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## MASTER'S THESIS

**Domain: Sciences and Technologies**

**Specialty: Hydrocarbons**

**Option: Gas Engineering**

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## THEME

**Enhancement of Gas Turbine Efficiency by Intake Air Cooling**

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## **Dedication**

My gratitude to my late father and my dearest mother are beyond measure – all through my life, they have always sacrificed to ensure that I had the best opportunities possible and they have constantly believed in me and encouraged me to dream big and to pursue those dreams. I cannot put into words what their support has meant to me over the years and I dedicate this thesis to them.

My family has always been a great source of support, encouragement, and guidance in all aspects of my life. My sisters, wife, and kids are always looking for ways to brighten my day, remind me of the great times we've spent together, and plan future family objectives. Family has always been and will always be the most important thing in my life. Only because of them and their inspirations I was able to keep going during the tough times.

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## List of symbols and abbreviations

Variable	Designation	Unit
<b>A</b>	Section	[m <sup>2</sup> ]
<b>C<sub>p</sub></b>	Specific heat at constant pressure	[kJ/(kg.K)]
<b>D</b>	Mass flow rate of water in the cooler	[kg/s]
<b>fr</b>	Air-fuel ratio	[-]
<b>H</b>	Enthalpy	[kJ/kg]
<b>HR%</b>	Relative humidity	[-]
<b>m</b>	Mass flow rate of air	[kg/s]
<b>P</b>	Pressure	[bar]
<b>P</b>	Power	[kW]
<b>PCI</b>	Lower calorific value	[kJ/kg]
<b>Q</b>	Heat quantity	[kJ]
<b>Q<sub>v</sub></b>	Volumetric flow rate	[m <sup>3</sup> /s]
<b>T</b>	Absolute temperature	[K]
<b>V</b>	Velocity	[m/s]
<b>R<sub>p</sub></b>	Pressure ratio	[-]
<b>W</b>	Specific work	[kJ/kg]
<b>Z</b>	Altitude	[m]

### Greek Variables

Variable	Designation	Unit
<b>η</b>	Efficiency	[%]
<b>τ</b>	Compression ratio	[-]
<b>γ</b>	Isentropic exponent	[-]
<b>δ</b>	Thickness	[m]

### Subscripts

Indices	Designation
<b>1, 2, 3, 4</b>	Positions of the cycle presented by different elements of the gas turbine.
<b>a</b>	Air
<b>Adm</b>	Admission
<b>Amb</b>	Ambient
<b>C</b>	Compressor
<b>CC</b>	Combustion chamber
<b>Comb</b>	Combustion
<b>Echap</b>	Exhaust
<b>ISO</b>	Standard conditions
<b>Opt</b>	Optimal
<b>Ref</b>	Backflow
<b>SC</b>	Heat exchange surface
<b>T</b>	Turbine
<b>U</b>	Useful
<b>éva</b>	Evaporator

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### **General Introduction:**

Gas turbines are thermal machines that convert thermal energy into mechanical energy (based on thermodynamic transformations), have experienced significant development in recent years in many industrial applications, particularly in the hydrocarbon and thermal power plant sectors.

In Algeria, the oil / gas industry primarily uses gas turbines to generate electricity in isolated areas of the country, as well as for the transportation of gaseous (natural gas) and liquid (condensate) hydrocarbons through pipelines.

In Hassi R'mel region, a natural gas production zone in Algeria, there are over 80 gas turbines distributed across different units, including gas processing modules, gas reinjection stations , and boosting units.

Despite their advantages, gas turbines are highly sensitive to the influence of ambient air temperature, which varies significantly between day and night, summer and winter, resulting in a decrease in their thermal operating efficiency.

Gas turbines are generally designed based on specific ambient conditions (ISO standards), including an ambient temperature of 15°C, relative humidity of 60%, and an altitude of 0 meters. However, during operation, these conditions are not always met due to variable weather conditions from day to day and region to region (dry, humid, arid, hot climates). As a result, the performance of the same gas turbine is not constant and varies throughout the year.

The gas turbine cycle is a very flexible cycle, allowing for the improvement of performance parameters by adding additional components to the simple cycle.

This work is focused on studying the effect of several parameters, such as ambient temperature, atmospheric pressure, climate humidity, and performance of gas turbine installations.

Various methods (regeneration, intercooling, preheating injection of water steam and combustion air cooling) have been used to improve gas turbine performance. The advantage of all these methods is to increase specific power compared to a dry gas turbine cycle. The addition of water steam to the gas turbine cycle also helps reduce exhaust emissions.

Several techniques have been developed to condition gas turbine installations on-site. Among these techniques are water evaporation cooling (mist injection or runoff) and cooling using a refrigeration system (compression or absorption). The objective of this project is to study the improvement of performance parameters of this machine by using combustion air cooling systems. This involves an evaporative cooler system with water runoff installed downstream of the intake filter to evaporate a quantity of water into the air, extracting the latent heat necessary for the evaporation of the air itself.

## General Introduction

This work is divided into four chapters:

- The first chapter provides an overview of gas turbine.
- The second chapter focuses primarily on explaining the different technologies used to cool the combustion air of gas turbines.
- The 3rd chapter focuses on studying and modeling of the water runoff cooler.

Our study will be concluded by a general conclusion

.

# Chapter I

## Gas turbine overview

**I-1 Historical Note on the Development of Gas Turbines**

The practical applications of gas turbines first occurred from 1939 to 1941. In 1939, the Swiss company Brown Boveri used a gas turbine to generate electricity. Also in 1939, the first flight of an aircraft powered by a gas turbine developed by Hans vonOhain took place in Germany. Another aircraft gas turbine was developed by Frank Whittle, who powered an aircraft in 1941 in England. From these applications, the gas turbine has been developed to the point where it is now the most important power plant for aircraft in service [1]. Advances in materials technology and in-depth research on combustion have resulted in rapid improvements in performance in terms of specific power and efficiency by increasing the maximum temperature in the thermodynamic cycle. The following table shows the progress history of the MS5002 gas turbine since 1970 (the model on which our study was conducted) [2].

Table I-1 Development History of the MS5002 Gas Turbine

Ship Dates	Output hp (kW)		Heat Rate** Btu/hp-hr (kJ/kWh)		Firing Temp F/C		Air Flow 10 <sup>3</sup> lbs/hr (10 <sup>3</sup> kg/hr)		Exhaust Temp (F/C)	
	RC	SC	RC	SC	RC	SC	RC	SC	RC*	SC
MS5002A 1970-Present	25,200/ 18,792	26,250/ 19,575	7,390/ 10,455	9,780/ 13,837	1,705/ 929	1,690/ 921	773/ 351	773/ 351	967/638/ 531/337	975/ 524
MS5002B 1970-1975	31,050/ 23,154	32,550/ 24,273	7,480/ 10,583	9,240/ 13,073	1,710/ 932	1,700/ 927	923/ 419	923/ 419	940/660/ 504/349	932/ 500
MS5002B 1975-1978	32,000/ 23,862	33,550/ 24,981	7,180/ 10,158	8,910/ 12,606	1,710/ 932	1,700/ 927	899/ 408	925/ 420	942/679/ 505/359	930/ 499
MS5002B 1978-Present	32,000/ 23,862	35,000/ 26,100	7,070/ 10,003	8,830/ 12,493	1,710/ 932	1,700/ 927	899/ 408	966/ 438	936/667/ 502/353	915/ 491
MS5002C Present	35,600/ 26,547	38,000/ 28,337	6,990/ 9,889	8,700/ 12,309	1,770/ 966	1,770/ 966	957/ 434	982/ 445	970/693/ 521/367	961/ 516
MS5002D July 1997	-	43,000/ 32,066	-	8,650/ 12,235	-	1,807/ 986	-	1,113/ 504	-	950/ 510

Includes 0/0 inches H<sub>2</sub>O Inlet/Exhaust Pressure Drops Base Load Operation on Natural Gas Fuel

\* First Number Is Turbine Exhaust; Second Is Regenerator Stack

\*\* Heat Rates Are Lower Heating Value. To Convert to % Thermal Efficiency, Divide 2547 Btu/hp-hr by Heat Rate (Btu/hp-hr) and Multiply 100

RC = Regenerative Cycle SC = Simple Cycle

GT18463G

MS5002 Performance History - ISO Rating

**I-2. Description of Gas Turbine Components:**

In the simplest case, a gas turbine consists of an air intake filter, a compressor, a combustion chamber, an expansion turbine, and the exhaust system to the atmosphere, as shown in Figure (I.1).

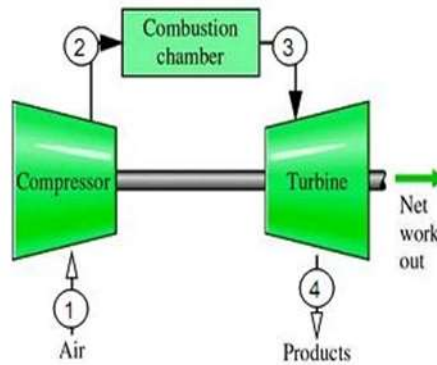


Fig. I.1: Components of a Simple Gas Turbine

**I-2.1 Air Intake System:**

It includes a filtration system that generates a pressure drop modeled by a pressure drop coefficient, which can be adjusted to a pressure drop of 0.6% at full power. In the case where the gas turbine has a cooling system upstream of the compressor, the temperature should not drop below 5 to 7°C to avoid icing problems. Cooling is done through water evaporation systems or through a refrigeration system, either compression or absorption. The first and last of these systems induce an additional pressure drop of about 0.25%. The first two are effective in hot and dry air conditions and use the enthalpy of water vaporization to cool the air by increasing its humidity to 90% and 95% respectively. (LAISSAOUI Mohamed)

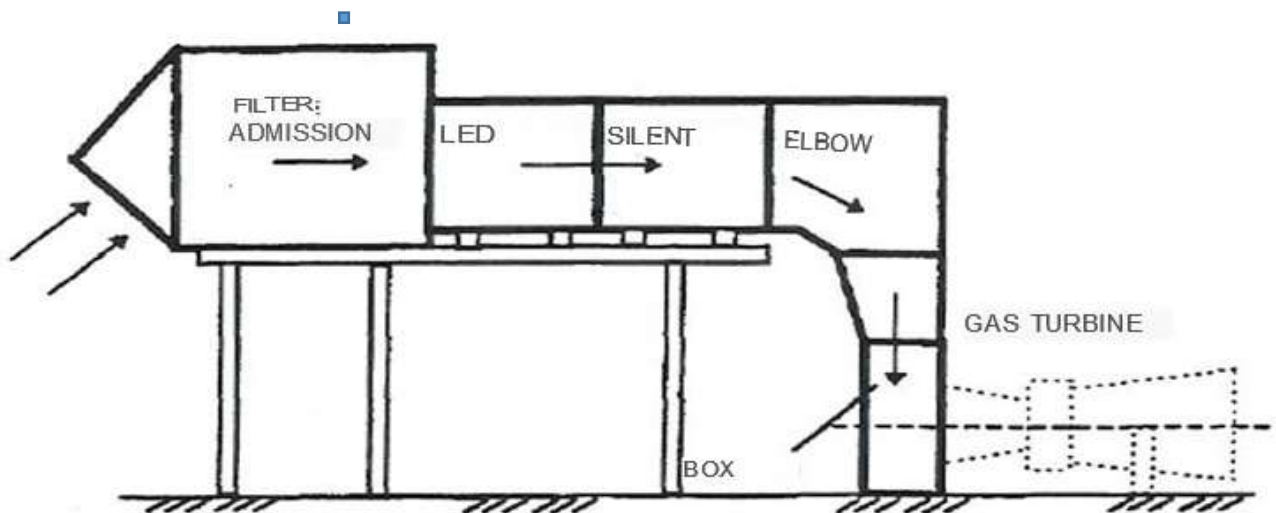


Fig I.2: Representation of an Intake Compartment

**I. 2.2 Compressor:**

Its role is to compress the air before it enters the combustion chamber, using more than half of the power produced by the expansion turbine.

**I.2.3 Combustion Chamber:**

It results in a pressure drop of about 6% [3] and an increase in air temperature due to the combustion of the gas, with a typical efficiency of 98%. As its knowledge determines the lifespan of the hot parts, the temperature  $T_3$  at the "turbine inlet" is limited.

- The ISO turbine inlet temperature (as defined by ISO 2314) assumes that all the air flow at the gas turbine inlet passes through the combustion chamber and that there is no air extraction from the compressor and that the air intake and exhaust occur without pressure drop. This is the lowest value.
- The temperature at the turbine wheel inlet is calculated considering that the air at the outlet of the combustion chamber is perfectly mixed with the cooling air from the inlet guide vane. This is an intermediate value about 80 °C higher than the previous one, which means that the cooling air flow for the downstream blades and cavities is about 8% of the total flow.
- The temperature at the combustion chamber outlet is calculated with the air flow that passes through the flame tubes, which is about 80% of the air flow at the compressor inlet. This is the highest temperature with a difference of about 80 to 100 °C compared to the previous one. The air flow through the flame tubes can be accessed by measuring the reduced flow/pressure drop curve of a flame tube on a partial load test bench and their pressure drop on the machine.

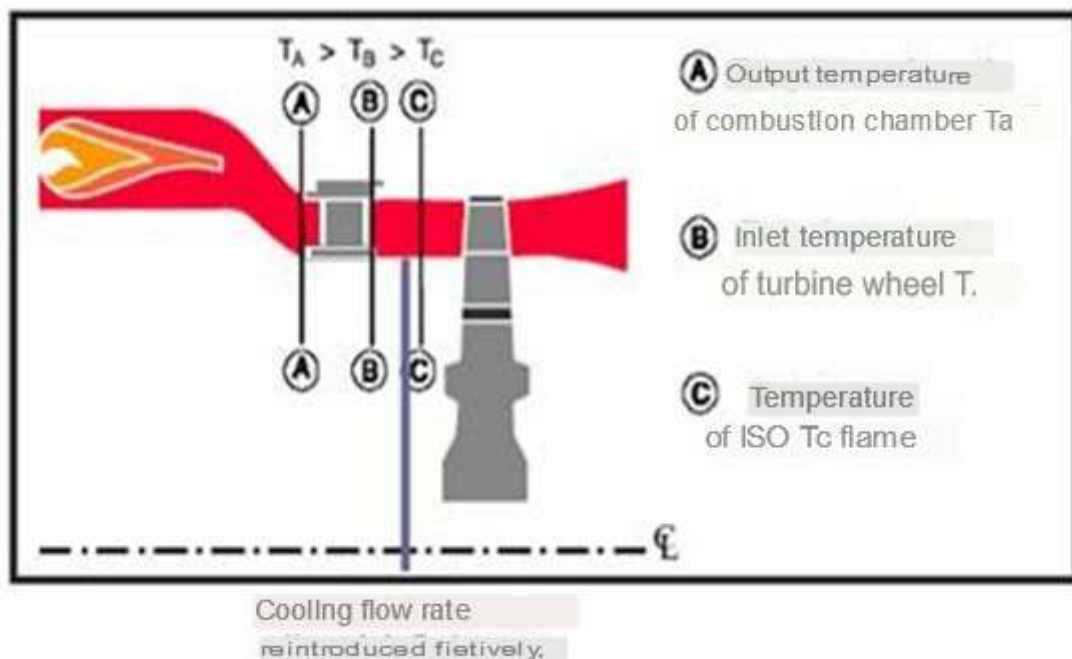


Fig: I-.3: Flame Temperature

**I-2.4 Expansion Turbine:**

Produces mechanical work by expanding the combustion gases to drive the compressor or other devices.

