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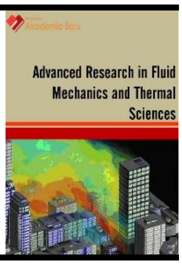

Study of The Performance of The Gas Turbine Power Plants From The Simple To Complex Cycle: A Technical Review

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Thamir Khalil Ibrahim[1,*] , Mohammed Kamil Mohammed[1], Wadhah Hussein Abdulrazzaq Al Doori[1], Ahmed Tawfeeq Al-Sammarraie[3], Firdaus Basrawi[4]

[1] Department of Mechanical Engineering, Tikrit University, Tikrit, Iraq
[2] Department of Mechanical and Nuclear Engineering, University of Sharjah, United Arab Emirates
[3] Department of Mechanical Engineering, University of California, Riverside, CA 92521, USA
[4] Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pahang, Malaysia

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ABSTRACT

In this study, a comprehensive review of previous studies on GT power plants was conducted. The recent decades have witnessed several studies on the modelling and simulation of GT performance. This review concentrated on a simple cycle GT power plant (GTPP) with a 2-shaft, regenerative, reheat, intercooler, complex cycle GT with effect intercooler, regenerative and reheat. Further reviews focused on the influence of operating conditions on the performance of GTPP with more emphasis on the complex and simple cycles of the GT. Finally, the technical review focused on the improvement of the performance of the GTPP. However, information can be found on the assessment of the performance of GTPPs, especially, for GTPP operation in both ambient conditions and complex configurations. This review adopted a systematic approach to ensure that this study can be conducted properly to contribute to the existing information in this field.

Keywords:
Gas turbines, power plant, strategy, intercooler, regenerative, reheat

1. Introduction

The first gas turbine built in 1903 by Aegidius Elling, a Norwegian, using rotary dynamic compressor and turbines marked the beginning of GT. This effort was credited with the building of the first GTPP that produced about 8kW [1]. This design was further improved by Elling in 1904 to operate at about 20 000 rpm and achieve about 33kW with an exhaust gas temperature of 773 K from the previous 673 K [2]. A practical GT was successfully built in 1905 by The Societe Anonyme des Turbomoteurs French Company when they assembled a GT [3,4]. At first, this engine was built to operate at constant pressure and under its own power, with an efficiency of 3%; the input to the machine was the fuel while useful shaft power was the output [1,5,6]. The engine was also built with a multistage centrifugal compressor of 20 or more stages, compressor efficiency of <60 %, pressure ratio of 4, and turbine inlet temperature of approximately 393ºC [2,7-9]. However, several years

* *Corresponding author.*
E-mail address: thamirmathcad@yahoo.com (Thamir Khalil Ibrahim)

passed (until in 1939) before the establishment of a Brown Boveri (BBC) unit in Neuchatel, Switzerland, for emergency electric power supply. The efficiency of this unit was about 18% with an output of 4,000 kW. The first ever gas turbine set built with a single combustor is depicted in Figure 1. This unit operates at a turbine inlet temperature of 550ºC, rotating at 3000 rpm, and generating about 15,400 kW. Out of this generated power rating, about 11000 kW were used to power the compressor of the system at an ambient temperature 20ºC [10-13].

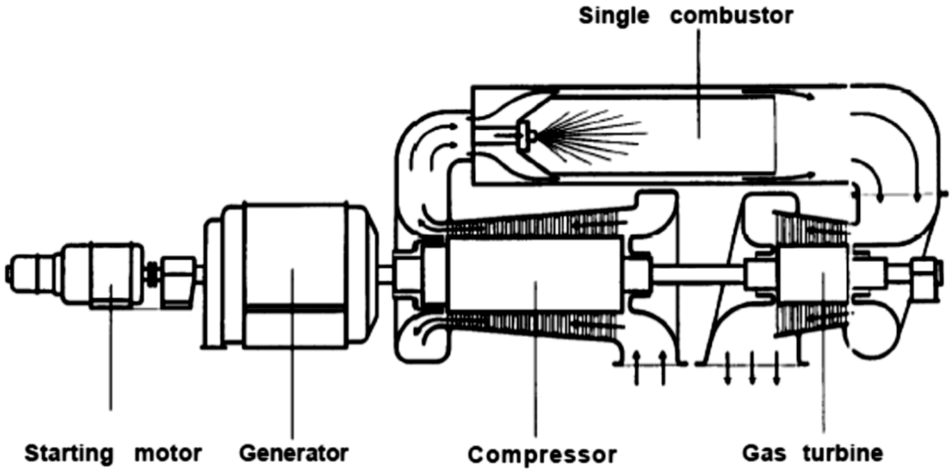


Fig. 1. The first ever built industrial GT set with a single combustor

In 1949, the first electric utility gas turbine built by General Electric (GE) Company as a part of a CCGT plant was installed in Oklahoma (USA) [1,14,15] with a power rating of about 3.5 MW. Until the mid-70s, the efficiency and reliability of this system were consistently low and poor [16,17]. In the 1990s, GE manufactured GTs with a pressure ratio of 13.5, power rating of 135.7 MW, and thermal efficiency of 33 % under a normal cycle operation. Recently, GE manufactured a GT that produced power of up to 300 MW at a turbine inlet temperature of 1425ºC and a thermal efficiency 40 % under a normal cycle mode [18-21].

Recently, industrial mechanical power has been mainly produced from GTs in various industries; GT power has also been used in other power-driven activities such as driving of loads generators, propellers, process compressors, and pumps [22-24]. Initially, GT evolved as a relatively simple engine but has recently become a complex and dependable prime mover with high-efficiency [3, 25-27]. In most industries (such as in civil and military aviation, oil and gas production, and power generation), profitability depends on the performance and reliability of GTs [2,7]. The recent advancements in GTs have seen the compressor pressure ratio s increased from about 4:1 to more than 40:1, power output to around 350MW, operating temperatures of about 1800 K, and thermal efficiencies of >40 % [28,29].

