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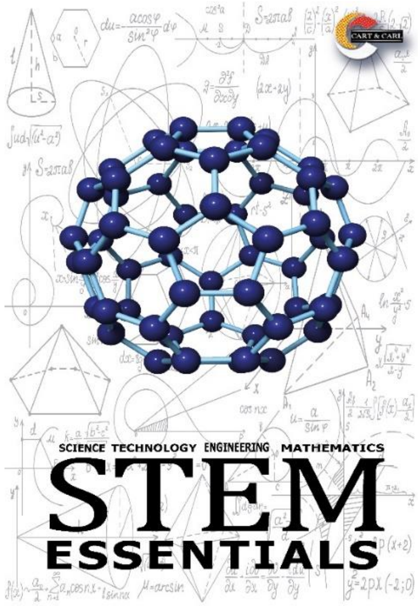

Gas Turbine Plants Efficiency For Power Generation Efficiency: A Review

Authors
[a] Nwachukwu, E. E.

[a] Department of Engineering Management, University of Port Harcourt, Nigeria

Corresponding Author
Nwachukwu, E. E.
(nwachukwuee127@gmail.com

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Abstract

This paper reviews the efficiency of gas turbine plants (GTPP) for power generation with emphasis on open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT). Rising global electricity demand and reliance on fossil-fuel thermal power plants have underscored the need for technologies that offer higher efficiencies, lower emissions, and improved cost-effectiveness. Gas turbines, owing to their reliability and flexibility, remain critical in electricity generation and industrial applications. The paper traces the historical development of gas turbines from early 20th century prototypes to modern high-performance units with increased pressure ratios, turbine inlet temperatures, and outputs up to 350 MW. Classification based on working cycle and component arrangement (single- versus two-shaft systems) is outlined, alongside the operational criteria for adopting OCGT or CCGT systems. Comparative analysis highlights CCGT's superior efficiency and environmental performance, while recognizing OCGT's lower capital costs and simpler operation. Recent research and innovations, including exergoeconomic assessments and parametric optimization, are discussed as key drivers for enhancing performance, reducing emissions, and improving fuel economy. The review concludes that integrating waste-heat recovery and combined heat and power applications can significantly enhance gas turbine efficiency, making them more environmentally sustainable and economically viable for modern power generation.

Keywords : Gas Turbine Plants, Open Cycle Gas Turbines, Combined Cycle Gas Turbines, Electricity

Introduction

The world electricity demand is predicted to increase by more than two-thirds over the period 2011-2035 according to World International Energy Agency (Conti et al., 2013; Sulaiman et al., 2017). This implies that the power sector will represent over half of the global primary energy use. This increase demand will be marred with more energy consumption which will consequently result in emission if adequate measures are not put in place. Therefore, it is important to find improved technologies for power generation with high electrical efficiencies and specific power outputs, low emission of pollutants and economical for a sustainable use of fuel. Presently, 80% the world electricity is generated from fossil fuels (coal, petroleum, fuel-oil, natural gas) fired thermal power plants while the remaining 20% is compensated from different sources such as hydraulic, nuclear, wind, solar, geothermal and biogas (Sulaiman et al., 2017).

The turbine is the most satisfactory power developing unit among various means of producing mechanical power due to its exceptional reliability (Domkundwar, 2011; Nkoi et al., 2018). Generally, turbines are any kind of spinning that uses the action of a fluid to produce work (Nkoi et al., 2018).

They are prime-movers used for driving rotating equipment like pumps, compressors etc., or for generating the electricity required for process industries or a community. The idea of using the axial flow compressors, combustion chamber and turbine was conceived as early as in 1872 (Domkundwar, 2011; Nkoi et al., 2018). The gas turbine plant can be either open cycle or closed cycle. The major difference between the closed cycle and open cycle is that the working fluid (product of combustion) is continuously circulated in the closed cycle as the fluid coming out from the turbine is cooled to its original temperature in a cooler using an external cooling source before passing into the compressor whereas, in the open cycle, the working fluid is continuously replaced as they are exhausted into the atmosphere (Domkundwar, 2011; Nkoi et al., 2018).