**I-2.5 Gas Turbine Exhaust:**

Influenced by the pressure drop created by all downstream components: exhaust diffuser (0.5 to 1%), tranquillization grid (0.5%), gas heating system (0.3%), boiler, valves, elbows and chimney.

**I-3. Operating principle of a gas turbine**

A gas turbine operates as follows:

- It extracts air from the surrounding environment;
- It compresses the air to a higher pressure;
- It increases the energy level of the compressed air by adding and burning fuel in a combustion chamber;
- It delivers high-pressure and high-temperature exhaust gas to the turbine section, which converts thermal energy into mechanical energy to rotate the shaft. This serves to provide useful energy to the driven machine, coupled with the machine through a coupling, and also provides the energy required for air compression, which takes place in a compressor directly connected to the turbine section;
- It discharges low-pressure and low-temperature gases resulting from the aforementioned transformation to the atmosphere. The standard design conditions are conventionally classified as ISO conditions, with the reference values mentioned above.

**I-3.1 Evolution of gases through the different components of a gas turbine:**

The compressor (C), consisting of a set of wheels with blades, compresses the external air (E), simply filtered, up to 10 to 15 bars, or even.

Gas (G), or atomized liquid fuel, is injected into the combustion chamber (Ch) where it mixes with the compressed air and ignites. The hot gases expand as they pass through the turbine (T), where the thermal energy of the hot gases is converted into mechanical energy. The turbine consists of one or more wheels also equipped with blades. The burned gases escape through the chimney (Ec) via a diffuser. The rotational movement of the turbine is transmitted to the shaft (A), which drives both the compressor and a load, which is another device (machine) receiver (ice) (pump, alternator...) coupled to its right end. For startup, a starting motor (M) is used as a starter, as shown in figure (I-4). Power and rotational speed adjustment is possible by controlling the air flow rate at the inlet and the fuel injection.

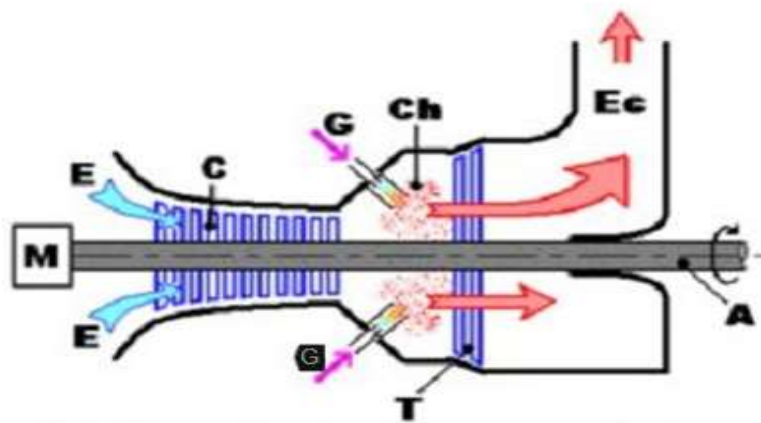


Fig. I.4: Evolution of gases through a gas turbine

**I-4. Gas turbine technologies [15]:**

**I-4.1 Single-shaft gas turbine:**

The compressor and turbine sections of these machines consist of a single simple rotor, where the turbine produces the energy to drive the compressor as well as the energy to drive the load. Single-shaft turbines are favorable in cases where the load is constant. Single-shaft turbines are suitable for driving machines that operate at a constant speed, such as alternators, and for this reason, they are used in power generation.

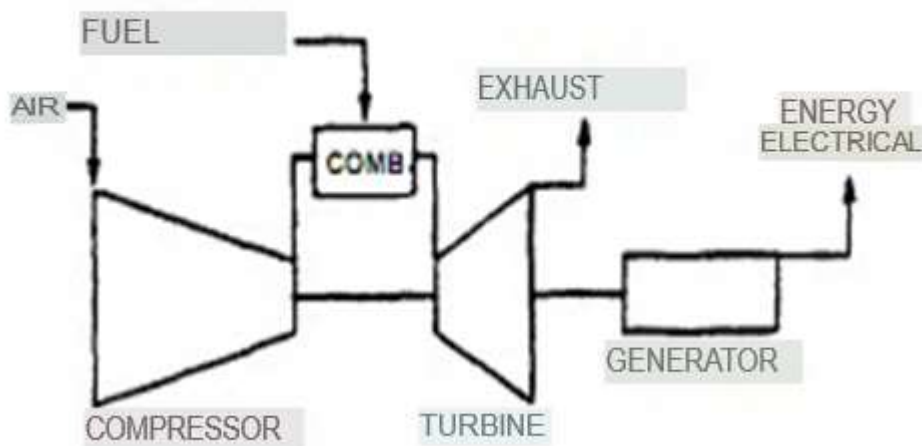


Fig. I-5: Single-shaft gas turbine

**I-4.2 Two-shaft gas turbine :**

In applications where power is adjusted by varying the speed of the driven machine, two-shaft gas turbines are normally used, as shown in figure I-6. In this case, the turbine is mechanically divided into two separate sections:

- A high-pressure section, which operates at a constant speed within a range of powers and exclusively drives an axial compressor.
- A low-pressure section connected to the driven machine via a coupling. This section can change its rotational speed independently of the high-pressure turbine section.

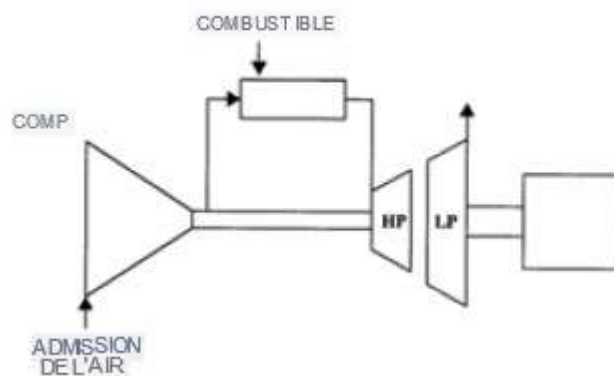


Fig. I-6: Two-shaft gas turbine

**I-5. MS5002C gas turbine (which represents our study):****I-5.1 General information:**

Fuel and air are used to produce horsepower on the shaft. The axial compressor rotor contains 16 stages. The gas turbine has two mechanically independent wheels. The first stage (high-pressure section), the wheel drives the compressor rotor. The second stage, (the low-pressure section,) the wheel drives the charge compressor. The function of the unconnected wheel is to allow the two wheels to operate at different speeds to perform various tasks of the centrifugal compressor load.

The gas turbine has a four-bearing configuration that uses oscillating and elliptical journal bearings with pressure lubrication. Bearings No. 1 and 2 support the axial compressor rotor and the first-stage wheel. Bearings No. 3 and 4 support the second-stage wheel and the load shaft. The four-bearing configuration ensures that the critical speeds of the rotating parts are higher than the turbine's operating speed. It also allows for quick startup, loading, and shutdown.

Both turbine wheels have long-stem lost-wax cast blades. This innovation effectively protects the rim and blade base from the high temperature of the main gas jet. The turbine wheels are

cooled by air extracted from the tenth stage of the axial compressor. The MS-5002 two-shaft turbine is designed to operate on fuel gas.

### **I-5.2 Operating Principle:**

The high-pressure compressor/turbine rotor is initially brought up to 20% speed by a starting device. Atmospheric air entering the compressor is brought into the combustion chambers where fuel is delivered under pressure. A high-voltage flame ignites the fuel-air mixture (once ignited, combustion will continue in the chambers). The hot gases increase the speed of the high-pressure compressor/turbine rotor and in turn increase the discharge pressure of the axial compressor. As the pressure begins to rise, the low-pressure turbine rotor starts to rotate, and both turbine rotors accelerate to the operating speed. The combustion products (high-pressure and high-temperature gases) expand, first inside the high-pressure turbine and then inside the low-pressure turbine, and then the gases are discharged into the atmosphere.

As the expanded gases pass through the high-pressure turbine, they cause a drop in pressure on the turbine blades, causing the turbine to rotate; thus, turning the axial compressor and applying torque to the driven accessories. The gases also rotate the low-pressure turbine before exhaust; thus, turning the charge compressor. The rotor rotates clockwise when observed from the suction side.

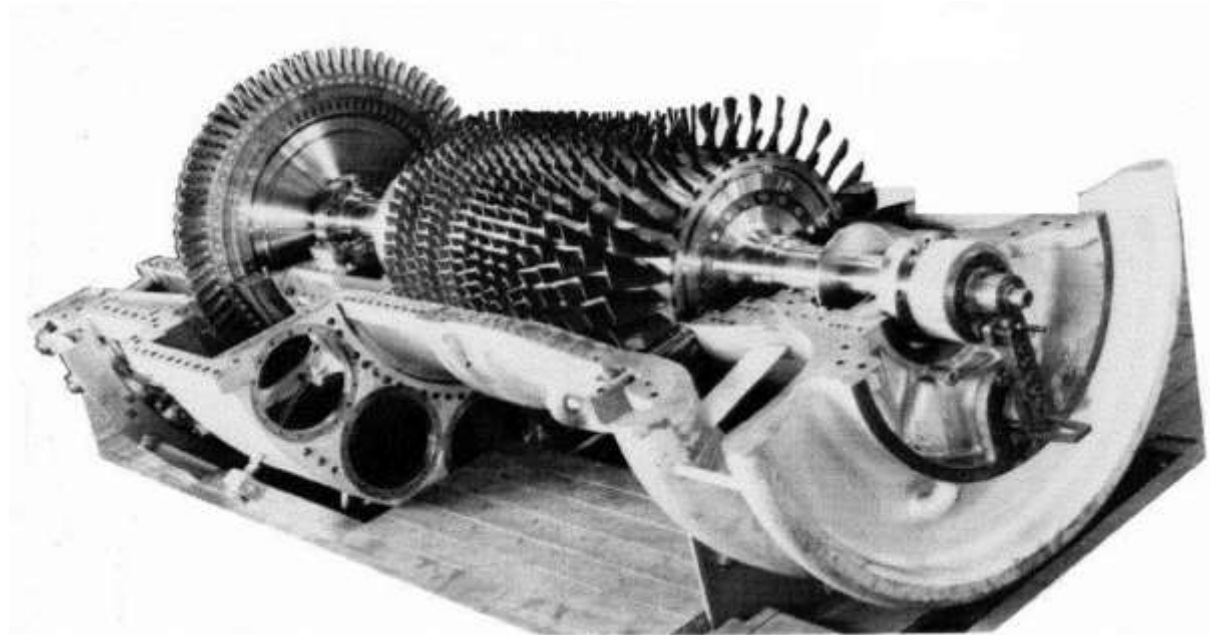


Fig. I-7: Model 5002 compressor casing and high-pressure turbine rotor assembly

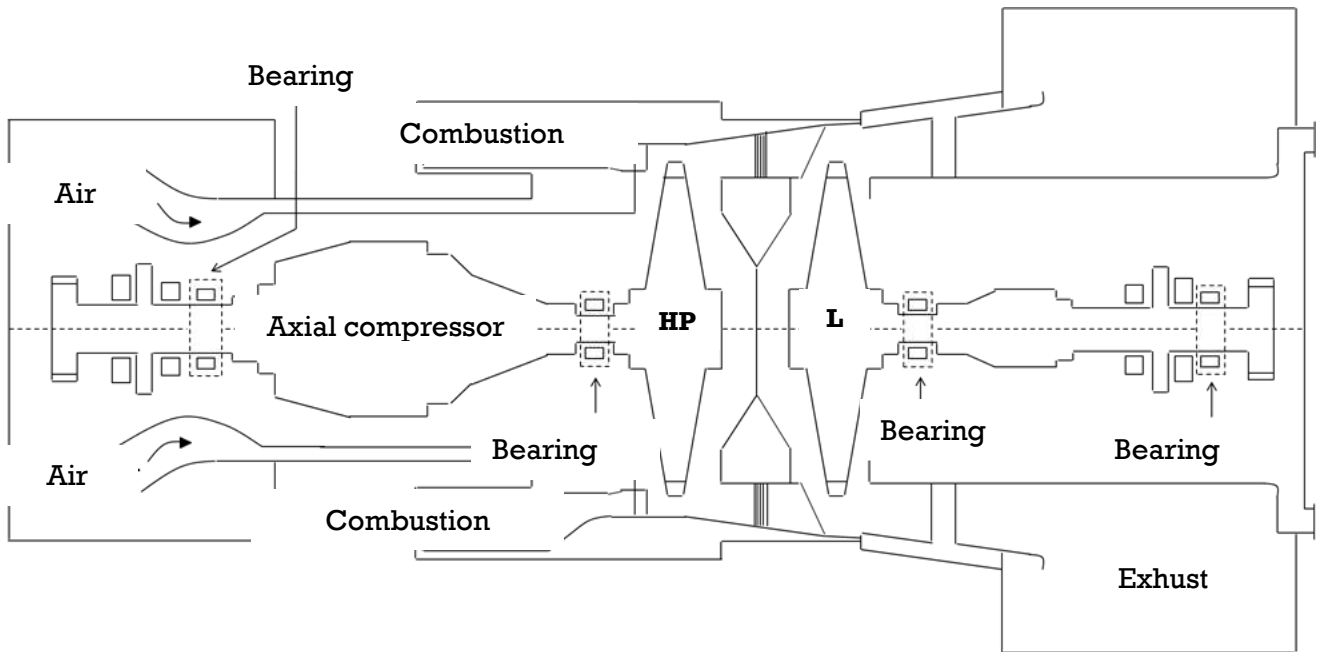


Fig. I-8: Simplified diagram of a model 5002 gas turbine.

# Chapter II

## Air Cooling Techniques for Gas Turbine Inlet

**Introduction:**

Gas turbine installations are designed to operate under ISO ambient conditions, which include a temperature of 15°C, atmospheric pressure of 1.013 bars, and relative humidity of 60%. However, ambient conditions are not stable throughout the year (even between day and night) and vary from one region to another. As a result, the performance of gas turbine installations is often variable or poor during hot and dry periods when the airflow through the installation is low and the compressor inlet temperature is higher.

To address this issue, air cooling systems are used upstream of the compressor to improve the performance of these installations by increasing the airflow through the machine. This is achieved by lowering the temperature of the air at the compressor inlet, which subsequently reduces the emissions of nitrogen oxides in the combustion chamber.

The currently used cooling systems are as follows:

- Water evaporation cooling
- Evaporative cooler or water trickle cooling
- Mist injection
- Use of compression refrigeration units
- Direct refrigeration (single circuit)
- Indirect refrigeration (two circuits)
- Mechanical refrigeration with ice storage
- Mechanical refrigeration system with cold water storage
- Use of absorption refrigeration units

The location of these cooling systems is shown in Figure II-1

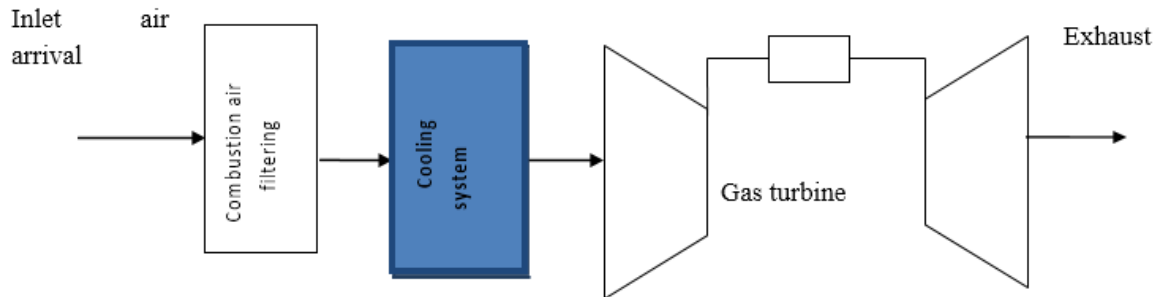


Fig II-1: Schematic representation of a gas turbine installation with combustion air cooling

### **II-1 Evaporative cooler:**

#### **II-1. Operating principle:**

The principle of evaporative cooling is the same as that which occurs in nature. A mass of treated water is evaporated in the intake channel, and the latent heat required for evaporation comes from the air itself. The air that exits after this cooling system is therefore cooled and humidified. The cooling process does not require an energy input. Water evaporative coolers are suitable for hot and dry areas. Two techniques exist to achieve water evaporation cooling.

