:

$$SFC = \frac{3600 \dot{m}_f}{W_{net}} \qquad (23)$$

III.3 Numerical solution

The mathematical model was solved using MATLAB personal computer software. Numerical calculations were conducted regarding the ambient air temperature and the thermal and physical properties of the soil in the state of Biskra on days of (04–07 August 2013)[28]. The initial distribution of soil temperature was calculated initially, and the initial temperature of the buried pipe was assumed to be equal to the soil temperature at the initial time (t = 0). After disturbing the soil thickness, the soil temperature remains constant at its initial temperature, referred to as the undisturbed soil. For the air, the initial temperature is fixed at 47.29°C.

III.4 Model validation

The table (1) details theoretical and experimental results measured along a pipe's length, highlighting the corresponding errors. Analysis shows a decrease in both theoretical and experimental results with length, with errors increasing from 0% to about 7.35% at longer lengths. Theoretical accuracy diminishes with length due to potential unaccounted factors or measurement limitations. Discrepancies may arise from measurement errors, environmental factors, or material property changes. Improvements include refining the model, conducting controlled experiments, and taking repeated measurements. The data indicates the need for model improvements or accounting for additional variables over longer distances.

Table 1. Results of model validation against both the experimental and theoretical data.

Pipe length (m)	Theoretical Results	Experimental Results	Error%
0	47,29	47,29	0
3,63	42,5851	44,52	4,34
7,69	38,5433	39,82	3,20
11,73	35,4996	36,28	2,15
16,04	33,062	34,82	5,04
20,07	31,352	33,41	6,15
24,12	30,0505	31,95	5,94
26,37	29,4696	31,53	6,53
29,07	28,8815	31,06	7,01
33,1	28,1838	30,42	7,35
37,01	27,6687	29,64	6,65
38,86	27,4693	29,37	6,47
40,82	27,2839	29,14	6,36
45,1	26,9565	28,49	5,38
48,8	26,7415	28,34	5,64

III.5 The results and discussion

III.5.1 Earth-to-air heat exchanger performance

The four graphs(figures 24, 25, 26, 27) provided show the outlet air temperature (T_a) of an Earth-to-Air Heat Exchanger (EAHE) as a function of the length of the EAHE for different parameters. Let's analyze each graph:

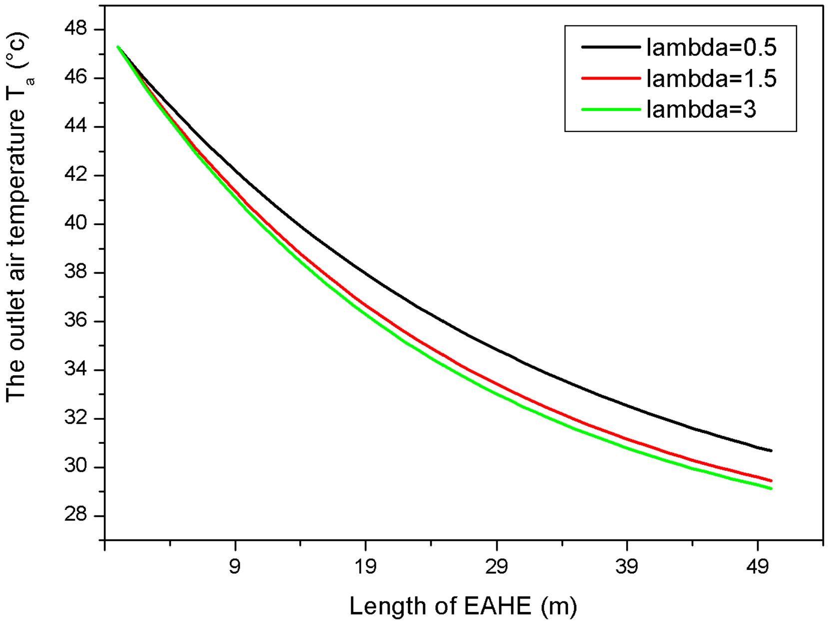

Figure 27. Variation the outlet air temperature (T_a) with the thermal conductivity ratio.