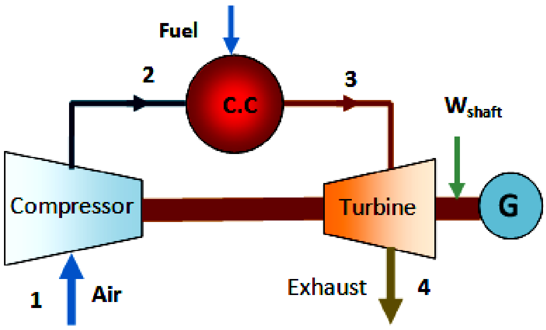
2. Classification of Gas Turbines

Different arrangements of the GT components have developed in the past. Some of these arrangements are appropriate for power generation and the others used to mechanically drive applications such as compressors and pumps [2]. In this section, GT was classified based on the working cycle, components arrangements, and the field of application as follows:

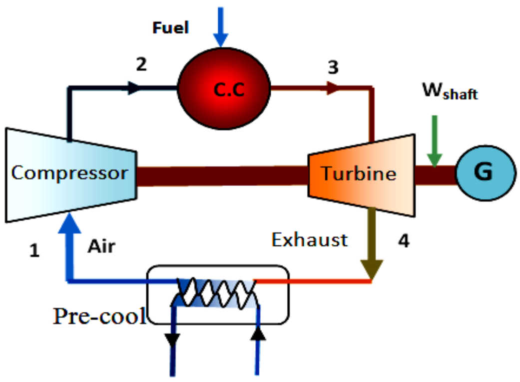
2.1 Based on the Working Cycle

For CCGT and basic GT units, open cycle is the commonly used cycle. In this system, fresh air is continuously drawn into the circuit through an air compressor while energy is supplied to the system from the burning of fuel in the combustion chamber [30-32]. The waste gases and other products of the combustion process are expelled from the system into the air through the turbine as depicted in Figure 2(a) [6,33-35].

As in the open cycle of a GT, gases or working fluids are repeatedly circulated through the machine. The required energy in the system is added to a heat recovery while an auxiliary fan supplies the air required to burn the fuel [36-38]. Typically, the closed cycle of a GT resembles that of an ST plant by virtue of the gases produced from the combustion process not directly moving through the turbine as depicted in Figure 2(b) [39,40].



(a) Open cycle



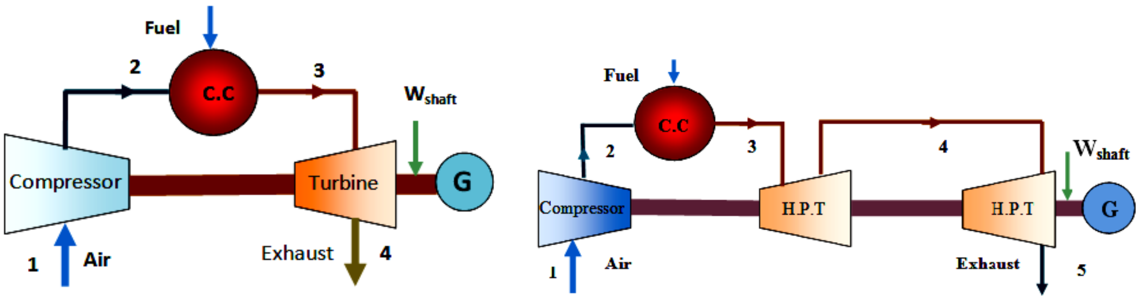
(b) Close cycle

Fig. 2. Simple gas turbine cycles

2.2 Based on the Components Arrangement

As depicted in Figure 3, GTs can be designed based on either a single or two-shaft arrangement. The compressor and turbine of a single shaft gas turbine (SSGT) are both driven on a common shaft connected to a driver [41-43]. For the two-shaft or split shaft GT, a common shaft drives the compressor and the turbine while another shaft drives the free power turbine [44,45]. In this arrangement, the rotational speed of both shafts may vary to ensure a large extent of load control flexibility [31,46-48]. Often, the set comprised of the compressor, the combustion chamber, and the compressor-turbine in the split-shaft arrangement is usually referred to as the gas generator [40,49]. In the SSGT power plant, the compressors directly deliver compressed air into the combustion chamber for subsequent heating and mixing with the products of the combustion process at relatively constant pressure [50-54]. On entering the turbine of the GT, the hot gas expands and get expelled to the immediate environment via a chimney (Figure 3 (a)) [55,56]. About 60 % of the turbine power output from a GT plant is utilized by the compressor [10,13,57] while the rest is used to either power the generator or lost to the environment with the expelled gases [11,58].

When there is a need for load control flexibility, the two-shafts GTPP is deployed, such as in driving a road vehicle or the marine propeller as depicted in Figure 3(b) [33,59]. In this type of GT, the compressor is driven by a high-pressure turbine while the generator of the GT plant is driven by a low-pressure turbine [60-63]. A significant advantage of this system is that it can be started with ease compared to the SSGT plant while its drawback lies in the rapid shedding of electrical load which can cause the turbines to over-speed rapidly [64-66].



(a) Single shaft gas turbine (b) Two shaft gas turbine

Fig. 3. The schematic representation of simple gas turbines

2.3 Based on the Field of Application

In terms of application, the aircraft industry accounts for the highest application of GTs as their ability to produce high-power output despite their low engine weight has made them the ideal propulsion system in aviation for both military and civilian purposes [67-69]. They have also found application as the ideal propulsion system in both ground armored and marine military equipment. The propulsion system of an aircraft is depicted in Figure 4 [70]. In the aviation field, a thermal jet engine is simply a jet propulsion device that depends on fuel combustion and air from its environment to produce the fluid jet used for propulsion purpose [71]. The period of the Second World War witnessed the basic development of jet engines when it was parallelly developed by Whittle and Von Ohain in England and Germany, respectively [1]. Gas turbine application in the aviation sector comes in many designs, including Turbojet, Turboshaft, Turboprop, Ramjet, Turbofan or bypass engines. The Turbojet is the most designed engine that resembles that of the basic cycle GT as it was designed to produce power that is just sufficient to power drive the compressor [68,72-74]. In this system, a high-velocity jet is produced by the expelled gas from the turbine which at a high temperature and pressure, expands to the atmospheric pressure in the propelling nozzle [75,76].