#### **II.2.1 Evaporative cooler with humidified module:**

Water trickle cooling, as shown in Figure II-2, involves passing the air after filtration through a humidified media composed of treated corrugated cellulose paper. This media acts as a conventional evaporator. Water flows over the corrugated surface of the evaporating panel, as shown in Figure II-2. Some of the water is evaporated due to the action of the dry and hot air passing through the evaporating panel. The remaining water falls into a tray located below the evaporator. The air at the outlet of the cooler is cooled, and before passing through the gas turbine compressor it passes through a water droplet removal system to ensure proper operation of the gas turbine compressor.

The main component of the water trickle cooler is the humid media, which is corrugated paper in a honeycomb form. Water flows through a distribution system positioned above the media. The efficiency of evaporative coolers with humidified media can reach up to 90%.

(23)

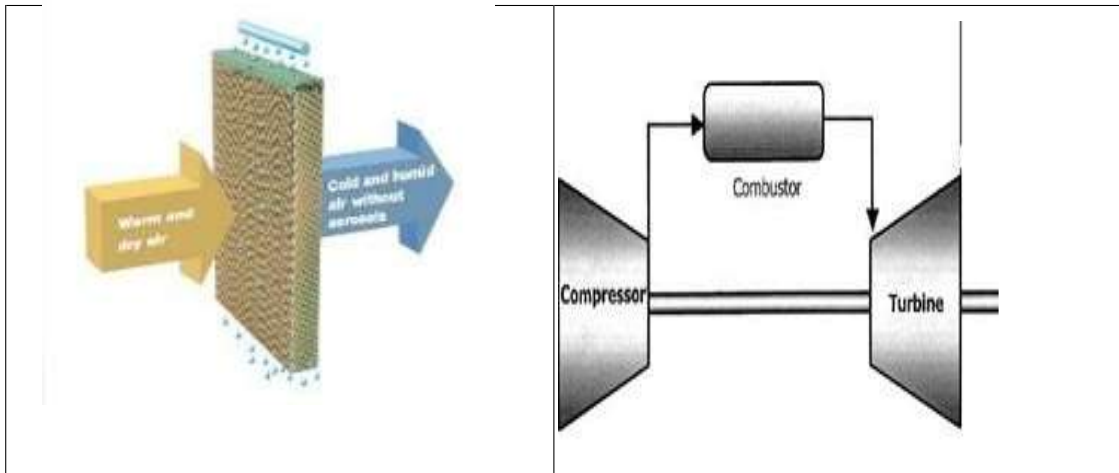


Fig. II-.2: Evaporative cooler

Generally, it is recommended to place the evaporative cooler after the intake air filter, rather than before. This arrangement will protect the media from dust and other airborne contaminants. (23)

#### **Advantages:**

- Easy and quick to install
- The estimated installation cost is 1/8 to 1/2 compared to refrigerated air conditioning.
- The estimated operating cost is 1/4 of that of refrigerated air.
- It functions as an air intake washer and cleaner.
- An increase in power produced by the gas turbine allows for coverage of peak demands, especially during hot periods.

#### **Disadvantages:**

- Limitation on capacity improvement
- It is not suitable for humid sites.
- Consumes a quantity of water.
- The water must be treated before use.

#### **II.2.2 Cooling by atomization or water spraying:**

In this system, humidification is achieved by spraying water in the form of small particles through high-pressure atomization nozzles (60 to 140 bar), as shown in figure

(II -.3). The water evaporates into the air, reducing the air temperature and increasing the specific humidity. The efficiency of spray humidifiers can reach 100%.

The size of the sprayed water droplets is very fine (approximately 10 $\mu$ m to 20 $\mu$ m), making it easily evaporate into the air. (23 )

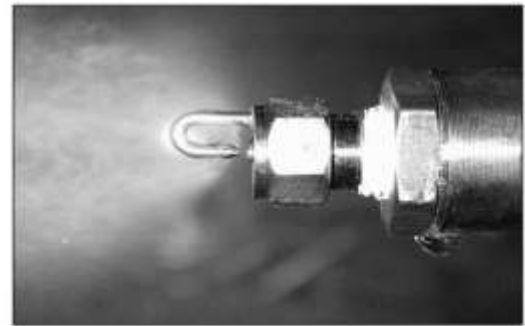


Figure 5. Fine-spray HP nozzle in operation.

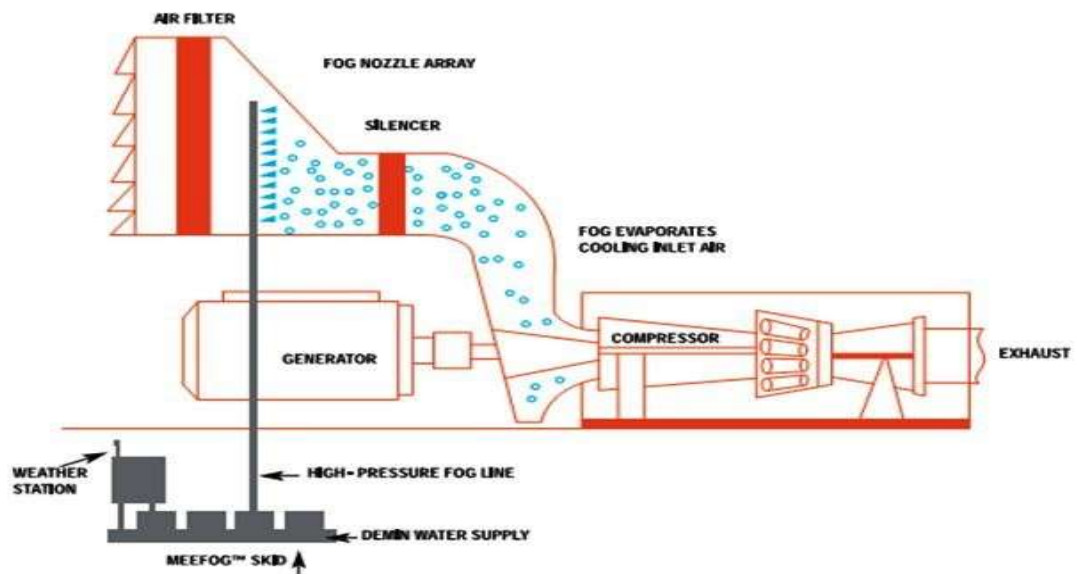


Figure II -.3: Cooling by water spraying.

Before using a water spraying system to cool the combustion air of gas turbines, the water must be treated in a treatment or demineralization station. The characteristics of this water are summarized in the table below:

Table II.1: of water spraying characteristics (Laboratory plants)

Quantity of dissolved solids	Maximum 5 PPM
pH	6-8
Na + K	Maximum 0.1 PPM
Silica (SiO <sub>2</sub> )	Maximum 0.1 PPM
Chlorides	Maximum 0.5 PPM
Sulphate	Maximum 0.5 PPM
Table 4.1: Characteristics of sprayed water	

**Advantages:**

- Easy installation
- Low investment cost
- Can improve gas turbine performance better than evaporative cooling

**Disadvantages:**

- Capacity improvement is limited.
- It only adapts to dry sites.
- It requires a high-power pump.

**II-3) Mechanical refrigeration systems [9]:**

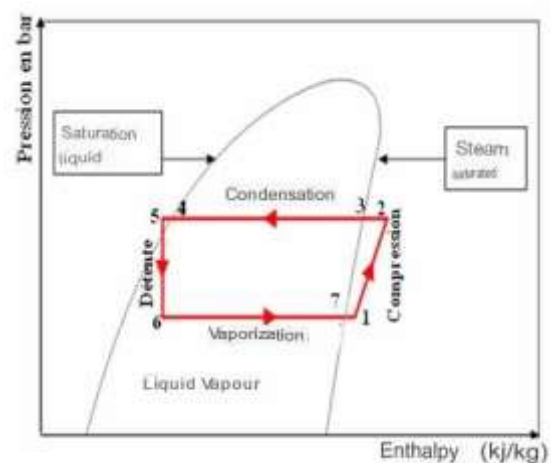
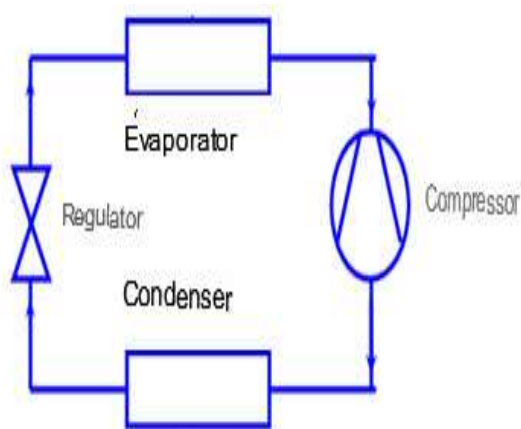


Fig. II -4: Low cycle of a compression refrigeration machine on the left: components - on the right: thermodynamic cycle

this system, heat is extracted by using a heat exchanger where a colder fluid absorbs the heat from the air, resulting in its cooling. The reference thermodynamic cycle is performed in a compression refrigeration machine, as shown in figure (II -4).

This thermodynamic machine consists of a closed and sealed circuit in which a refrigerant fluid circulates in liquid or gaseous state depending on the organs it passes through. These organs are four in number: the evaporator, the compressor, the condenser, and the expansion valve. The use of mechanical cooling systems is applicable in places where the relative humidity is high. Compression refrigeration machines are used in two different ways, namely direct or indirect mode:

a) Direct type

The air directly exchanges heat with the refrigerant fluid circulating in the machine, so the air passing through the evaporator will cool down.

Advantages:

- They provide better improvement than water evaporation systems.
- Constant air temperature at intake.

Disadvantages:

- High installation and operating costs.
- It requires an additional load to operate the refrigeration unit.
- It is harmful to gas turbine components in case of leaks.
- It requires periodic maintenance.

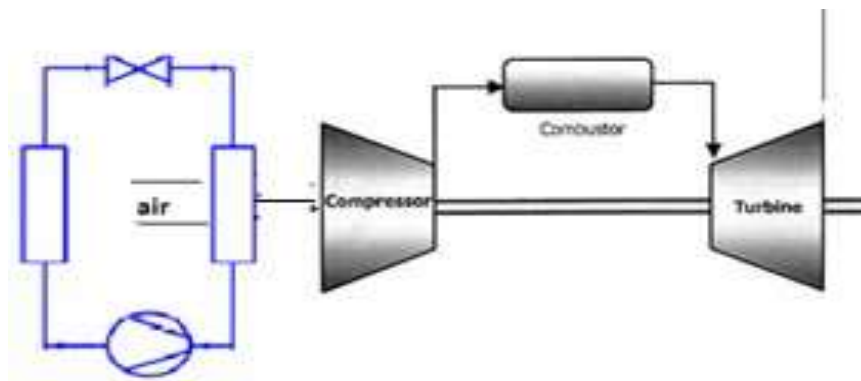


Fig. II -5: Combustion air cooling by direct compression type machine

**b) Indirect type:**

In an indirect cooling system, there are two circuits: primary and secondary. The primary circuit is the refrigeration system circuit (cold production) where the working fluid or refrigerant flows, and the secondary circuit is the cold transport circuit, also known as the refrigerant fluid circuit.

The refrigerant fluids used are not harmful to the gas turbine installation in case of leaks. Among these fluids are air and water.

**Advantages:**

- Can improve gas turbine performance better than evaporative coolers (using media and spraying).
- Not sensitive to the wet bulb temperature of the ambient air.
- No danger of refrigerant leaks and losses.

**Disadvantages:**

- High installation cost.
- Requires additional load compared to the direct system to operate the secondary circuit (refrigerant fluid circuit)

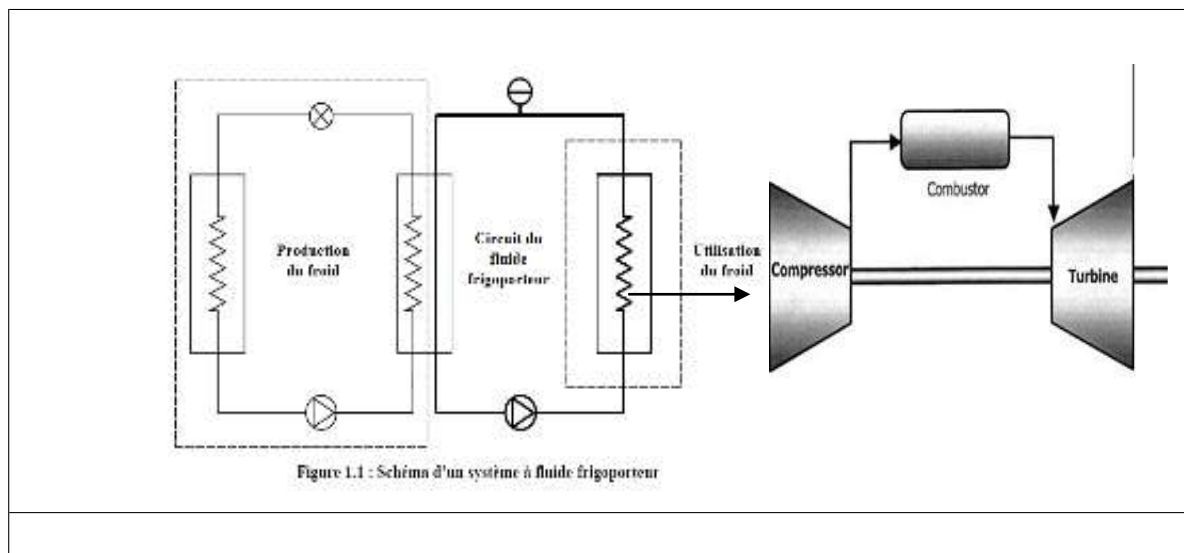


Fig II.6 Schéma d'un système à fluide frigoporteur

**II-4 Mechanical refrigeration systems with storage:**

Two techniques for cold storage are used: ice storage and chilled water storage.

**II-4.1 Ice storage [5]:**

Ice is produced by a compression refrigeration system and stored in a reservoir (see figure below), then the water passes through the reservoir and is cooled, transporting this cold to the combustion air through a heat exchanger.

The ice produced during the night when demand is low is utilized during the day when demand reaches its peak.

**II-4.2 Chilled water storage [10]:**

It follows the same principle as ice storage, except that in this system, chilled water is stored in the reservoir.