Figure 24 displays the outlet air temperature (Ta) against the length of the EAHE for different values of the thermal conductivity ratio (lambda). The black line (λ = 0.5) shows the outlet air temperature starting at the highest point compared to the other values of lambda and dropping at a slower rate as the length of the EAHE increases. The red line (λ = 1.5) starts at a lower temperature than the black line and decreases at a faster rate. The green line (λ= 3) begins with the lowest temperature and decreases the fastest, showing a rapid initial decline that tapers off more gradually. Analysis indicates that higher values of lambda lead to a greater reduction

in outlet air temperature as the EAHE length increases, suggesting that materials with higher thermal conductivity are more effective in reducing outlet air temperature over the same length.

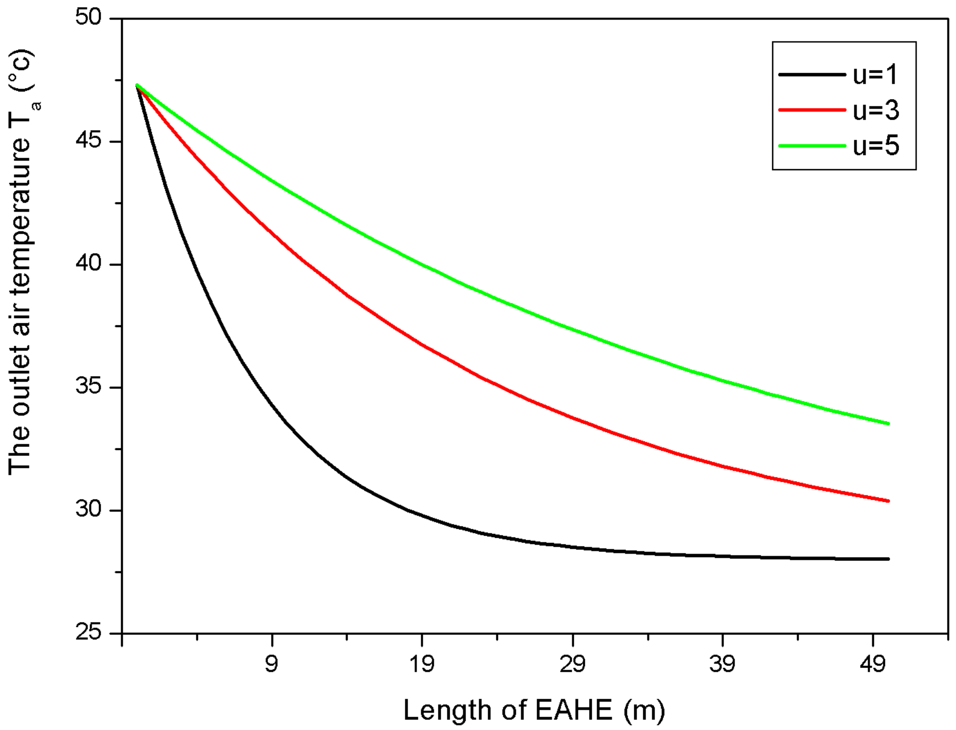

Figure 28. Variation the outlet air temperature (Ta) with Air Velocity (u).

Figure 25 shows the outlet air temperature (Ta) against the length of the EAHE for different values of air velocity (u). The black line (u = 1) starts at a lower temperature and decreases significantly as the length increases. The red line (u = 3) starts at a higher initial temperature compared to the black line and decreases at a moderate rate. The green line (u = 5) begins with the highest temperature and decreases the least rapidly. Analysis indicates that lower air velocities result in a greater reduction in outlet air temperature along the length of the EAHE, as higher air velocities reduce the time air spends in the EAHE, leading to less cooling