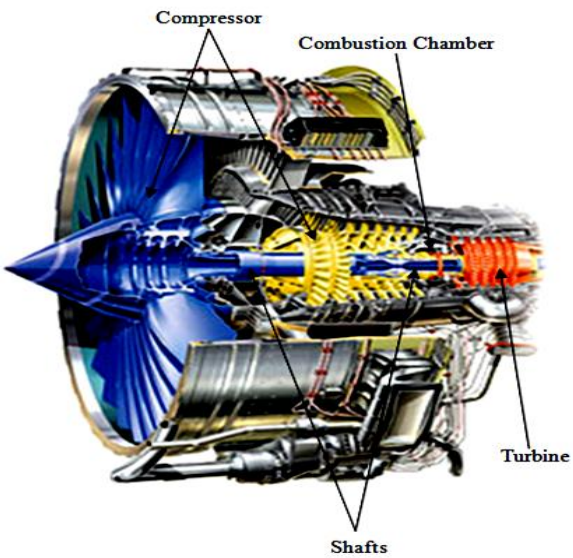


Fig. 4. Aircraft propulsion

Gas turbines for industrial application were designed after World War II but introduced to the public in the 1950s [77]. The design of the early heavy-duty GT design was to an extent an extension of the ST design; there was no consideration for weight and space in these early designs as they were comprised of heavy-wall casings split on horizontal centerlines, large-sized combustors, stators, and large frontal areas, sleeve bearing, as well as thick airfoil sections for blades [53,78]. An industrial plant is meant to serve a service life of approximately 100,000-200,000 h but this is not the case with the aviation GTs where there is a wastage of the kinetic energy of gases expelled from the turbine in a simple cycle due to the absence of a steam generator for heat recovery [79,80]. As depicted in Figure 5, the heavy-duty GT mainly use axial-flow turbines and compressors. Most of the U.S. designs use can-annular combustors while European designs utilize a single-stage side combustor [81]. A fixed or free power turbine is usually used to build GTs for industrial applications since their design is mainly based on the driven load [24,82]. Some are designed to directly drive loads (as in pipeline compressors or alternators) while some are designed to drive loads via gearbox reduction (a requirement for increasing the speed of power turbines) as found in marine propellers [83,84].

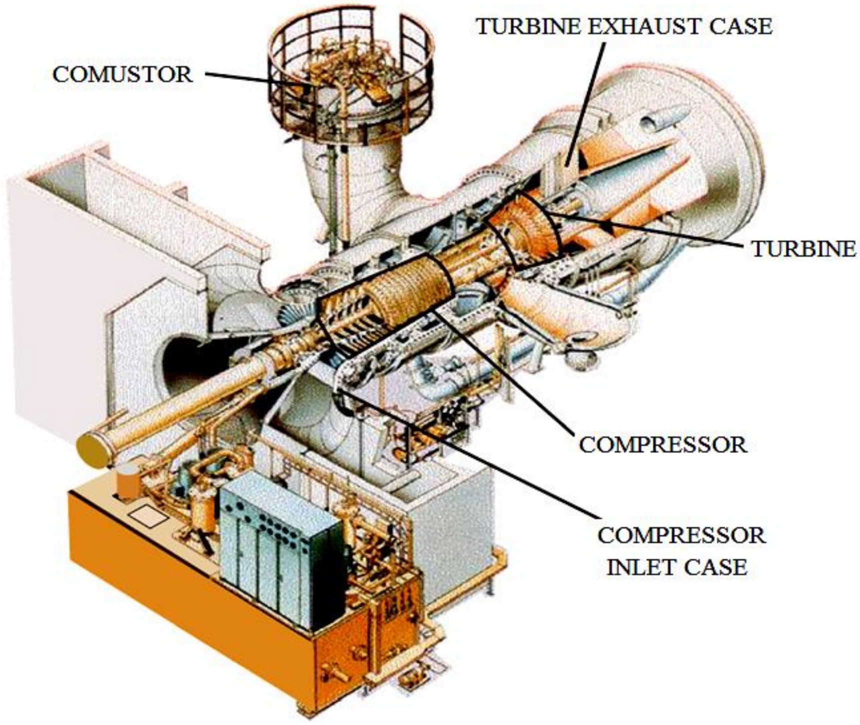
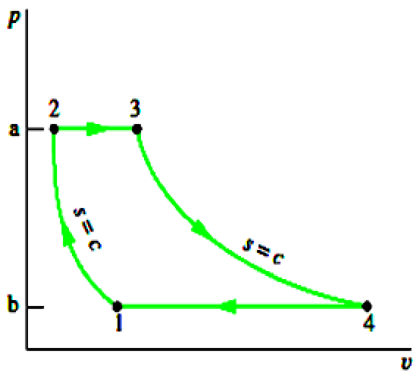


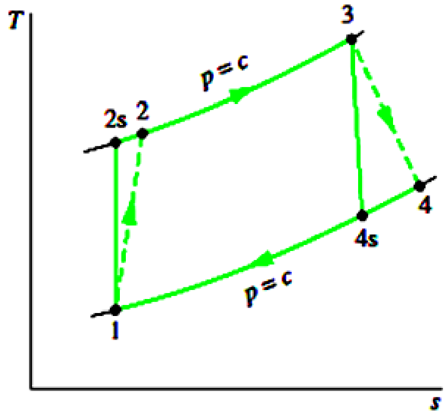
Fig. 5. An industrial-scale GTPP

3. Actual Gas Turbine Cycle

In the GT, an actual cycle comprises of the chemical reaction that occurs in the combustion chamber and the combustion processes that terminate in the production of high-temperature gases [85]. These processes are different from the reactants that increase the working fluids' enthalpy [86]. Although the compression processes in the axial flow and centrifugal compressors used in GTs are irreversible, they are adiabatic. A depiction of the expansion process in the GT turbines is presented in Figure 6. As a result of this irreversibility, there is a need to ensure that GTs are designed to increase the required work output to drive the compressor and withstand the mechanical losses in the drive [30, 87, 88].