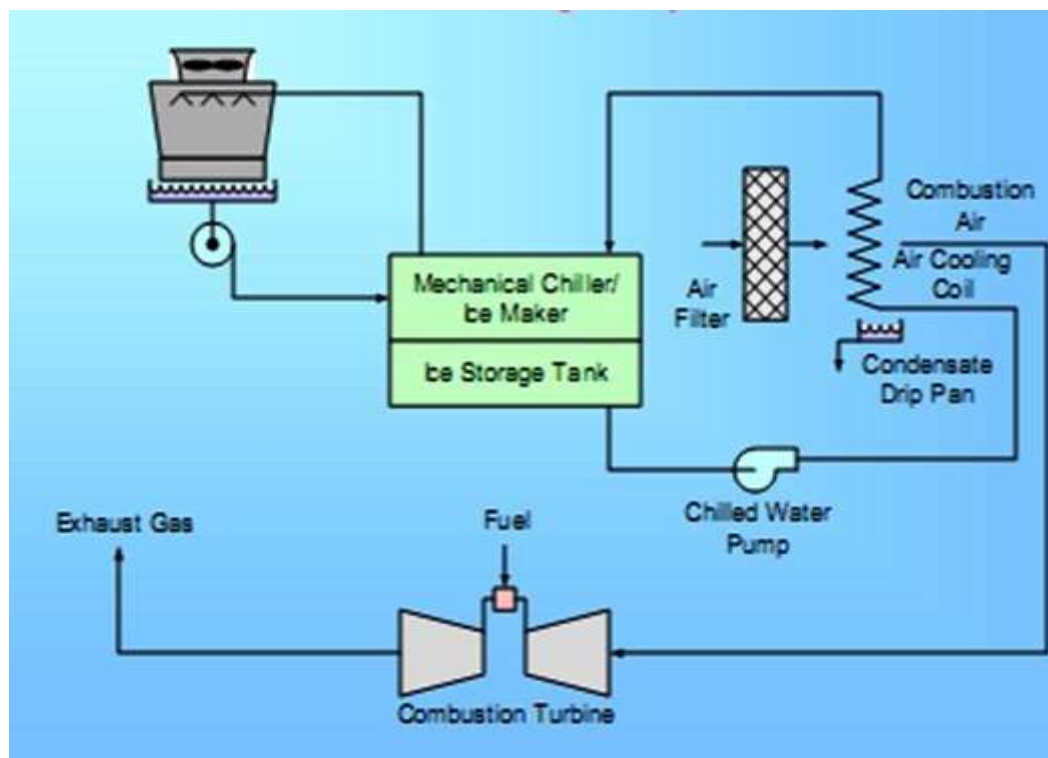


Fig. II -.7: Mechanical refrigeration systems with ice storage

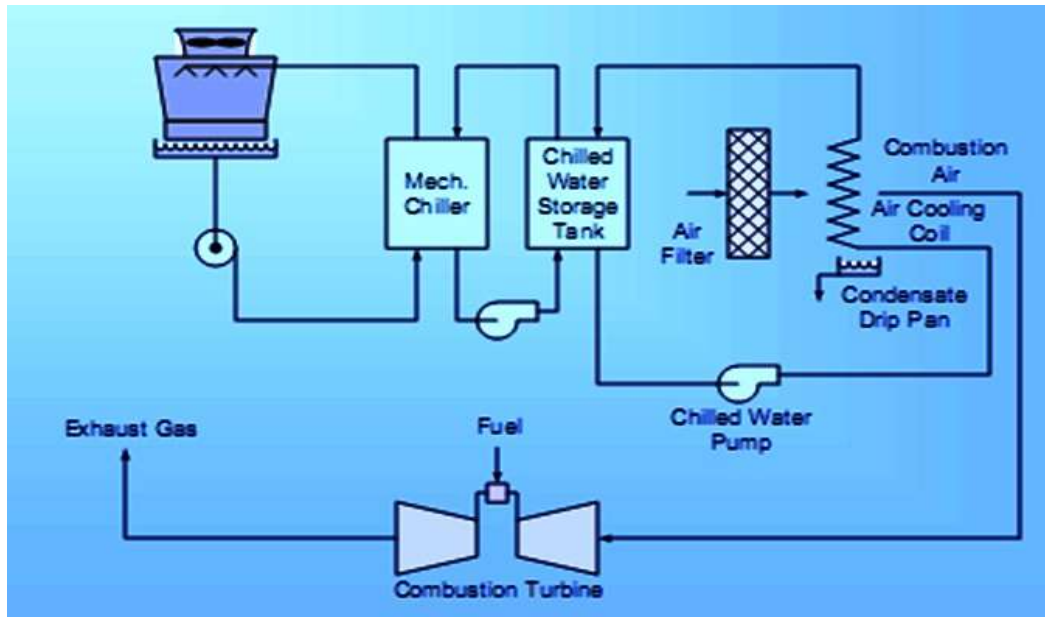
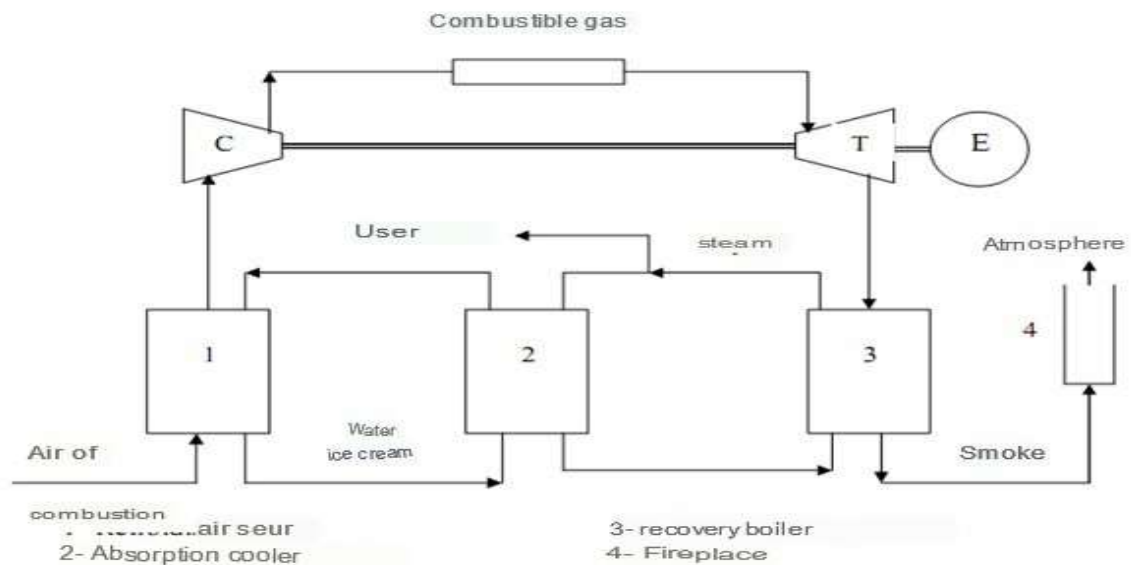


Fig. II -8: Mechanical refrigeration systems with chilled water storage

**II-5 Absorption chiller system [11]:**

Unlike compression systems that require electricity, absorption refrigeration systems can produce cold using a heat source.

These machines are mainly used when there is free energy available in the form of superheated steam, solar input, or exhaust gases from gas turbines, to operate an absorption machine.



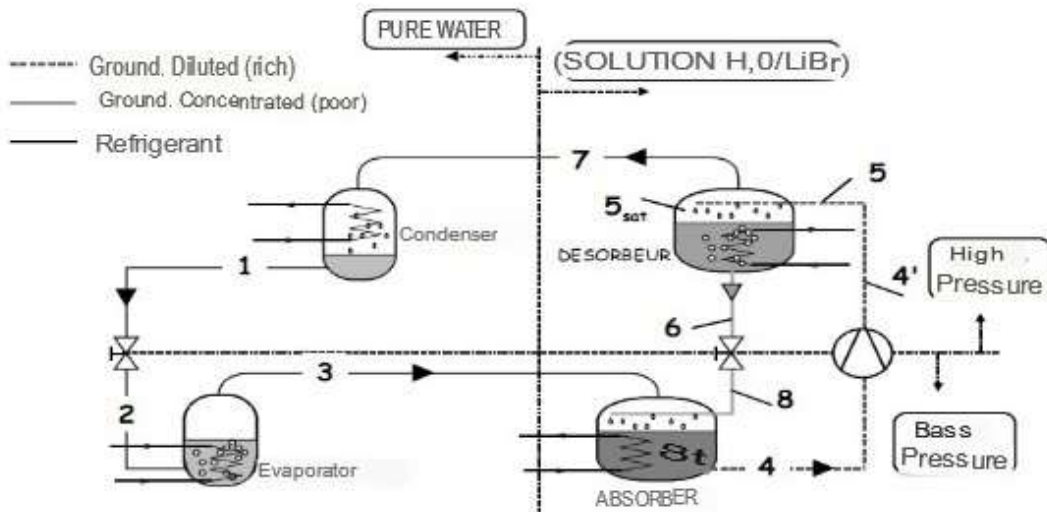


Fig. II -9: Representation of an absorption air cooler for gas turbines

**II-5.1: The basic cycle of an absorption machine [11]:**

Schematically, a liquid absorption machine consists of the elements shown in the figure (IV-10). This machine, like all compression machines, includes the condenser, evaporator, and expansion valve, through which only the pure refrigerant (water) flows. This assembly is connected to the chemical part of the process (absorber and desorber).

**The condenser:** a component similar to that of the compression machine, the temperature of the heat transfer fluid feeding the condenser determines the condensation temperature and therefore the pressure in the desorber/condenser assembly. The condensation of the refrigerant requires the release of a quantity of heat  $Q_{cond}$  (path 7-1 in figure (II -10)).

**The evaporator:** at the outlet of the condenser, the liquid refrigerant expands through the expansion valve (1-2), then evaporates, producing the power  $Q_{evap}$ . The evaporation temperature and pressure in the evaporator/absorber assembly are determined by the temperature of the cold source (medium to be cooled).

**The generator or desorber:** the diluted solution (rich in refrigerant) receives the quantity of heat  $Q_{from}$ , which causes the desorption of part of the refrigerant dissolved in the solution. The desorber thus produces a refrigerant vapor (7) and a concentrated solution (poor in refrigerant) (6). This organ carries out a concentration (5-6) of the sorbent (XLi B) or a depletion of refrigerant ( $XH_2O$ )

**The absorber:** the steam leaving the evaporator (3) meets the concentrated (lean) solution coming from the desorber (8). It is absorbed by this solution which is enriched with refrigerant. Heat  $Q_{abs}$  released by this exothermic transformation is evacuated by a heat transfer fluid at the temperature  $T_m$  at the absorber outlet (4). We thus obtain a diluted solution (rich in refrigerant). This component therefore carries out a dilution (path 8-4) of the sorbent (XLiB) or an enrichment in refrigerant (XH<sub>2</sub>O)

**Advantages of the absorption cooling system:**

- It allows for better performance of gas turbine installations than water evaporative cooling systems.
- low electrical power consumption than the compression system
- Not sensitive to the humid temperature of the ambient air.
- It allows for the recovery of waste heat from exhaust gases.

**Disadvantages:**

- . High investment cost
- A high implementation time compared to other cooling systems.
- It is not applicable with open gas turbine installations.

**Conclusion**

Several cooling systems exist for the conditioning of gas turbines, but the choice of the appropriate system needs to be studied considering the installation site (ambient conditions) because ambient conditions (temperature and relative humidity) vary from one region to another, and each system has priorities compared to another.

## **Chapter III**

**Analysis and modeling of a  
water trickle cooler for gas  
turbine**

**introduction**

Hassi R'mel gas us region has a park of 80 gas turbines of different types installed in the gas treatment, reinjection, and recovery units. Their role is to drive centrifugal compressors and alternators. These gas turbines are installed in a field that covers 10 units within a radius of over 50 km. The distribution of the 80 gas turbines in HassiR'mel according to the different units is summarized in the following table:

**Table III.1:** Park of installed gas turbines in Hassi R'mel gaseous field ( reference )

	Gas turbine task	
Stations	Driving Centrifugal compressors	Driving alternators
South compression station "SCSUD"	18 MS5002B type gas turbines	01 MS1002B type gas turbine
North compression station "SCNORD"	18 MS5002B type gas turbines	01 MS1002B type gas turbine
SBC	09 MS5002C type gas turbines	
MPP2	02 MS5002B type gas turbines 04 MS5002C type gas turbines	01 MW101L type gas turbine
MPP3	02 MS5002B type gas turbines 04 MS5002C type gas turbines	01 MW101L type gas turbine
MPP4	02 MS5002B type gas turbines	-----
PHASE B	05 MS5002B type gas turbines	-----
Associated gas recovery station "SRGA"	04 PGT10B type gas turbines 02 MS5002C type gas turbines	-----
Storage and transportation facility center "CSTF"	05 TB4000 type gas turbines	-----
DjebelBISSA "DJBISSA"	01 PGT10B type gas turbine	-----

**III-1. Description of the MS 5002C gas turbine:****III-1.1 Characteristics of the MS5002C gas turbine:**

The two-shaft series 5002 gas turbine is a machine used to drive a centrifugal compressor. This turbine contains an air intake compartment where a self-cleaning filtration system is located.

**a) Gas turbine series: MS5002C:**

- Turbine application: mechanical drive of a compressor Cycle: single
- Shaft rotation: counterclockwise
- Operating type: continuous
- Shaft speed: 5100 rpm for HP; 4900 rpm for LP
- Control: Mark V SPEEDTRONIC solid-state electronic control system Protection: overspeed; overheating; vibration and flame detection
- Cooling mechanism: ratchet gear reducer
- Noise attenuation: intake and exhaust silencer according to local requirements

**b) Compressor section:**

- Number of compressor stages: 16
- Compressor type: heavy-duty axial flow Joint design: horizontal flange
- Type of inlet guide vanes: variable
- Turbine section:

- Number of turbine stages: 2 (two shafts) Joint design: horizontal
- 1st stage guide (Nozzle): fixed surface
- 2nd stage guide (Nozzle): variable surface

**c) Combustion section:**

- Type: 12 reverse flow combustion chambers.
- Room configuration: concentric around the compressor Ignition plugs: 2 types of self-retracting injection-spring electrodes Flame detector: 4 types of ultraviolet

**Nominal regime identification plate:**

Base output: 38000 hp ISO 28.34MW Thermal efficiency: 29.2% Compression ratio: 8.9:1

d) Exhaust gas flow rate: 126kg/s

Specific consumption: 12310kJ/kWh Inlet temperature: 59 °F (15°C) Outlet pressure: 14.7 psi (1atm)

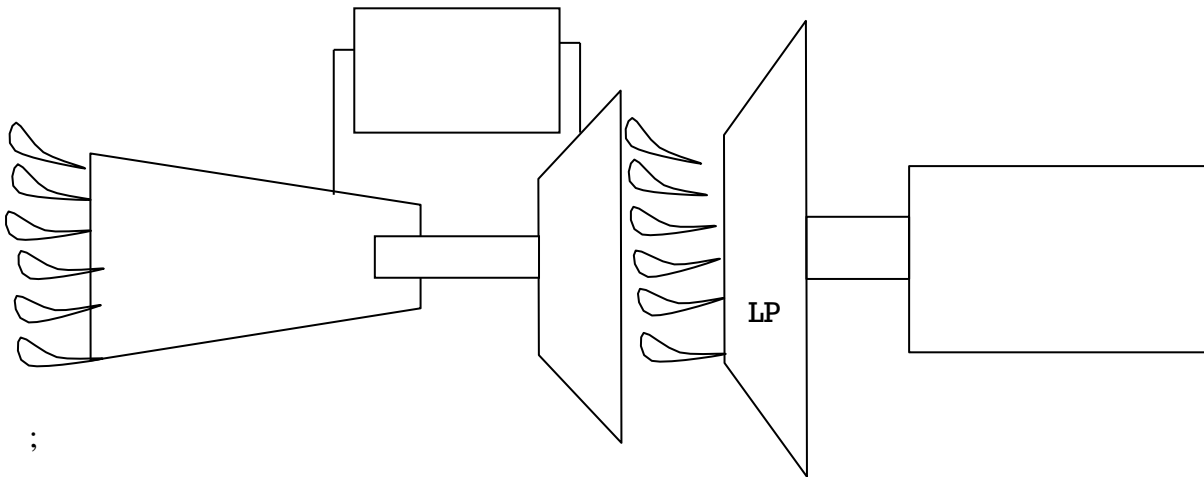


Fig. III -1 MS 5002c Gas Turbine Diagram

### **III-2) Analysis and modeling of a direct evaporation cooling system for a gas turbine installation:**

#### **III-2.1) Description of the water dripping cooling system [17]:**

In our study, we chose the water evaporation cooler because it is suitable for hot and dry areas (such as the Saharan region). The humidifier is used to increase the water content in the air, which decreases the absolute humidity and air temperature. For humidification to occur, there must be close and intensive contact between the air and the moisture source. The dripping humidifier with pump recycling, as shown in Figure III -2, works as follows:

- Water drips on a support with a large surface area;
- Air flows through the thickness of this support and comes into contact with the wet surface;
- Water evaporates due to the heat transferred by the air.
- Humidification is adiabatic.