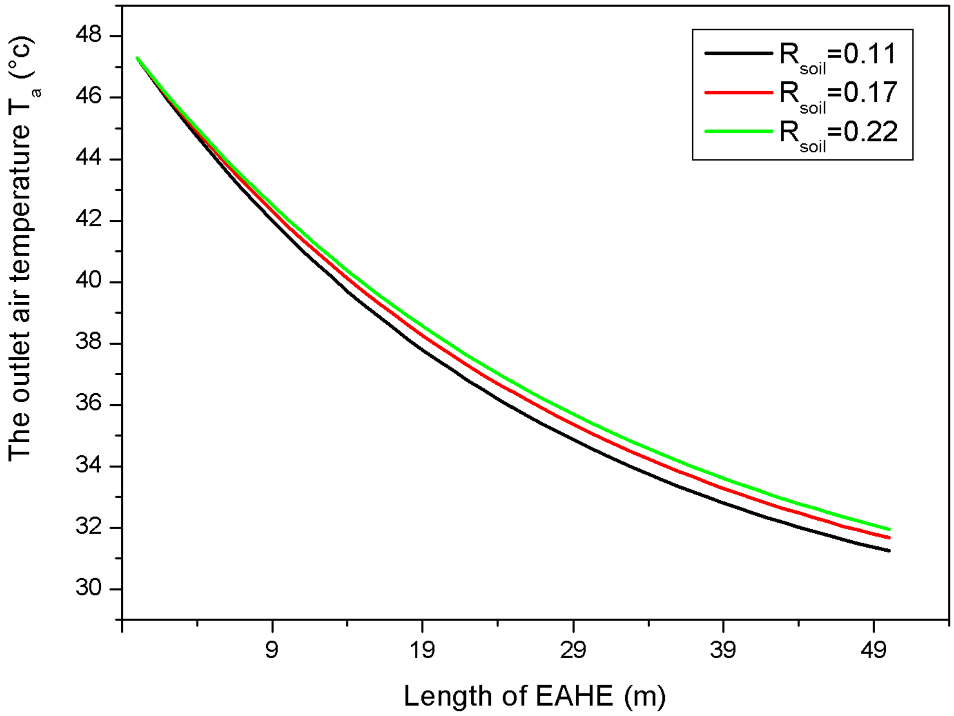

Figure 29. Variation the outlet air temperature (T_a) with Soil Thermal Resistance (Rsoil).

Figure 26 depicts the outlet air temperature (Ta) against the length of the EAHE for different values of soil thermal resistance (Rsoil). The black line (Rsoil = 0.11) starts at a high temperature and decreases steadily with increasing length. The red line (Rsoil = 0.17) starts at a lower temperature compared to the black line and decreases more rapidly. The green line (Rsoil = 0.22) begins with the lowest temperature and shows the fastest initial decrease, although the difference with other lines diminishes as length increases. Analysis indicates that higher soil thermal resistance results in a greater reduction in outlet air temperature over the same length, suggesting that soil with higher thermal resistance enhances the cooling effect of the EAHE.