(a)



(b)

Fig. 6. a) *p-v* and b) *T-s* diagrams of GTs

4. Gas Turbine Performance

In terms of performance, GT plants built in the 1940s had a simple-cycle efficiency of approximately 17 % as a result of low turbine and compressor isentropic efficiencies and low turbine inlet temperatures [2,89]. The applicability of GT plants was limited despite their versatility and ability to produce energy from different forms of fuel [90-93].

The determination of the performance of GTPPS and their components during the developmental stage has mainly been performed via experiments on the prototypes of the whole GTPP and its major components. However, this approach is not just expensive but time inefficient [94]. Moreover, GTs are meant to usually operate at full load conditions over a significant period of their service life; therefore, there is a need for a detailed study of their cycle performance [32,95]. The most efficient solution for the determination of the performance of a power plant is a mathematical modelling approach using computational techniques [96-99]. To enhance power production, reduce fuel consumption, and boost the performance of power plants, there is a need for continuous studies and in this direction, areas of power leakage in the system can be identified and addressed to achieve the maximum performance efficiency [100,101]. There is a need to develop the tools and equipment that will bring about improvements in the performance of power plants and assist in future design and energy analysis of power plants [102-105]. In this regard, there is a need to mathematically model GTPPs.

The inlet and exit conditions of a GTPP determines its performances in terms of power outputs, thermal efficiency, and fuel consumption [106,107]. The determination of the most important factors (turbine inlet temperature and pressure ratio) depends on the combination of the values of the ambient conditions and changes associated to pressure loss during the installation [108,109]. The two areas of research and development towards improving the cycle efficiency of GTPP are as follows.

I. Improvement of the factors that influence the performance of GTs, such as the ambient and operation conditions by
   - Following ISO standards when developing GTs.
   - Improving the compressor pressure ratio and turbine inlet temperatures.
   - Ensuring an increased efficiency of the components of the turbo-machinery.

II. Modification of the basic GT cycle (e.g. Two-shaft, intercooler, regeneration, and reheated).

4.1 Parametric Influences

Before now, GTs are used for capacity enhancement [110-112] but nowadays, they are used with alterations in power-generation systems and for increased thermal efficiency, especially in the baseload power. The 1930s saw a rapid development of GTs as propulsion devices for jet aircraft but it took until early 1980 for the reliability and efficiency GT plants to progress sufficiently and be widely used in stationary power applications [113]. The size of GTPPs range from 30 - 350 MW [42,55,114].

The performance of GTPPs is influenced by the ambient conditions and these conditions vary with time and place [115]. Both air density, pressure ratio, air mass flow, and power output are greatly reduced in hot days due to low pressure, high temperature, and low air mass flow. These changes significantly affect GTPP performances [116,117]. Therefore, the power output decreases and fuel consumption (SFC) increase when the ambient temperature increases [10,118]. Changes in the flow rate of the air mass entering a GT affects the performance of the whole system, including changes in the air pressure, humidity, and temperature, all of which affects the air density [119-121]. The performance of GTPPs can be decreased in hot days due to the following reasons.

I. Air density reduction.
II. Airflow rate reduction.
III. Pressure ratio n reduction.
IV. High air temperature, low pressure ratio, and low air mass flow rate which decreases the power output.
V. Decrease power output which increases specific fuel consumption.
VI. Decrease in thermal efficiency due to the aforementioned reasons.

Increase in ambient temperatures results in increased temperature and decreased pressure in all stations. The effect of ambient temperature on the performance of GTPPs has been investigated by several studies [106,108,109,122-125]. The monthly ambient temperature changes have been shown to cause a significant reduction in power output from 1.7 to 7.2 %. Similarly, increased ambient temperature has been reported to decrease power generation and increase fuel consumption. A reduction of ambient temperature by about 10 was reported to increase power output by about 0.4 to 7.5 % [120].

The performance of a GTPP is commonly estimated based on its thermal efficiency, specific fuel consumption, work ratio, and power output. However, the performance of a GTPP can be adversely affected by several other parameters like the pressure ratio , combustion inlet temperature, ambient temperature, and turbine inlet temperature [35,126,127]. The effects of ambient temperature, exhaust gas temperature, and ambient pressure on the performance of a GTPP has been studied and reported as depicted in Figure 7 [16]. Evidently, an increase in the ambient temperature caused a decrease in the power output; an increase in the air ambient temperature from 15ºC to 30 ºC decreased the net power output by about 10 %. This is a typical scenario in the tropical regions with an annual average temperature of about 25 to 35 ºC [128,129]. Mostly, the capacity of CCGT power plants is mainly improved by lowering the intake air temperature to about 15ºC at a relative humidity of 100 % prior to entering the GTPPs' air compressor [130]. Usually, the efficiency and output power of a GT module is measured by calculating the efficiency operation conditions for the module [131-134]; however, the estimated parameters may sometimes not always be optimal within the gas turbine. Hence, it is important to control the input parameters when aiming to improve the performance of GTPPs [135,136]. Meanwhile, the influence of the pressure ratio, air-fuel ratio, ambient temperature, turbine inlet temperature, compressor isentropic efficiency, and turbine isentropic efficiency on the performance of GTPPs was investigated. Consequently, the management of the operation conditions of a system requires a parametric study on the effect of operation conditions [13,124]. It is, therefore, necessary to develop a strategy for estimating the performance of GTPPs that considered the influence of operating and ISO conditions [82].