The main element in a water dripping cooler is the wet media, as shown in Figure (III -3), where water is in direct contact with the air. The material of this media is characterized by good porosity to ensure good contact between the two fluids; it is usually made of treated cellulose paper, and there is a distributor above it to ensure water distribution over the entire surface. A tray below the dripping surface is used to collect the non-evaporated water. After

adding a defined amount of water to deconcentrate the water in the tray (pH, bicarbonate and calcium content), it will be reused using a pump. Downstream of this cooling system, the humid air passes through a droplet eliminator to prevent water droplets from passing through the compressor.

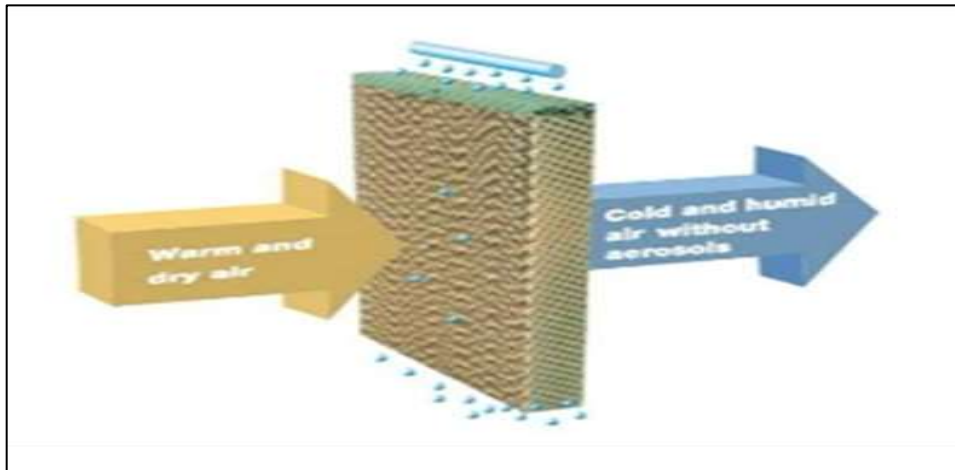


Fig. III -3: Dripping surface

**• Wet media geometry:**

The dripping surface in the form of a honeycomb is composed of corrugated panels. Water falls by gravity and passes through inclined panels at an angle of  $60^\circ$  in the opposite direction of the air. On the other hand, the air passes through panels inclined at  $45^\circ$  below. The main purpose of panel inclination is to maintain long contact between the air and water and prevent the air from lifting water droplets.

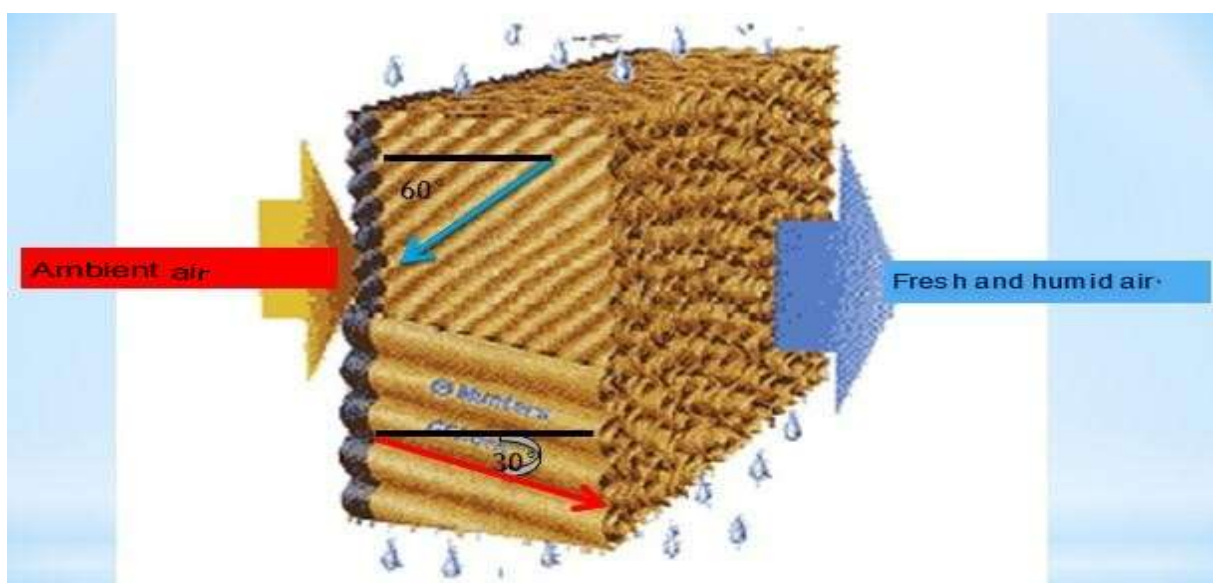


Fig. III -4 Wet media geometry

**III-2.2) Effect of cooler geometry on evaporation efficiency:**

The performance of this cooler varies depending on the thickness of the runoff surface and its porosity. In our study, we used an empirical relationship to define the efficiency of the runoff cooler. We used the empirical relationship (III.1) published by J.M. Wu, X. Huang, H. Zhang [18] which allows for the calculation of the cooler's performance according to the GLASdek7090 configuration.

$$\eta_{\text{ev}} = 1 - \exp \left[ - \frac{A \cdot \delta^2}{P_a \cdot C_p \cdot V^{0,35}} \right] \quad (\text{III.1})$$

$C_p$  Specific heat

$P_a$  Air density

$\delta$  Cooler thickness

$A$  Section

$V$  Air velocity

The figure (III -5) represents the trend of evaporative cooler efficiency as a function of thickness for different air velocity values.

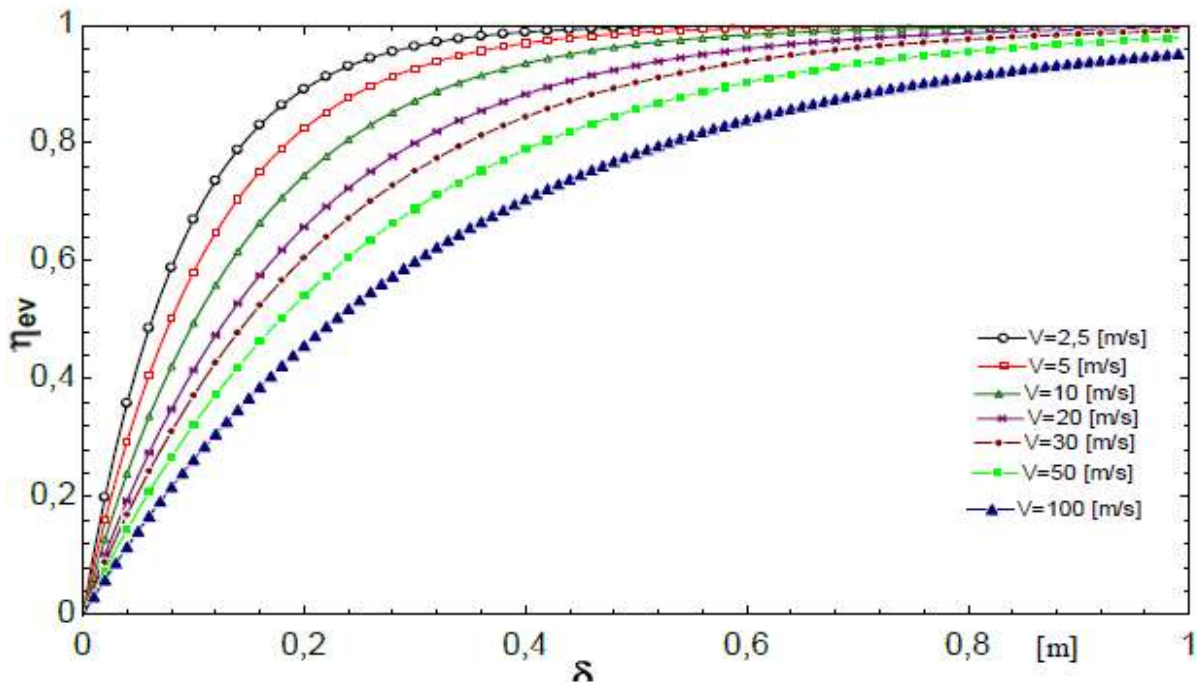


Fig. III-5: Variation of cooler performance as a function of thickness and velocity

The thickness of the cooler and the air velocity directly influence the cooling efficiency, as shown in Figure (III -5). It is clear that the thicker the cooler, the higher the performance with a lower velocity. However, there is a constraint that prevents increasing the thickness of the cooler, which is the pressure drop. Therefore, it is necessary to find a balance between the two factors: thickness and pressure drop. In our study, we chose a cooler with a thickness of 45 cm and an efficiency of 85%. (23) because of the cost.

#### **III-4) Thermodynamic study of the MS5002c turbine:**

##### **III-4.1) Study and modeling of the MS5002c gas turbine with intake air cooling:**

In the following, we present a thermodynamic calculation of the different characteristics of the MS5002C gas turbine using manufacturer data, in order to determine the influence of ambient conditions on its characteristics while presenting the characteristic points not provided by the manufacturer.

##### **•Thermodynamic calculation of the MS5002c gas turbine:**

##### **Calculation of the admission temperature at the outlet of the cooler:**

The air evolution through the evaporative cooler is isenthalpic. The temperature at the outlet of the cooler is calculated based on the cooler's efficiency and the temperature upstream of it. The cooler's efficiency is calculated using the following relationship:

$$\eta_{ev} = \frac{T_1 - T_h}{T_1 - T_{bh}} \quad III.2$$

Where:

$T_1$ : ambient temperature

$T_h$ : temperature at the outlet of the humidifier

$T_{bh}$ : saturation temperature (100% relative humidity)

##### **a) Evolution 1-2 (Axial compressor):**

We will determine the compressor's discharge temperature  $T_2$  and its work  $W_c$

##### **Discharge temperature $T_2$ (actual):**

The temperature of the air after a polytropic compression is given by the following relationship:

$$T_{2=T_1} \cdot \tau^{\left(\frac{\gamma-1}{\gamma \cdot \eta_{pc}}\right)} \quad III.3$$

With:

$\tau = \frac{P_2}{P_1}$  compression ratio

$\eta_{pc}$  Polytopic compressor efficiency (see appendix 2)

The value of atmospheric pressure is calculated using the following correlation (19)

$$P = P_0 \left[ 1 - \frac{0,0065 \cdot Z}{288,5} \right]^{5,31} \quad III.4$$

With:

P: atmospheric pressure at sea level  $P=1.013\text{bar}$

Z: the altitude of the studied site (for the Hassi R'mel region  $Z=750\text{m}$ ).

#### W<sub>c</sub> compressor work:

$$W_c = \frac{\dot{m}_{air} \cdot C_{p_{air}} \cdot (T_2 - T_1)}{\eta_m} \quad III.5$$

$\eta_m$  The mechanical efficiency of the compressor

The values of Cp are given by the solver we used for modeling.

#### Evolution 2-3 (Combustion chamber):

We will determine the combustion heat  $Q_{cc}$  and the injected fuel flow rate  $m_c$  or the air/fuel ratio

#### Combustion heat:

$$Q_{cc} = (\dot{m}_{air} + m_{comb}) \cdot C_{p_g} \cdot (T_3 - T_2) \quad III.6$$

$\eta_{cc}$  Combustion chamber efficiency

$C_{p_g}$  Specific heat of burned gases

$m_{comb}$  Fuel flow rate

And on the other hand, the heat provided by combustion is given by:

$$Q_{cc} = \dot{m}_c \cdot PCI_m \cdot \eta_{cc} \quad III.7$$

The temperature  $T_3$  is fixed, so each time we will calculate the air/fuel ratio corresponding to the initial conditions to maintain this temperature value. In our study, the temperature  $T_3$  is  $966^\circ\text{C}$ .

**•Evolution 3-4 (HP and LP Turbines):**

We will determine the exhaust gas temperature  $T_4$ , the turbine power, and the useful work (useful power):

**HP Turbine exhaust temperature:**

The relationship that describes the polytropic expansion is as follows:

$$\frac{T_3}{T_4} = \tau_{HP} \left( \frac{k-1}{k} * \eta_T \right) \Rightarrow T_4 = \frac{T_3}{\tau_{HP} \left( \frac{k-1}{k} * \eta_{pT} \right)} \quad III.8$$

$\tau_{HP}$  wheel expansion ratio

$\eta_{pT}$  the polytropic efficiency of turbine

$$\tau_{HP} = \frac{P_3}{P_4} \quad \text{with } P_3 = P_2 - dP$$

dP pressure drop at the combustion chamber (dP=0.1bar) .