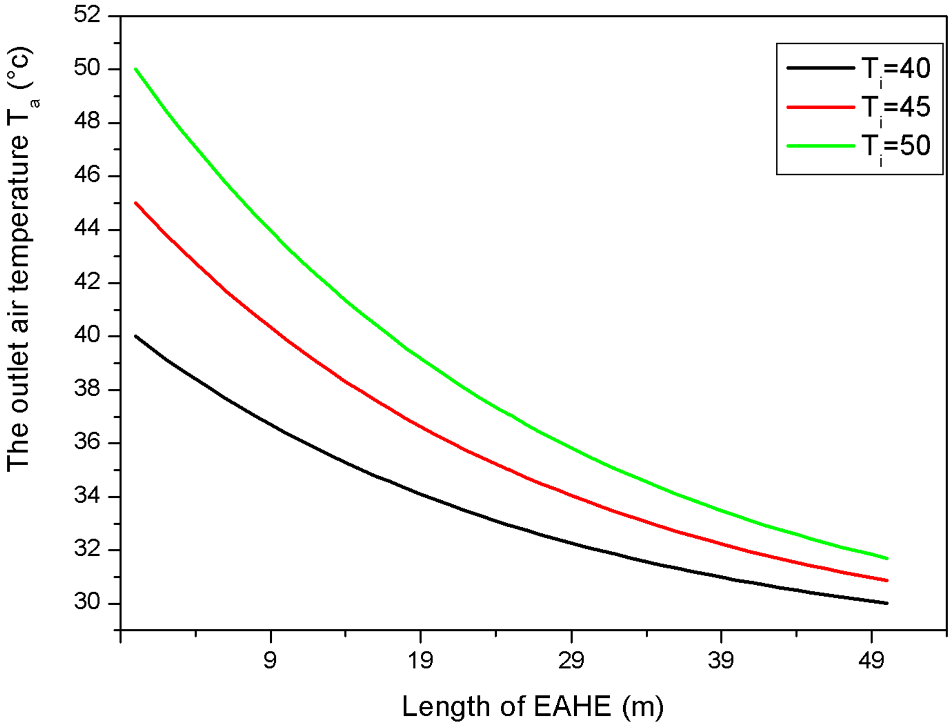

Figure 30. Variation the outlet air temperature (T_a) with Inlet Air Temperature (T_a).

Figure 27 illustrates the relationship between outlet air temperature and the length of an Earth Air Heat Exchanger (EAHE), a system utilizing earth's thermal energy through buried pipes to regulate air temperature. Three curves depict variations in inlet air temperature (Ti): black (Ti=40°C), red (Ti=45°C), and green (Ti=50°C). Across all curves, as EAHE length increases, outlet air temperature decreases, indicating enhanced heat exchange with the earth for more effective cooling. Higher inlet temperatures correspond to higher outlet temperatures; notably, Ti=50°C yields the highest outlet temperatures, while Ti=40°C results in the lowest. Temperature reduction is most rapid initially with shorter EAHE lengths, leveling off as length increases, suggesting diminishing returns in cooling efficiency. This highlights the EAHE's greater thermal efficiency at shorter lengths, with longer lengths offering limited additional cooling benefits. Design considerations should factor in the choice of inlet temperature to meet specific cooling requirements effectively.

Summary:

Higher thermal conductivity (λ) and lower soil thermal resistance (Rsoil) result in more substantial reductions in outlet air temperature as the length of an Earth Air Heat Exchanger (EAHE) increases. Similarly, lower air velocities (u) contribute to greater decreases in outlet air temperature along the EAHE length. Understanding these relationships is crucial for optimizing EAHE design and performance, aiming to achieve efficient cooling. It's recommended to design EAHE systems to a length where the temperature reduction meets application requirements effectively, considering the diminishing returns observed with longer lengths. By carefully selecting materials, controlling air velocities, and assessing soil properties, designers can enhance the cooling efficiency of EAHE systems while ensuring sustainable utilization of earth's thermal energy resources.

III.5.2 Gas turbine performance

we choose a gas turbine monoshaft to do that study and the table below shows the technical specification of the selected gas turbine

Table 2. Technical specification of the selected gas turbine.

Item	Adopted values
Gas turbine output, MW	124.269
Air inlet temperature (ISO), °C	15
Relative humidity ,%	60
Ambient pressure, bar	1.009
Average air mass flow rate, kg/s	446.7431
Fuel gas mass flow rate, kg/s	6.640592
Inlet temperature to turbine, °C	1150
Exhaust gases temperature, °C	552.1111
Gas lower heating value, kJ/kg	48,741
Compression ratio	12.046
Combustion chamber pressure loss, bar	1.5
Isentropic efficiency of compressor, %	85
Isentropic efficient of turbine, %	88
Combustion efficiency, %	99
Natural Gas lower heating value, kJ/kg	47,040
Efficiency, %	37.2

The table 3 shows the analysis compares gas turbine efficiency with and without cooling over a period of 6 to 20 hours. Initially, efficiencies are close, starting at 0.33998 without cooling and 0.34354 with cooling at 6 hours. Without cooling, efficiency slightly declines to 0.3361 at 15 hours before recovering to 0.33705 at 20 hours, whereas with cooling, efficiency remains consistently higher, around 0.34333 from 12 to 19 hours, rising to 0.3435 at 20 hours. The gain efficiency, starting at 1.03626943 at 6 hours, increases notably to 2.105845688 by 15 hours, stabilizing thereafter. Cooling significantly enhances efficiency over time, indicating its importance during extended operations or higher loads. This improvement underscores the strategic advantage of cooling systems in maintaining higher efficiency levels and suggests potential savings in fuel consumption and operational costs.