The most significant developments in the thermal efficiency of GTPPs over the last 70 years are due to the efforts made towards increasing the inlet temperature of turbines as driven by the advancement in materials technology and blade cooling technologies [133,137-139]. Such advancements have brought about the use of advanced steam air technologies for metallic turbine blades in large CCGT plant with an overall performance efficiency of 60 % [138,140,141]. Regarding large GTPPs, this advancement has significantly increased the turbine inlet temperatures to about 1800 K but for the small GTPPs, ceramic components must be used due to the geometry of the blade irrespective of the difficulty of its cooling [141]. Another factor that causes an increase in the turbine inlet temperature is the expelled gases from the GT plants [103,142].

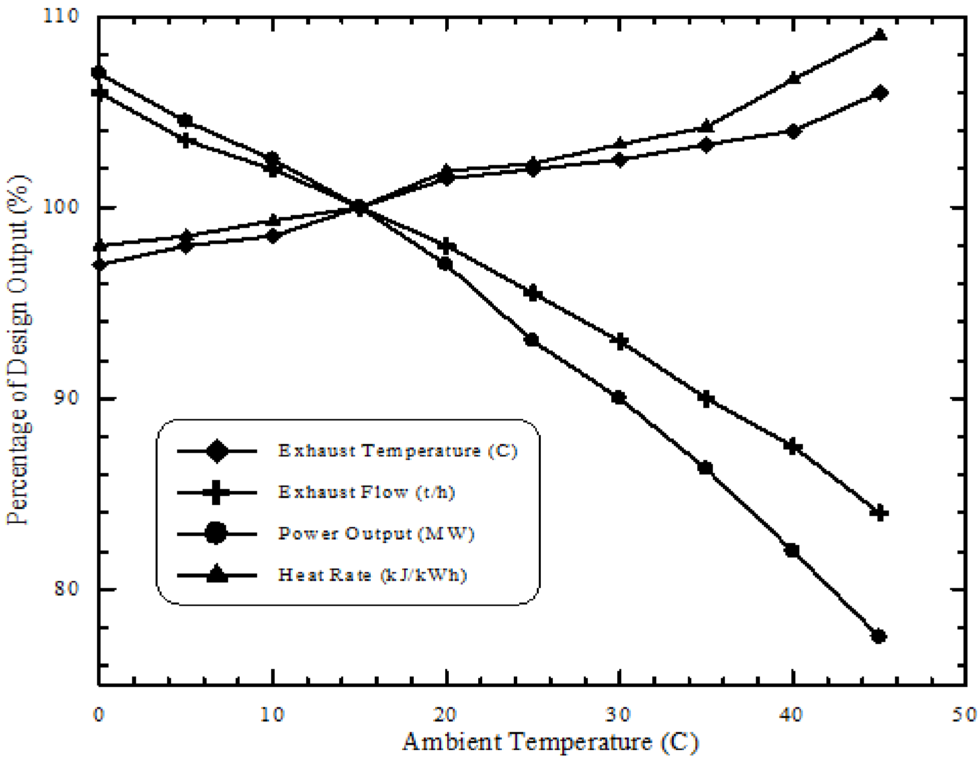


Fig. 7. Ambient temperature effects on the performance of GTs

A parametric study on the effect of various parameters (including turbine inlet temperatures, combustion efficiency, pressure ratio , and isentropic turbine and compressor efficiencies) on GTPPS performance has been carried out by [136]. The values of the performance parameters were calculated based on the basic cycle equations with assumptions of a constant value of the thermodynamic properties. Furthermore, Arrieta and Lora investigated the influence of ambient temperature on CCGT plant performance [119] by considering the ambient temperature effects on the performance of the system at the design stage. Shi and Che [143] suggested a CCGT plant work that utilizes Liquefied Natural Gas as a fuel. The study investigated the effects of the operation parameters on them in a bid to assess the influence of the turbine inlet temperature, pinch point, fuel heating temperature, and condenser pressure on the systems' performance.

A decrease in the condenser pressure at any given turbine inlet temperature will increase the overall thermal efficiency of the system. The reduced fuel consumption associated with the heating of the fuel gas temperature increases the thermal efficiency of GTPPs [144,145]. However, the occurrence of a higher exhaust temperature of an HRSG system at a higher turbine inlet temperature has been reported [104,146]. A GT system has been thermodynamically studied by Gülen [147] with emphasis on the modelling and analysis of the effect of the pressure ratio , isentropic compressor and turbine efficiency, and turbine inlet temperature on the performance of GTPPs. The performance of the system was measured using the thermal efficiency and power output as performance metrics. The selection of the maximum cycle temperature depended on the strength of the material used in the GTPP at full load and based on ISO recommendations [148].

A thermodynamic model for assessing the performance of an ideal open GT cycle has been proposed by Kurt *et al.,* [149]. This model investigated the influence of several parameters such as the pressure ratio, ambient temperature, and turbine inlet temperature on the systems' performance while the combustion efficiency, low heat values, and isentropic turbine and compressor and turbine efficiencies were kept constant. The performance of the GT was measured based on the cycle fuel consumption, thermal efficiency, and power output [30]. The study observed the optimal power output and thermal efficiency to occur at a high turbine inlet and low ambient temperatures [12,43,56,150].