P4 is the exhaust pressure.

$$P_4 = P_1 + dP \quad (\text{for } dP = 0.1 \text{ bar})$$

$\eta_T$  turbine efficiency ( $\eta_T = 0,86$ )

$T_4$  exhauste Temperature

k Polytropic coefficient of burned gases

**HP Turbine power:**

The mass flow rate of the intake air does not pass entirely through the combustion chamber, approximately 10% of the flow rate is used for bearing cooling plus leaks.

$$P_T = (\dot{m}_{air} * 0,9 + \dot{m}_c) \cdot Cp_g \cdot (T_3 - T_4) \quad III.9$$

**Useful power (to drive the load):**

This is the difference between the power delivered by the turbine and the power absorbed by the compressor.

$$P_U = P_T - P_C \quad III.10$$

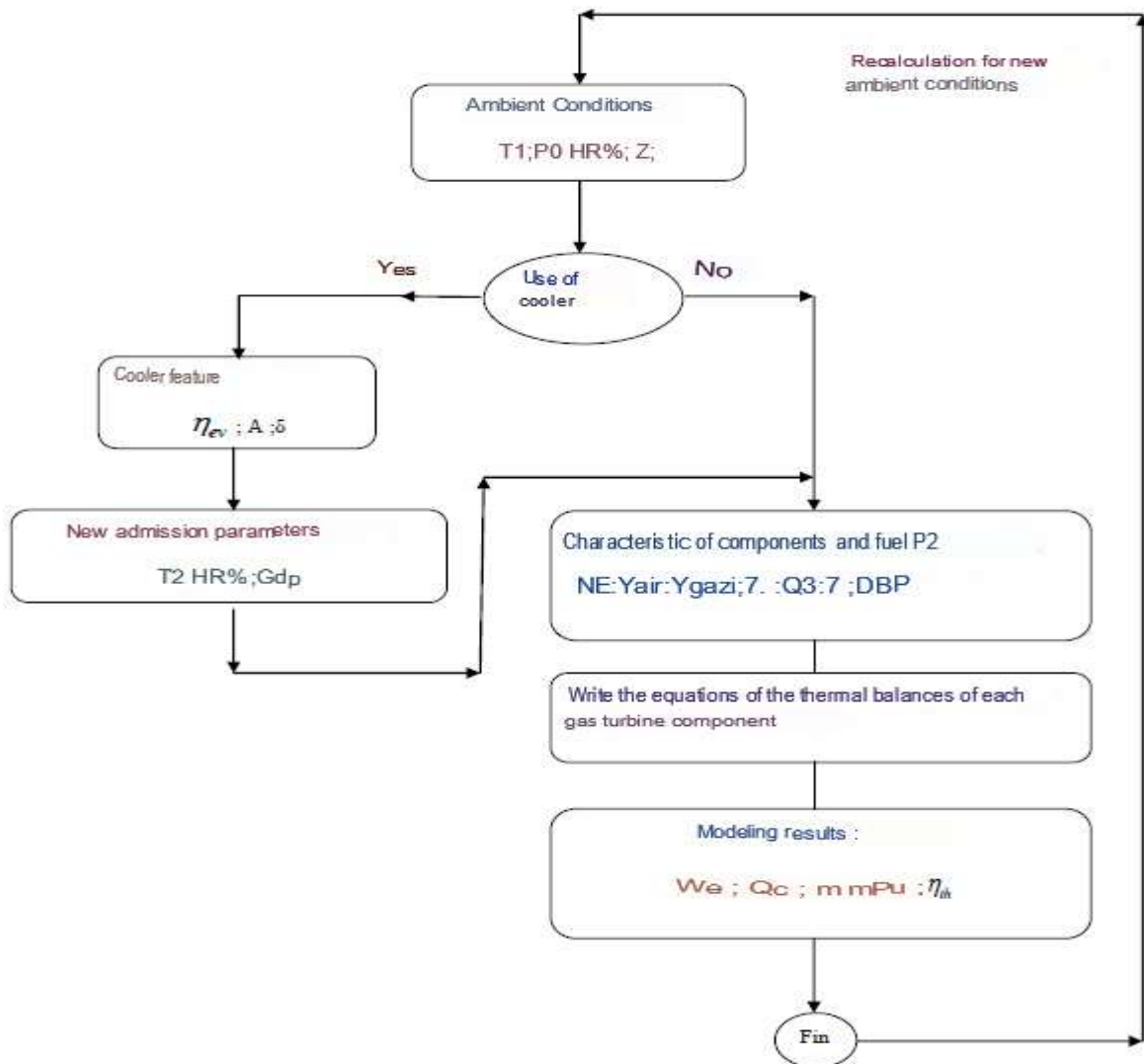
**Thermal efficiency of the gas turbine:**

The thermal efficiency of the gas turbine is the ratio between the net power and the heat provided by combustion.

$$\eta_{th} = \frac{P_u}{\dot{m}_{comb} * PCI} \tag{III.11}$$

All the necessary equations for modeling are introduced under a software called Engineering Equation Solver. This software provides all the physical properties of air based on temperature and pressure. The following flowchart shows the approach followed for modeling:

HR% humidité relative



**III-4.2 Results and interpretation:**

According to the analysis of the meteorological data collected during our internship in the gas zone of Hassi R'mel, we found that air humidification during the day is favorable because in this area, during the night, the ambient temperature decreases and the relative humidity increases.

**•Inlet temperature:**

Figure (III-6) shows the variation in intake temperature throughout the studied year during the day, where two curves are plotted. The red color represents the temperature variation without the use of a cooling system, and the blue color represents the case where the cooler is taken into account. The red curve is plotted based on data collected at the site where the gas turbine is installed (control room readings of the GT).

It is clear that the temperature is high in summer, reaching 40°C, and it is below 15°C (ISO temperature) only in the first two months of the year. This shows the need to cool the intake air. Finally, the blue curve in Figure (III-8) represents the variation in gas turbine intake temperature when the evaporative cooler is used. This allows the intake temperature to be lowered, resulting in a decrease in specific compression work. It can be observed that the gap between the two curves widens when the ambient temperature is higher, indicating that the cooling system is more effective in hot regions.

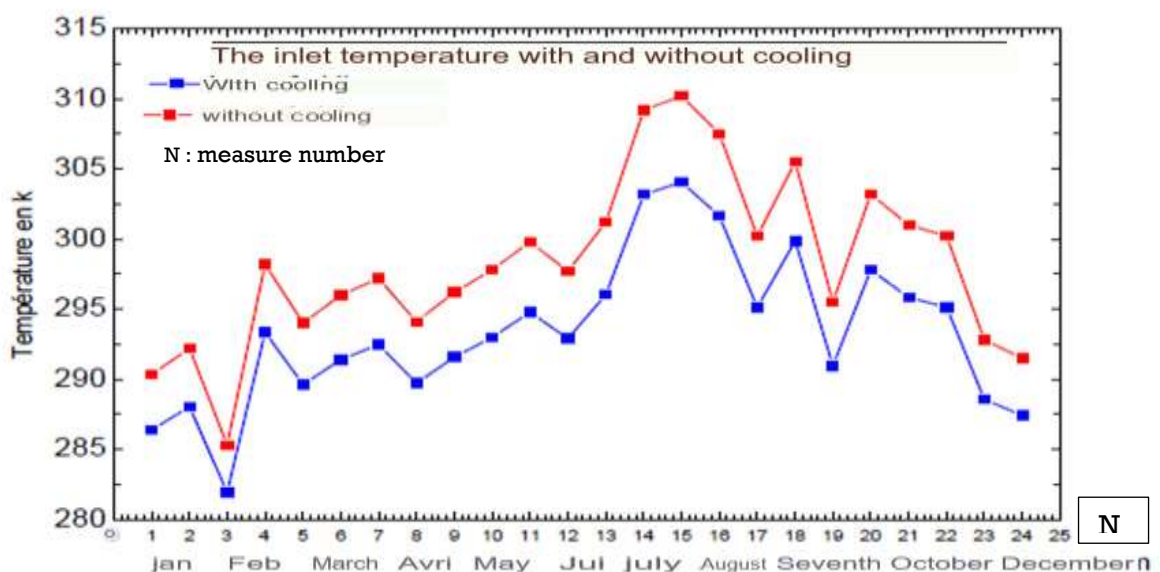


Fig. III-.6: Modeling result showing the variation in intake temperature with and without intake air cooling.

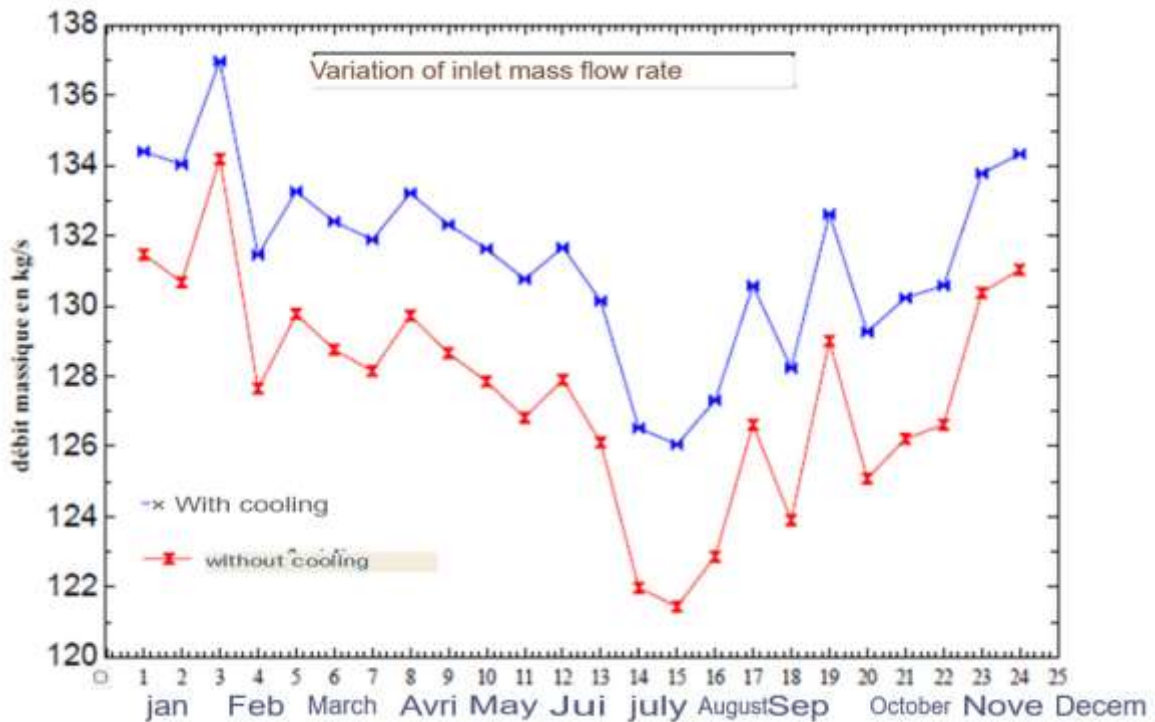


Fig. III-7: Modeling results showing the variation in intake mass flow with and without intake air cooling.

The mass flow rate of the intake air varies depending on its density. It can be observed that the flow rate is inversely proportional to the ambient temperature, where it is low in summer when the temperature is high. On the other hand, the cooling system used allows a certain amount of water to evaporate into the air, resulting in a slightly lower intake temperature and a better mass flow rate compared to the conventional case

### **Specific compression work:**

The specific work absorbed by the compression is calculated by the difference in enthalpies between the intake and discharge of the compressor. The obtained results are represented in Figure (III -8).

It can be observed that the compression work for 1 kg of air is proportional to the intake temperature, reaching 290 kJ/kg of air when the intake temperature is maximum. However, in the case where the intake air is cooled, the compression work decreases by 10 kJ/kg of air.

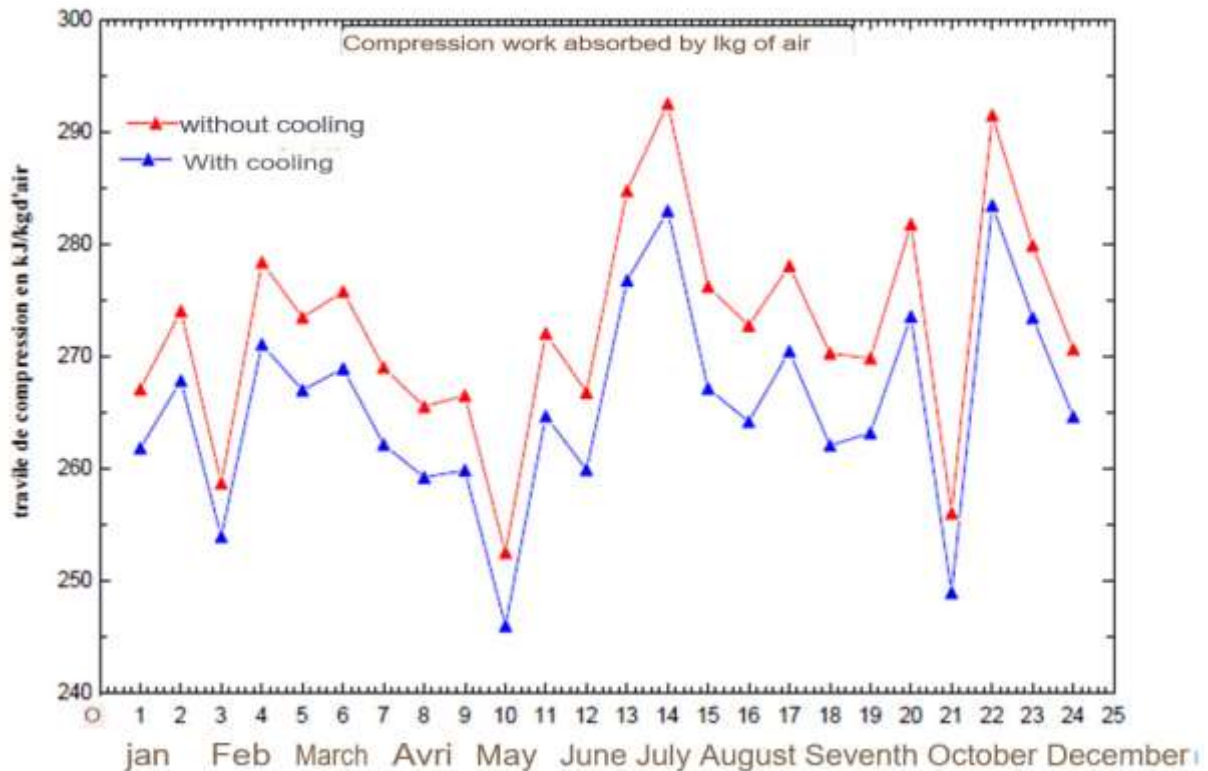


Fig. III-8: Modeling results showing the variation in specific work throughout the year with and without intake air cooling.

#### Mass flow rate of fuel to air ratio:

The fuel flow rate is not always constant; it varies depending on the mass flow rate of the air. The combustion thermal balance allows calculating the fuel flow rate and the air/fuel ratio for a constant turbine intake temperature. The MS5002c machine operates at a temperature of 966°C. The variation in fuel mass flow rate in the two studied cases (with and without intake air cooling) is represented in Figure (III-8).

The figure shows that the fuel flow rate varies between 2.15 and 2.55 kg/s. Its value is lower than that consumed when the intake air is cooled (2.45 to 2.8 kg/s), which is logical because when the air is cooled, the mass flow rate increases and the discharge temperature decreases. Even the air/fuel ratio is higher when the air is cooled (from 2.03 to 2.15%) compared to the conventional case (1.94 to 2.11%), but with a small variation.