Table 3. Variation of thermal efficiency with time.

Times (hours)	Gas turbine efficiency		gain efficiency
	without cooling	with cooling	
6	0,33998	0,34354	1,03626943
7	0,33961	0,3435	1,132459971
8	0,33936	0,3435	1,205240175
9	0,33874	0,34346	1,374250277
10	0,33804	0,34346	1,57805858
11	0,33788	0,34354	1,647551959
12	0,33664	0,34333	1,948562607
13	0,33655	0,34333	1,974776454
14	0,33622	0,34333	2,070893892
15	0,3361	0,34333	2,105845688
16	0,33614	0,34333	2,094195089
17	0,33651	0,34333	1,986427053
18	0,33651	0,34333	1,986427053
19	0,33655	0,34333	1,974776454
20	0,33705	0,3435	1,877729258

Table 4. Variation of output power with and without EAHE

Ambient temperature	Gas turbine output power	
	without EAHE	with EAHE
50	457.94	459,52
47,5	459.43	460,85
45	460.92	462,17
42,5	462.41	463,5
40	463.90	466,82
35	466.88	467,48
30	469.87	470,13
25	472.85	472.78

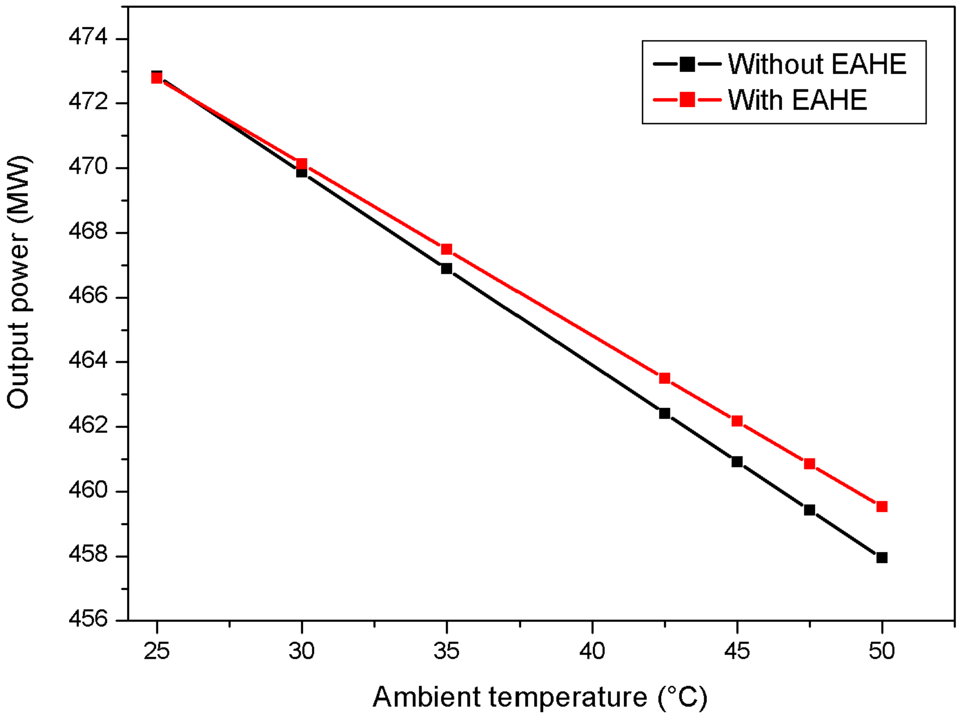

Figure 31. Variation of gas turbine output power with temperature.