4.2 Gas Turbine Cycle Modification

Gas turbine power plants are usually built light and compact for performance improvement [92]; however, this is the case for stationary power generation turbines [151,152]. The GTPPs have usually been used as heavy-duty plants for electricity generation and have been presented as better power generation systems [18]. Several strategies that could enhance the performance of GTPPs have been explored by several engineers [153] while different methods for increasing the net power of GTPPs have been used. One of the commonly used methods of enhancing the performance of GTPPs is the intercooler [4,43,154]. This method is mainly used to reduce the air temperature between the compressor stages as depicted in Figure 8. This is aimed at reducing the compressors' power consumption while maintaining a high expelled air pressure from the compressor [155]. The air between the compressor stages can be cooled by the compressor of GTPPs with a high pressure ratio to allow for the combustion of extra fuel and increase power generation using the intercooler [156]. However, the turbine inlet temperature is a limiting factor on the burnt due to the need to provide nozzle and blades on the initial phase of the turbine design using superior materials [157]. This limitation has been addressed by the recent advancements in materials technology.

The use of intercoolers in GTPPs can decrease the power consumption and consequently can increase the thermal efficiency of such systems and the net power output [158,159]. In the low-pressure compressor, air is compressed to intermediate pressure before being passed through the intercooler at a constant pressure to cool. This cooled air heads to a high-pressure compressor where it will be compressed to high pressure and later directed to the combustion chamber and to the expander [160,161]. The intercooler can also be applied in a multistage compression [162,163]. Several studies have presented parametric GT models with intercooler effect, with emphasis on the effects of ambient temperature, pressure ratio , intercooler effectiveness, and peak temperature ratio on the thermal efficiency and power output of such models [2,40,132,156,164,165]. The intercooler effect on GTPPs was analyzed and performances improved based on the first law of thermodynamics. Many studies have shown that for a given pressure ratio , a lower input power is required; however, using intercooler without reheating can decrease the thermal efficiency for at least low pressure ratio s [132,157,166]. This decrease is due to the remuneration of the dropped air temperature expelled from the compressor by boosting the inlet temperature of the turbine [138]. The incorporation of an intercooler in a GTPP can reduce the power consumption by the high pressure compressors (HPC), thereby, having a significant influence on the enhancement of the

GTPPs' performance [142,161,167]. As the temperature of the air entering the HPC is decreased, the air mass flow rate will be increased, thereby, boosting the power output. The low temperature discharged from the compressor carries enough air to cool the GT blades [158,168].

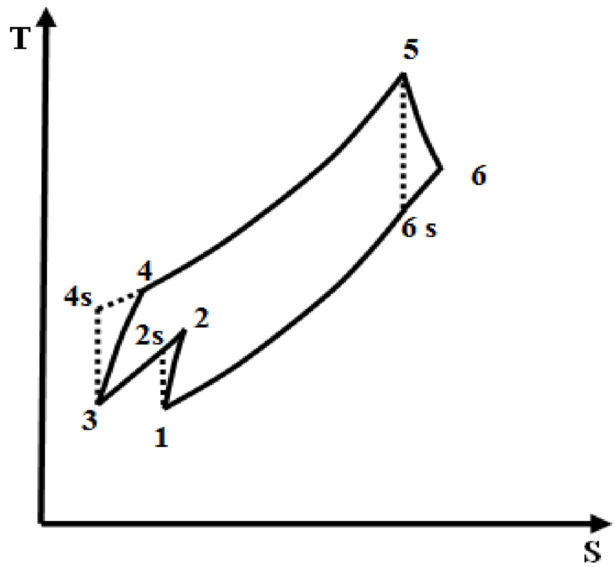
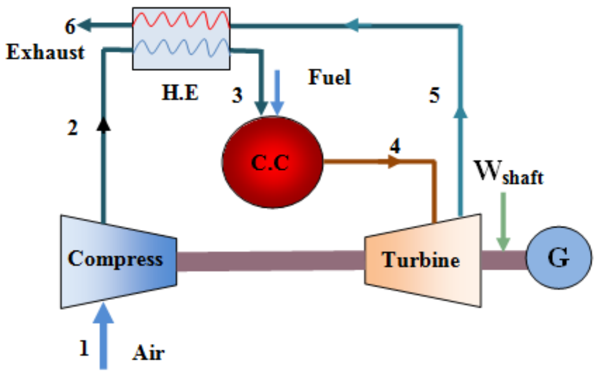


Fig. 8. T-S diagram for GT with an intercooler

The GTs manufactured by GE in the early 1990s generated a net power of135.7 MW, with a pressure ratio of 13.5, and a thermal efficiency of 33 % in a simple GT operation cycle [1]. These GTs produced up to 282 MW using a turbine inlet temperature of 1425 ºC at a thermal efficiency of 39.5 % in the simple GT operation cycle [17,129,169]. The GT plants increasingly becoming the ideal option for future power plants due to their reduced electricity cost, efficient fuel conversion, low installation and maintenance costs, and their ability to utilize a wide range of hydrocarbons are fuel [61,90,170]. They emit gases with relatively fewer pollutants and can be used to preheat air before entering into the combustion chamber; it can also be used for district heating as in combined power and heat plants [171-174]. The performance of a GT can be evaluated in terms of its power output, efficiency, specific fuel consumption, and the work ratio; however, several parameters such as the combustion inlet temperature and the inlet turbine temperature can affect this performance [56,58,175]. Obviously, GT manufacturers have improved on these parameters in recent times [149,176,177]. Meanwhile, the performance of GT plants can also be affected by the operating parameters like the altitude, humidity, ambient temperature, inlet, and exhaust losses. Normally, GTs draw air directly from the environment and as such, factors that affect air density or air mass flow rate into the compressor will affect its performance [108,109].

The exhaust gas expelled from the GT turbine is usually at a high temperature of about 500^{0}C while air exiting the compressor is at a lower temperature of about 300^{0}C [110,114,178]. Hence, the hot exhaust gas serves as a medium of heat transfer to the air that is leaving the compressor through a heat exchanger in a process known as recuperation or regeneration [179,180]. The Gt regenerators are typically tube and shell heat exchangers which are designed as tubes of small diameters. The air within these tubes is at high pressure while the exhaust gas is at a lower pressure in multiple passes outside the tubes [32,152,181]. The use of a regenerative heat exchanger in the cycle improved the thermal efficiency of the GT due to the regeneration of a portion of the heat lost to the environment in the exhaust gases and its subsequent use to preheat the air that is entering the combustion chamber [132,182]. Consequently, this process reduces the fuel consumption below the level required to generate the same power output in the GT [97,183,184]. It is, however, recommended to use regenerators when the exiting air temperature from the compressor is less than the exhaust gas temperature exiting the turbine [185-187]; otherwise, there will be a reverse in the heat flow direction which will cause a decrease in the efficiency of the system. This condition must be met to achieve a GT that operates at a high-pressure ratio [106,188-191].