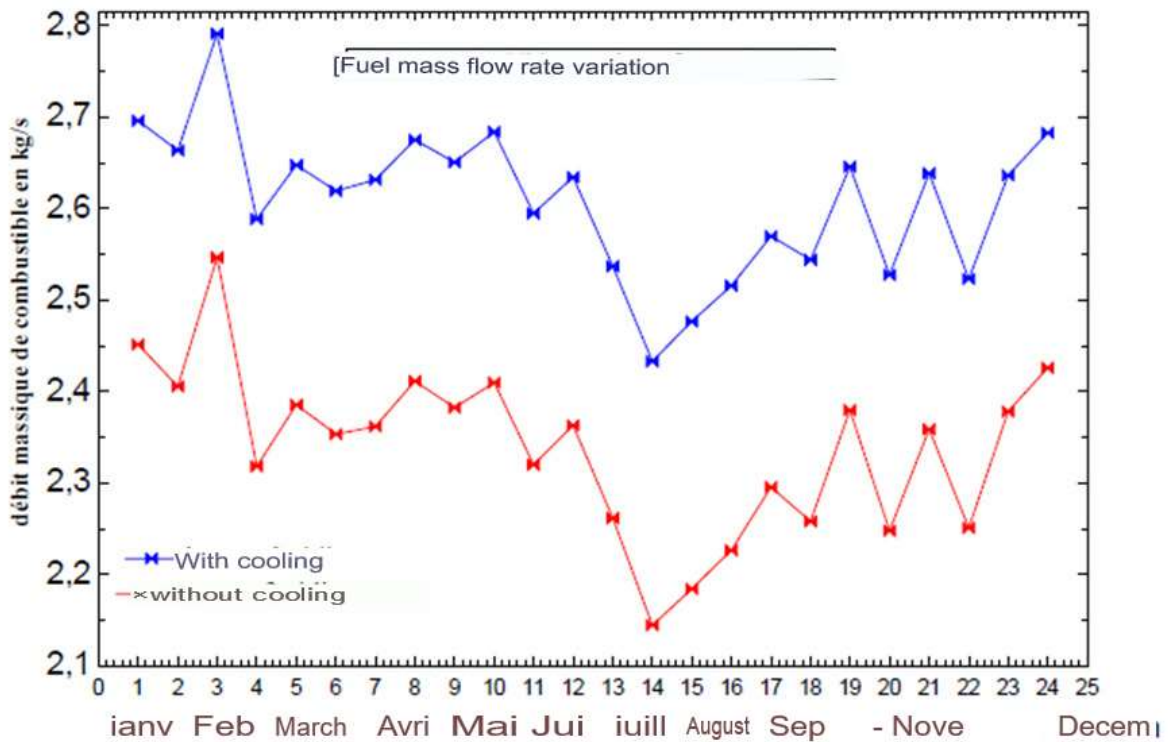


Fig. III -9: Modeling results showing the variation in fuel flow rate throughout the year with and without intake air cooling.

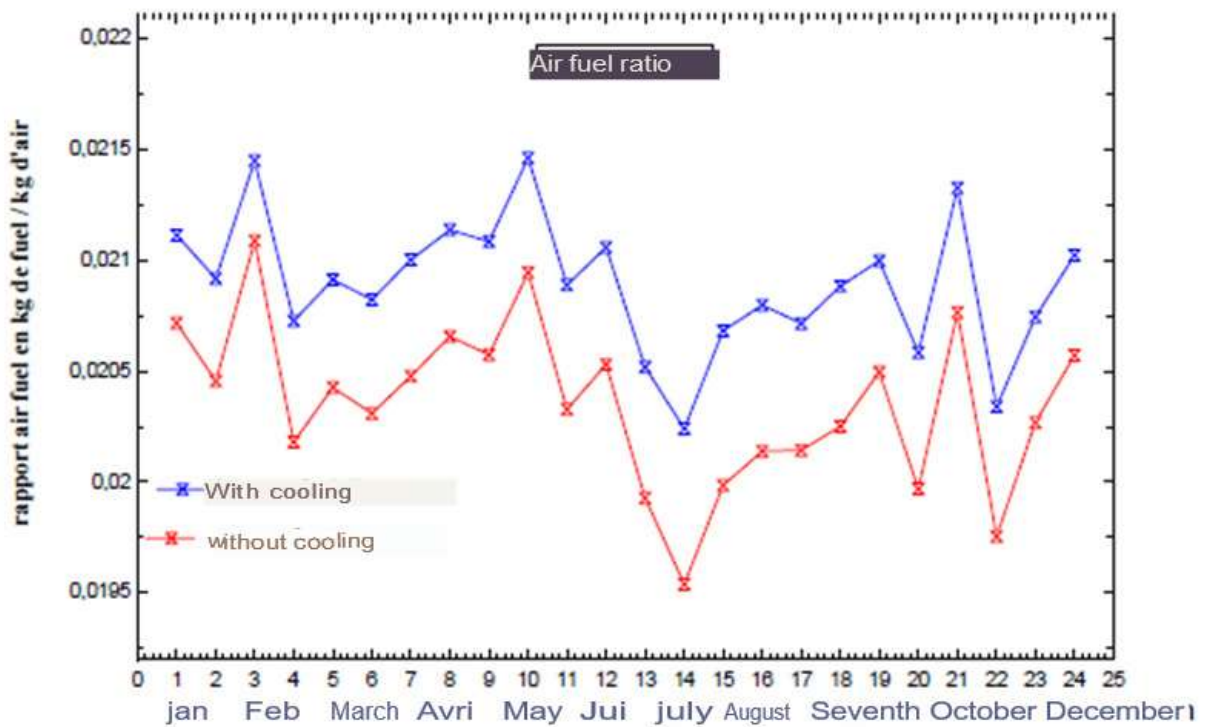


Fig. III -10: Modeling results showing the variation in air/fuel ratio throughout the year.

Figure (3.10) represents the variation in fuel consumption to produce 1 kW of net power.

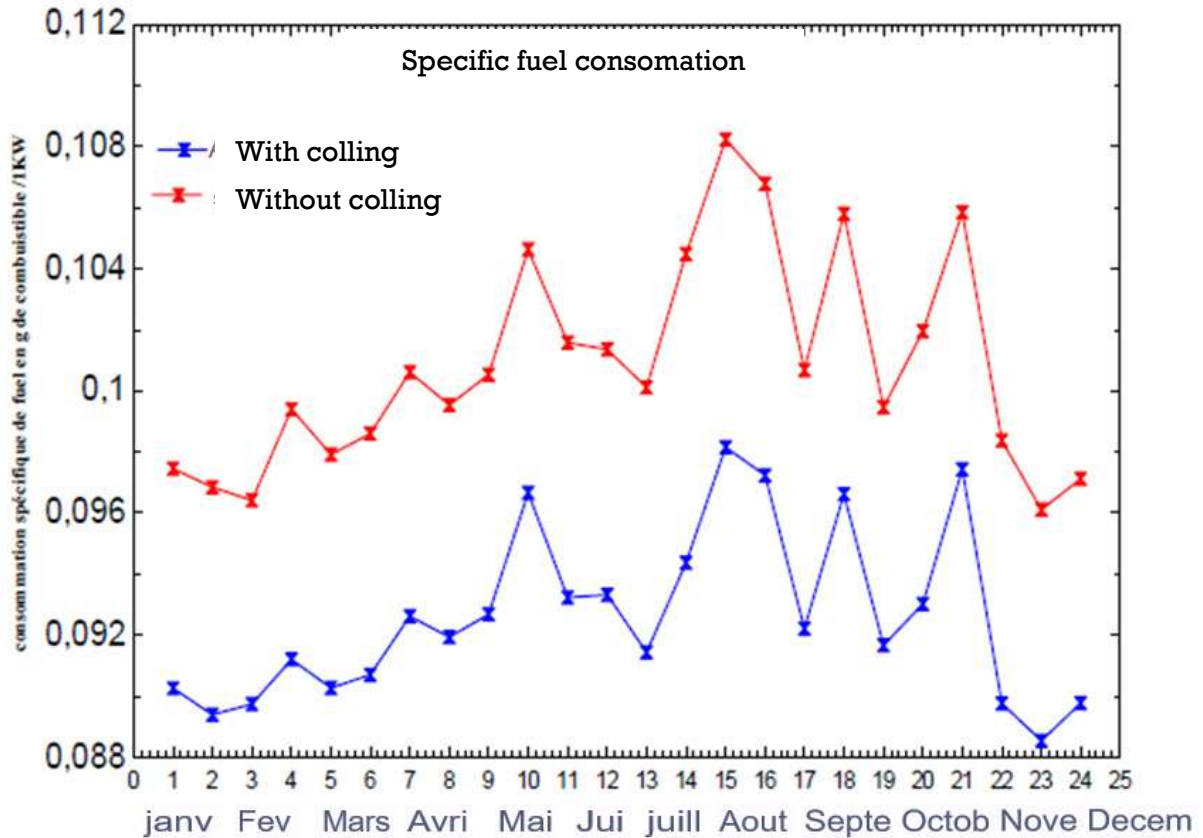


Fig. III -11: Modeling results showing the variation in specific fuel consumption.

According to the figure, the fuel mass for 1 kW of power is lower when the air is cooled.

Exhaust mass flow rate.

In a gas turbine installation, the admitted air flow does not pass entirely through the combustion chamber. A quantity of air is used for bearing cooling, and another quantity is lost due to leaks. In our case, according to the catalog provided by the gas turbine manufacturer MS5002c, this value is around 10% of the admitted flow.

Figure (III -12) shows the variation of the exhaust mass flow rate throughout the year.

It can be observed that the exhaust flow rate is lower in summer, but with the cooling system, it is increased by a value that can reach 10 kg/s.

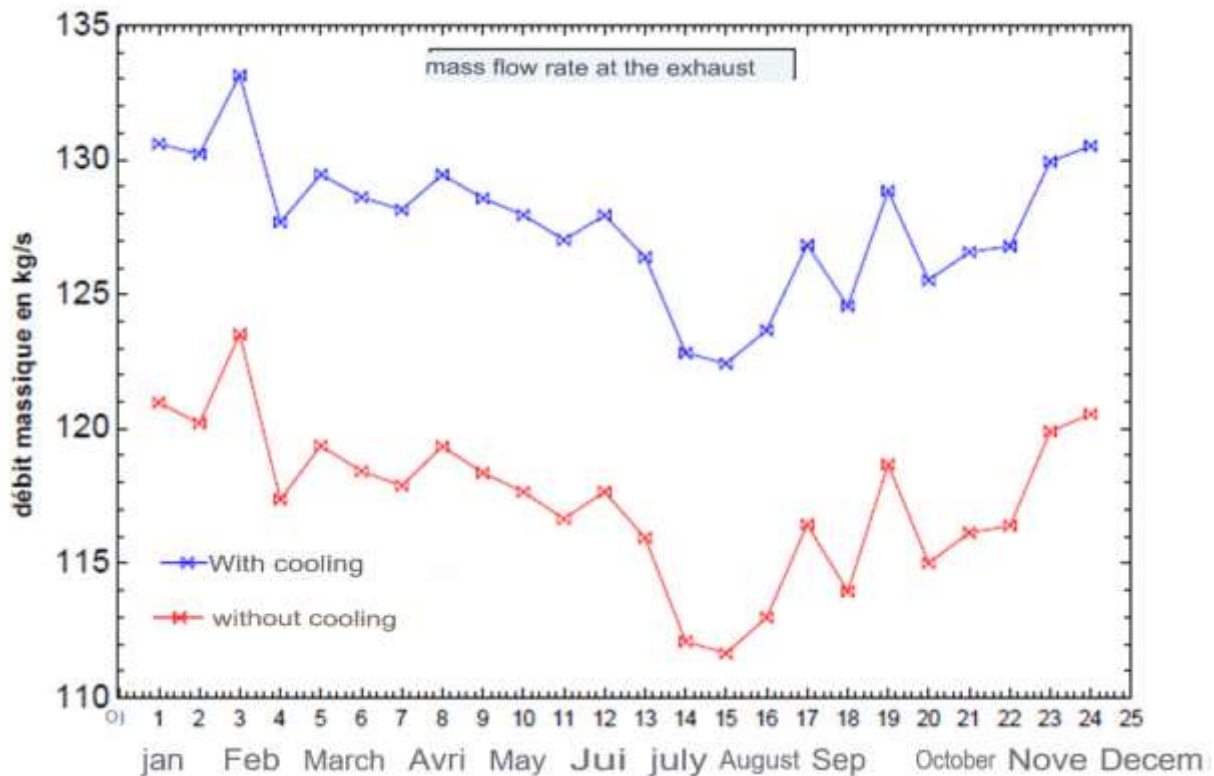


Fig. III -12: Modeling results showing the variation of the exhaust mass flow rate throughout the year with and without admission air cooling.

• **Useful power produced:** It is clear from Figure (III -12) the influence of the admission temperature on the power produced. Similarly, it can be noticed that the power is higher when the cooling system is used. This increase is caused by two parameters: the increase in mass flow rate due to water evaporation and the decrease in specific compression work due to the lowering of the admission temperature.

During the studied year, the net power gains of the studied gas turbine installation vary between 4.654 MW and 5.25 MW (see Figure [III -13]), which allows for additional load.

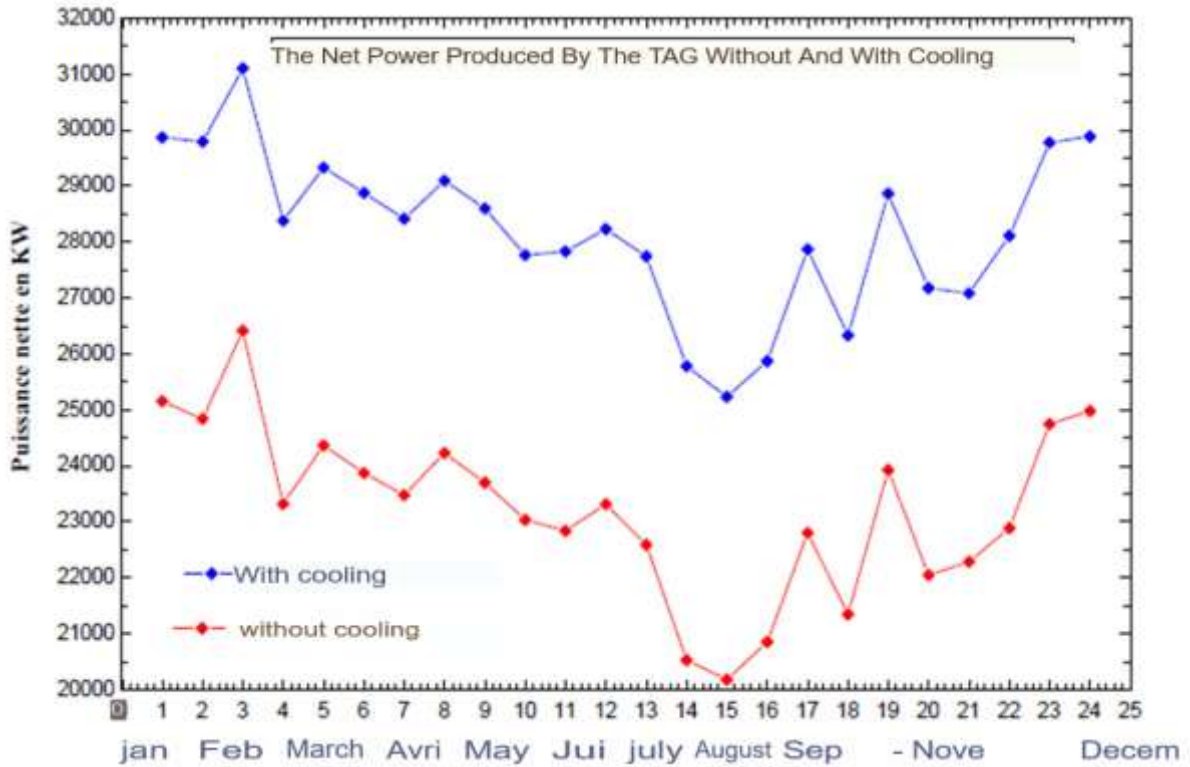


Fig. III -.13: Modeling results showing the variation of the net power throughout the year.