The figure 28 titled "Variation of gas turbine output power with temperature" shows the output power (MW) of a gas turbine as a function of ambient temperature (°C), with two data series: without EAHE (black squares) and with EAHE (red circles). Both curves indicate a decrease in output power as ambient temperature increases, a common characteristic of gas turbines. However, the output power is consistently higher with the Earth-Air Heat Exchanger (EAHE) at all temperatures, with the difference becoming more pronounced at higher temperatures. This suggests that the EAHE, by pre-cooling the intake air and increasing its density, significantly enhances turbine performance, especially in hotter conditions. The use of an EAHE leads to improved efficiency and potentially lower fuel consumption, making it particularly beneficial in hot climates or during summer months.

III.6 Conclusion

The mathematical modeling and simulation of the Earth-to-Air Heat Exchanger and gas turbine systems have provided substantial insights into the performance improvements achievable through renewable energy integration. The validated models demonstrate that incorporating EAHE can significantly enhance the thermal efficiency of gas turbines, leading to higher output power and reduced environmental impact. These findings underscore the importance of precise modeling and validation in advancing gas turbine technology and highlight the potential for future research and development in this field.

General conclusion

This study has successfully explored the enhancement of gas turbine performance using renewable energy sources, particularly through the integration of Earth-to-Air Heat Exchangers. The comprehensive analysis and modeling efforts have revealed significant potential for improving the thermal efficiency and output power of gas turbines, thereby contributing to more sustainable and efficient energy production. The findings emphasize the critical role of renewable energy in modernizing traditional energy systems and highlight avenues for future research to further optimize gas turbine performance. This work stands as a testament to the promising intersection of renewable energy technologies and conventional gas turbine systems, paving the way for more innovative and eco-friendly solutions in the energy sector.

The steady is structured into three main chapters, the first chapter provides an overview of gas turbine fundamentals, including their historical development, components, and operational principles. The second chapter offers a bibliographic synthesis summarizing existing research and theoretical models related to gas turbine efficiency. The third chapter presents the mathematical modeling and numerical simulation of both the EAHE and gas turbine systems, followed by model validation and performance analysis. The results indicate that EAHE integration can significantly improve gas turbine efficiency, suggesting a viable pathway for incorporating renewable energy into traditional gas turbine technology.

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Abstract

This master's thesis explores enhancing gas turbine performance by integrating renewable energy through Earth-to-Air Heat Exchangers (EAHE), emphasizing the role of renewable energy in advancing conventional energy systems and establishing a basis for future research. The study introduces two critical models: the EAHE model, which uses the energy balance principle, and the gas turbine model, which determines output power and efficiency. These models are essential for understanding thermal dynamics and potential efficiency improvements from renewable energy integration. Results indicate that incorporating EAHE boosts efficiency and cuts fuel consumption, especially in hot climates or during summer, with key findings showing that higher thermal conductivity (λ) and soil thermal resistance (R_soil) significantly lower outlet air temperature, and lower air velocities (u) are more effective in reducing outlet air temperature.

الملخص

تستعرض هذه الأطروحة تحسين أداء التوربينات الغازية من خلال دمج الطاقة المتجددة باستخدام المبادلات الحرارية أرض هواء (EAHE)، مما يبرز دور الطاقة المتجددة في تحسين أنظمة الطاقة التقليدية ويبني أساس للبحث المستقبلي. تقدم الدراسة نموذجين حيويين: نموذج EAHE الذي يستخدم مبدأ توازن الطاقة، ونموذج التوربين الغازي الذي يحدد الطاقة الناتجة والكفاءة. هذه النماذج ضرورية لفهم الديناميكيات الحرارية والتحسينات الممكنة في الكفاءة من خلال دمج الطاقة المتجددة. تُظهر النتائج أن دمج EAHE يحسن الكفاءة ويقلل من استهلاك الوقود، خاصة في المناخات الحارة أو خلال أشهر الصيف، مع النتائج الرئيسية نشير إلى أن الموصلية الحرارية العالية (λ) ومقاومة الأرض الحرارية (R_soil) تقللان بشكل كبير من درجة حرارة الهواء الخارج، وأن سرعات الهواء المنخفضة (u) تكون أكثر فعالية في خفض درجة حرارة الهواء الخارج.