Fuel consumption is reduced when the efficiency of the regenerator is high because the air entering the combustion chamber will be preheated to a higher temperature as depicted in shown Figure 9 [57]. However, such a high level of effectiveness can only be achieved with larger regenerators and such regenerators come at a higher cost and could cause a drop in the pressure because of the decrease in the shaft power. Due to the significant effect of pressure drop on the effectiveness of regenerators, it must be kept low on both sides [152,181]. The pressure drop of the air on the high-pressure side is usually maintained at < 2% of the overall discharged pressure from the compressor [179,192]. The effectiveness of most regenerators in practice is < 85 % [193]. Under the influence of a regenerator, the performance of an ideal Brayton cycle is dependent on the pressure ratio and on the maximum to minimum temperature ratio [57,179,194,195]. Mostly, regeneration is most effective at high maximum to minimum temperature ratios and lower pressure ratio s of the GT cycle [195,196].



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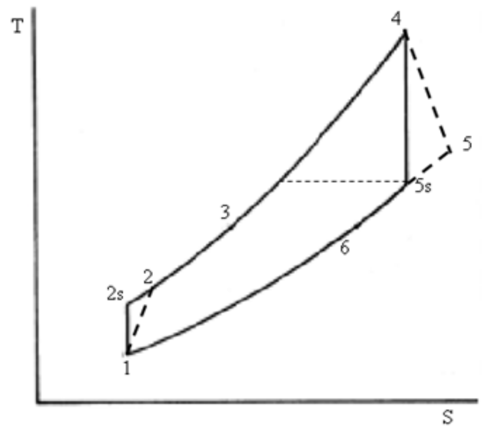
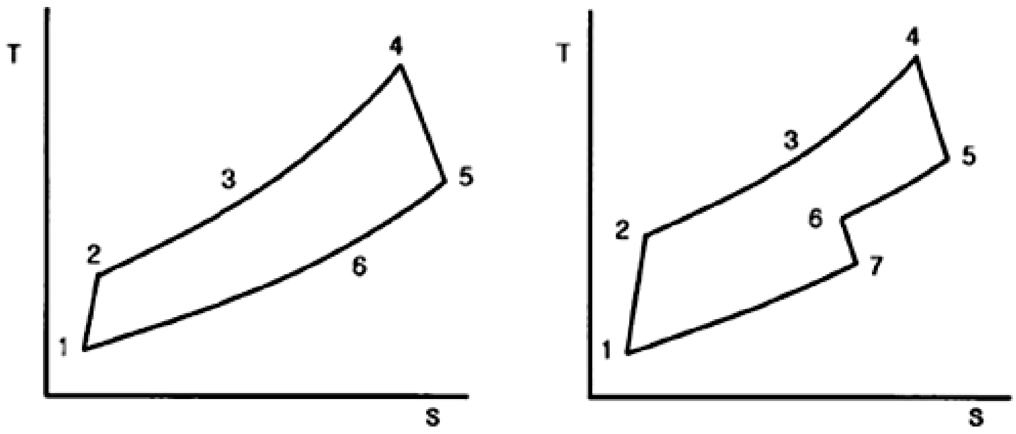


(b)

Fig. 9. (a) Schematic and (b) T-S diagram of regenerative GT cycle

An alternative regenerative GT approach has been proposed due to the growth of the regenerative GTPPs [47,197]. A comparison of the temperature-entropy plots of the regenerative GTPP and the proposed alternative regenerative GTPP is depicted in Figure 10. Facchini [198] suggested and analyzed the performance of an alternative regenerative GTPP while Facchini and Sguanci [199] performed an off-design performance evaluation of the alternative regenerative GTPP. The evaluations showed the proposed alternative regenerative GTPP to be possible even at high pressure ratio s and thus, making it possible to convert high pressure ratio regenerative GTPPs into the GT cycle for thermal efficiency improvement. The design performance of a GT cycle has been analyzed by Cardu and Baica and based on the analysis, the alternative regenerative GT cycle was concluded to be superior to the regenerative GT cycle [200].



(a) (b)

Fig. 10. Temperature-entropy diagrams of regenerative and alternative regenerative cycles (a) Regenerative gas turbine (b) Alternative regenerative gas turbine

The same cycle was also suggested by Dellenback [179] who conducted a performance and parametric analyses of the system. The analyses showed the pressure ratio of the alternative regenerative GT cycle to be higher compared to that of the regenerative GT cycle with a high maximum thermal efficiency. The results are, however, still unreliable since the model was based on constant properties. The obtained regenerative thermal efficiency was 50 % at the optimum pressure ratio of 22 while for a simple GT working at the same temperatures, the thermal efficiency will only be 43.8 % at an optimal pressure ratio of 50 [132,179]. Elmegaard and Qvale [201] analyzed an alternative regenerative GT cycle based on variable properties and posited that it is advantageous when there is a limited range of design parameters.