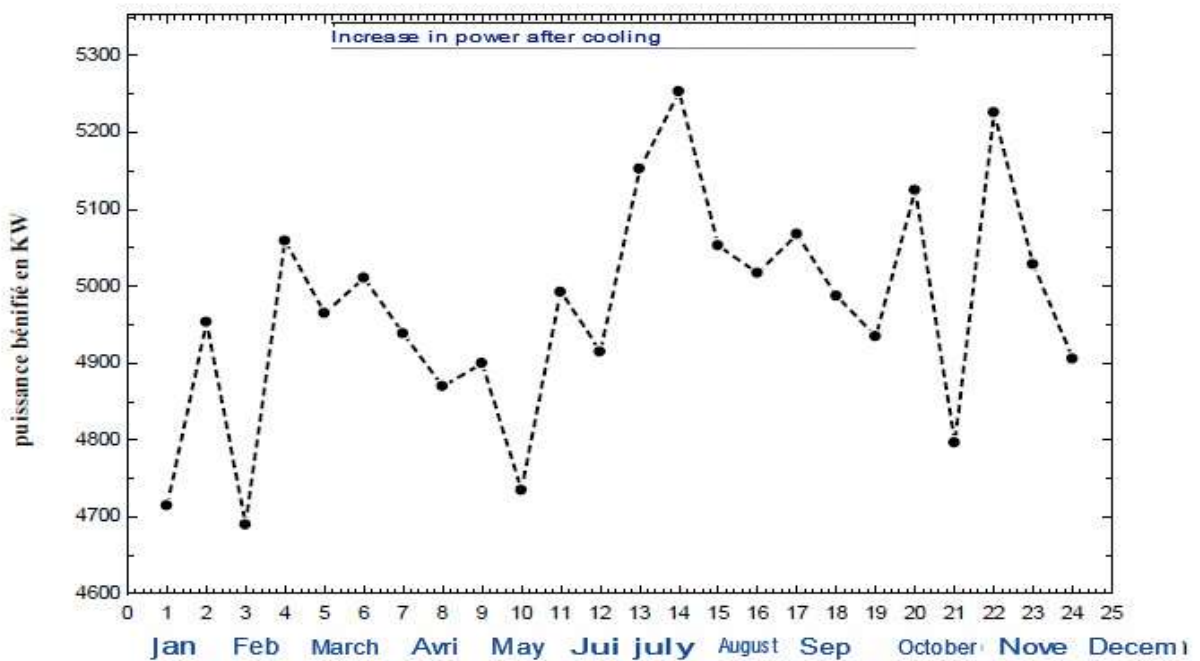


Fig. III -14: Modeling results showing the increase in net power throughout the year due to admission air cooling.

• **Thermal efficiency of the installation:**

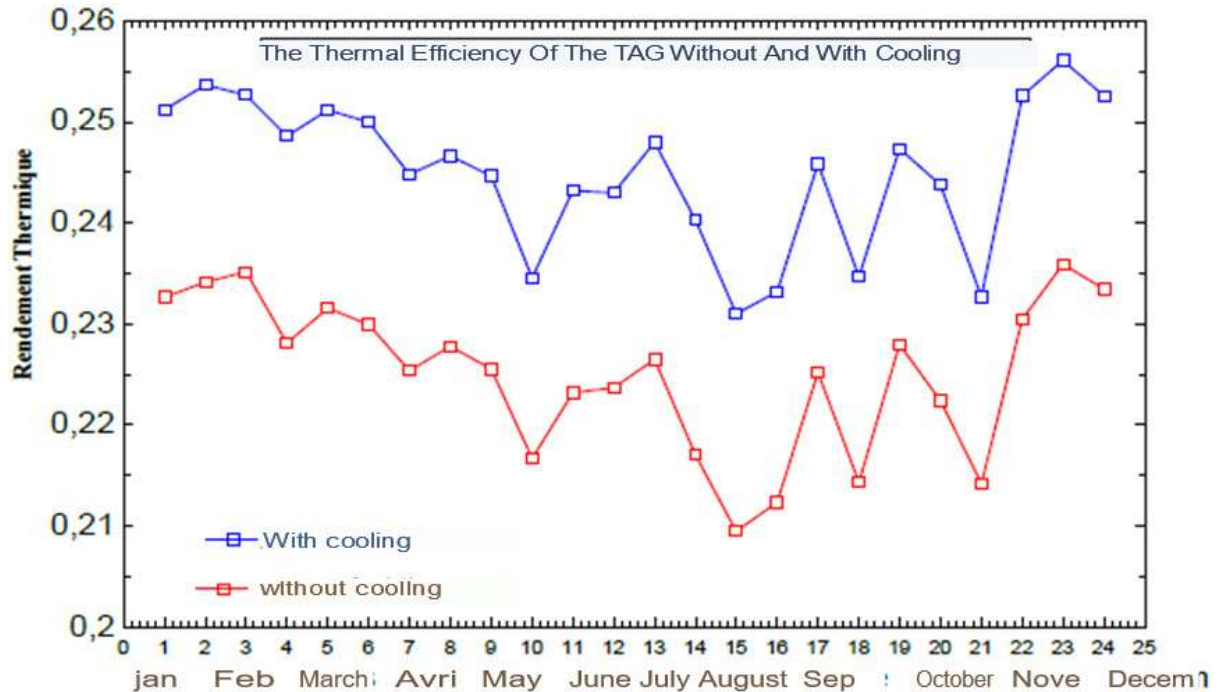


Fig. III -15: Modeling results showing the variation of the thermal efficiency of the installation.

The efficiency of this gas turbine varies between 20% and 23% throughout the year, as shown in Figure (III -15) (red curve). However, when the air is cooled at the admission, the efficiency improves (blue curve).

The increase in efficiency varies within a range of 1.7% to 2.4%. The results are represented in Figure (III -16).

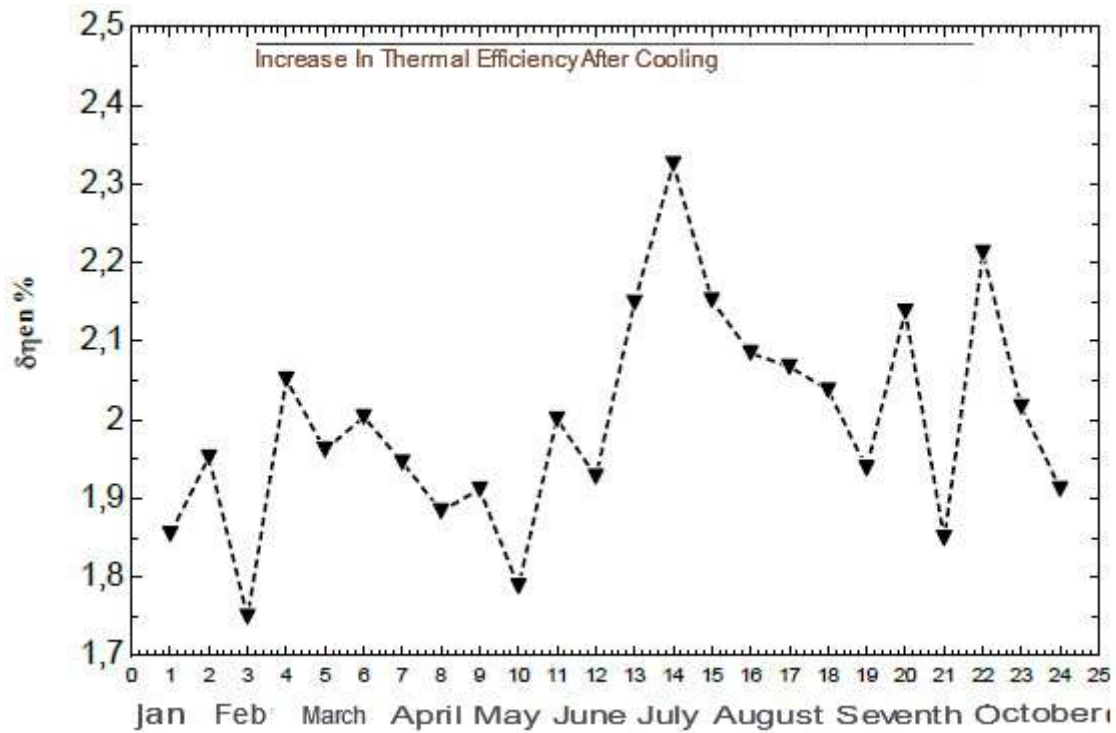


Fig. III -16: Modeling results showing the increase in thermal efficiency throughout the year due to admission air cooling.



# General Conclusion

### Conclusion:

Gas turbines are used worldwide for electricity generation in thermal power plants and in the hydrocarbon industry. They are installed in different geographical locations with varying temperature, pressure, and relative humidity conditions.

Gas turbines are highly sensitive to changes in ambient air temperature. Therefore, it is important to make the turbines used in the southern Algerian conditions insensitive to variations in ambient air temperature.

The gas turbine cycle is a very flexible cycle, such that its performance can be improved by adding additional components to the installation.

In recent years, a lot of research has been conducted in this field, including advanced gas turbine cycles such as steam-injected gas turbine cycle, humid air turbine, heat exchanger cycle, etc. The main objective of these investigations has been to increase the thermal efficiency of the gas turbine.

This work describes a theoretical analysis of the influence of ambient temperature on gas turbine performance. To this end, several air cooling techniques applied in a gas turbine cycle that increase the mass flow rate at the inlet, allow for some improvement in the performance of the gas turbine installation. This study has provided us with a good insight into the cooling efficiency of the gas turbine inlet air.

For this purpose, we have taken the characteristics of the GE MS5002 gas turbine, widely used in the oil industry as an application machine.

We have chosen the water spray cooler to cool and humidify the inlet air at the same time because this system is adaptable to hot and dry areas, such as the Hassi R'mel area (Saharan zone).

The modeling results show that the water spray cooler conditions the air before it enters the compressor. The presence of the cooling system reduces the ambient air temperature and increases the density (thus the mass flow rate), which directly influences the improvement of the performance (power output, thermal efficiency) of the studied gas turbine installation.



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**Annex:**

Specific heat capacity of air:

Specific heat capacity of gas: for calculating the specific heat capacity of burned gases, the relationship given by M. Alhazmy and Y.S.H. Najjar [21] was used.

$$C_{pg} = 1.0887572 * 10^3 - 1.4158834 * 10^{-1}T \\ + 1.916059 * 10^{-3}T^2 - 1.2400934 * 10^{-6}T^3 \\ + 3.0669459 * 10^{-10}T^4 - 2.6117109 * 10^{-14}T^5$$

**1) Calculation of isentropic efficiency of the compressor:**

The isentropic efficiency of the compressor according to M. Alhazmy and Y.S.H. Najjar [21] is given by the following empirical relationship:

$$\eta_c = 1 - \left( 0.04 + \frac{r_c - 1}{150} \right)$$

*r<sub>c</sub>* Compression ratio

**2) Calculation of isentropic efficiency of the turbine:**

The isentropic efficiency of the compressor according to M. Alhazmy and Y.S.H. Najjar [22] is given by the following empirical relationship:

$$\eta_t = 1 - \left( 0.03 + \frac{r_c - 1}{180} \right)$$

**Polytropic efficiency:**

The spreadsheet demonstrates the polytropic efficiencies of compressors and turbines for different generations of gas turbines.

<b>technological Level of GT</b>	<b>Temperature at Turbine Inlet °C (K)</b>	<b>Number of Cooled Stages</b>	<b>Polytropic Efficiency of Compressor</b>	<b>Polytropic Efficiency of Turbine</b>
5th Generation	1500 (1773)	3	0.91	0.89
4th Generation	1300 (1573)	2	0.90	0.89
3rd Generation	1100 (1373)	1	0.87	0.88
2nd Generation	900 (1173)	1	0.81	0.88
1st Generation	700 (973)	-	0.74	0.85

ملخص :

**العنوان : تحسين كفاءة التوربينات الغازية بتبريد هواء السحب**

**المؤطر: عبد المعز أحمد**

**الطالب :. جدّاه المحمّد**

يعد تبريد مدخل الهواء التوربيني أحد الأساليب التجارية المتاحة لتحسين كفاءة التوربينات الغازية الحالية. تحتوي الطريقة على العديد من التكوينات التي يمكن استخدامها لجميع توربينات الغاز المثبتة تقريبًا. يصف هذا العمل التحليل النظري لتأثير درجة الحرارة المحيطة على أداء توربينات الغاز. تحقيقًا لهذه الغاية ، تسمح العديد من تقنيات تبريد الهواء المطبقة في دورة التوربينات الغازية التي تزيد من معدل تدفق الكتلة في المدخل ، لتحسين بعض أداء تركيب التوربينات الغازية. لقد زدنا هذه الدراسة بنظرة جيدة حول كفاءة التبريد في هواء مدخل التوربينات الغازية. تُظهر نتائج النمذجة أن برودة رش الماء تبرّد الهواء قبل أن يدخل الضاغط. يقلل وجود نظام التبريد من درجة حرارة الهواء المحيط ويزيد من الكثافة (وبالتالي معدل تدفق الكتلة) ، مما يؤثر بشكل مباشر على تحسين الأداء (إخراج الطاقة ، والكفاءة الحرارية) لتركيب توربينات الغاز المدروسة.

**الكلمات المفتاحية : مدخل الهواء التوربيني , توربينات الغاز , الضاغط**

**Abstract :**

**Title Enhancement of Gas Turbine Efficiency by Intake Air Cooling**

**Student : M'Hammed Djeddah Supervisor Ahmed Abdelmouiz**

Turbine air inlet cooling is one of many available commercial methods to improve the efficiency of an existing gas turbine. The method has various configurations which could be utilized for almost all installed gas turbines. This work describes a theoretical analysis of the influence of ambient temperature on gas turbine performance. To this end, several air cooling techniques applied in a gas turbine cycle that increase the mass flow rate at the inlet, allow for some improvement in the performance of the gas turbine installation. This study has provided us with a good insight into the cooling efficiency of the gas turbine inlet air. The modeling results show that the water spray cooler conditions the air before it enters the compressor. The presence of the cooling system reduces the ambient air temperature and increases the density (thus the mass flow rate), which directly influences the improvement of the performance (power output, thermal efficiency) of the studied gas turbine installation.

**Key Words : Turbine air inlet cooling, Gas Turbine , Compressor**

**Résumé:**

**Titre ... Amélioration de l'efficacité des turbines à gaz par le refroidissement de l'air d'admission**

**Etudiant : M'Hammed Djeddah Encadreur Ahmed Abdelmouiz**

Le refroidissement de l'entrée d'air de la turbine est l'une des nombreuses méthodes commerciales disponibles pour améliorer l'efficacité d'une turbine à gaz existante. La méthode a diverses configurations qui pourraient être utilisées pour presque toutes les turbines à gaz installées. Ce travail décrit une analyse théorique de l'influence de la température ambiante sur les performances de la turbine à gaz. À cette effet, plusieurs techniques de refroidissement de l'air appliquées dans un cycle de turbine à gaz qui augmentent le débit massique à l'entrée, permettent une certaine amélioration des performances de l'installation de la turbine à gaz. Cette étude nous a fourni un bon aperçu de l'efficacité de refroidissement de l'air d'entrée de turbine à gaz. Les résultats de la modélisation montrent que le refroidisseur de pulvérisation d'eau conditionne l'air avant son entrée dans le compresseur. La présence du système de refroidissement réduit la température de l'air ambiant et augmente la densité (donc le débit massique), ce qui influence directement l'amélioration des performances (puissance de puissance, efficacité thermique) de l'installation de la turbine à gaz étudiée.

**Mots Clés: refroidissement de l'entrée d'air de la turbine ; Turbine à Gaz, Compresseur**