The last 3 decades have witnessed great development in the role of GTPP in electric energy generation. The flexible cycles of Gt due to performance parameters can be enhanced through the addition of new components to the simple GT cycle. Several methods have been developed for the enhancement of the performance of GT cycles [151]; thus, several studies have been conducted on advanced GT cycles, such as those on the humid air, turbine regenerative cycle, and the steam injected GT cycle [198,202,203]. The primary aim of most of these investigations is mainly to achieve higher thermal efficiency in GT cycles [166]. However, this performance improvement can be achieved through the use of an additional combustion chamber (reheat) in the GT cycle [2,7,57]. There are two processes in the expansion process within the reheat GT. An additional combustion chamber is positioned between the low-pressure and high-pressure turbines. In the GT cycle, the combustion process takes place at a higher air-fuel ratio [2,97,168]; therefore, the gases exiting the high–pressure turbine is saturated with oxygen. This gas enters the reheat combustion chamber to stimulate a supplementary combustion process that will increase the gas temperature. From the reviewed studies on reheat GT cycles, the reheating combustion chamber has been shown to increase the network and decrease the thermal efficiency compared to a simple GT cycle [204]. However, the maximum network is obtained in the reheat GT when there is an equal pressure ratio between the low and high-pressure turbines [86,133,164]. Da Cunha Alves *et al.,* [205], they presented A model for evaluation of the GT performance with effect of reheat and intercooler.

A comprehensive design method to obtain improved performance of GTPP has been presented in many studies [166,201,205-208]. Furthermore, a study on the influence of regenerated, intercooled, and reheated on a range of existing GTs has been presented in Figure 11 [34,209]. The proposed design steps have been applied on the 3 existing GT with varying design complexities while a comparison of the performance of GTs with these modifications has been presented. Furthermore, a stage-wise analysis of the turbine and compressor sections of the modified GT was conducted [47,210]. The analyses showed all the modified GT plants to exhibit higher performances, with an increase in the cycle efficiency from 9% to 26% compared to their original values [88,211]. A computational thermodynamic analysis method has been used to study the effects of the relative humidity, turbine inlet temperature, and pressure ratio on the performance of complex GT cycles. The studied complex GT cycle consisted of the indirect intercooled reheat regenerative GT with inlet air influenced by the indirect evaporative cooling and air evaporative aftercooling of the compressor discharge [196,207,209]. There was a significant variation in the effects of the power output and thermal efficiency compared to those of the pressure ratio, relative humidity, and turbine inlet temperature [122,177].

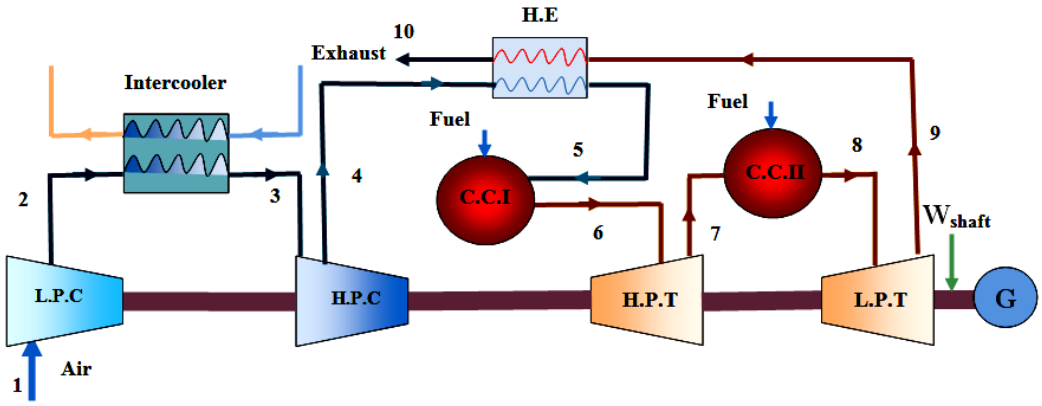


Fig. 11. A schematic representation of regenerative, intercooler, and reheat GTPP

Bassily [132] presented 6 different GT configurations with intercooled, reheat, and regenerative before proposing a parametric analysis for the influence of the turbine inlet temperature, the ambient temperature, and relative humidity on the systems' performance. From the results, the optimal pressure ratio was found to increase by about 1.5 after increasing the turbine inlet temperature (100 K). A simulation model for the study of the influence of the ambient temperature, the turbine inlet temperature, the ambient relative humidity, the pressure ratio , and the effectiveness of the regenerated heat exchanger on the performance of all configurations have been introduced by Bassily [165]. The study showed an increase in the regenerative heat exchanger capacity after increasing the turbine inlet temperature. This capacity increase translated into an increased effectiveness of the regenerated heat exchanger and a gain in the GT cycles' thermal efficiency. Ilett and Lawn [212] depended on thermodynamic analysis to derive the optimum efficiencies and work outputs of a simple GT cycle, equivalent CCGT cycles, and several advanced GT cycles. The performance of the advanced cycles with CCGT was improved significantly compared to the simple GT cycle; they were observed to achieve the lowest electricity cost for externally-powered heavy-duty power generation plants.

5. Conclusions

The significant progress in the performance of the GT plants research was apparently reviewed. In parallel, several uncertainties were revealed in the applicability of the developed advanced models to evaluate the performance of the power plants based on effective parameters and advanced configurations. These developments were mainly in the strategies used to improve the performance of GTPPs. A summary of the conclusions is as follows.

I. A decrease in the pressure ratio decreases the heat duty in both simple and complex cycles of GT plants but was increased with reduced ambient temperature and increased TIT (translates to enhanced thermal efficiency).
II. The efficiency of GTPPs is strongly affected by the pressure ratio s, the air-fuel ratio, the ambient temperature, and the isentropic efficiencies.
III. Most of the proposed models are obviously dependent on fixed-up cycles or performance analysis some have considered variable plant modeling configurations and have been based on energy analysis approach.
IV. Optimization techniques have been used to investigate the maximum technical parameters that could maximize the performance of power plants.

The literature review demonstrates that the ongoing power plant optimization research looks for peak performance. The employment of the optimization techniques has shown robustness, suitability for parallel computing, and efficiency; therefore, it does not require modification for a specific problem. The qualitative and quantitative identifications are a necessity for the vital effective parameters that requires to be included in the development of the performance of GT power plants.

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