The open cycle gas turbines (OCGT) can be started and stopped so easily compared with other power plants and therefore, are used for peak load power and tertiary reserve, and operate for a limited number of hours per year, typically 2000 and 5000 hours. The gas turbines used for electric power generation can produce electric power from the range of 20 to 250 MW with efficiencies of about 40% (Martha De Souza, 2012; Nkoi et al., 2018) These gas turbines typically have a single-shaft configuration, operate on Brayton cycle (Achuthan, 2009; Nkoi et al., 2018) and consist of a compressor, a combustion chamber, and a turbine. Air is drawn from the atmosphere and is compressed to a high pressure in the compressor (Nkoi et al., 2018). The high-pressure air enters the combustion chamber where fuel is sprayed (added) to the compressed air and ignited to increase the fuel-air mixture (gas) temperature at constant pressure. However, gas turbines that operate in simple cycles have low efficiencies because the emission from the turbine exhaust comprises of hot gases and this energy is lost to the atmosphere. In order to better the performance and reduce atmospheric emissions advanced cycles that utilize the energy in the hot emitted gases in a combined cycle gas turbine (CCGT) to generate more power are being proposed, designed and studied. Efficiencies of about 50% - 60% have been reported (Nkoi et al., 2018).

Gas Turbine Power Plants

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 Gas Turbine Power Plants (GTPP) that produced about 8kW (Jeffs, 2008; Ibrahim et al., 2019). 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 673K (Ibrahim et al., 2019). A practical GT was successfully built in 1905 by The Societe Anonyme des Turbomoteurs French Company when they assembled a GT (Olumide et al., 2019). 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. 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 (Ibrahim et al., 2019). However, several years 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 (Ibrahim et al., 2019).

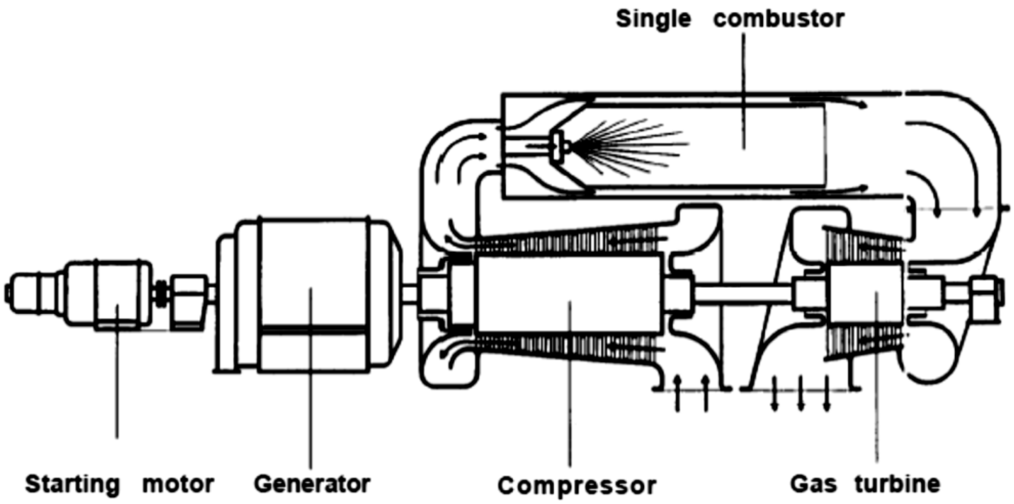


Figure 1: The first ever built industrial GT set with a single combustor
Source: Ibrahim et al. (2019)

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) (Ibrahim et al., 2019) 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 (Allouis et al., 2016). 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 (Ibrahim et al., 2019).

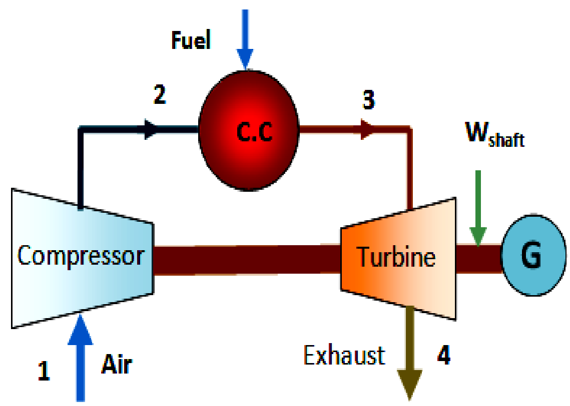
Recently, industrial mechanical power has been mainly produced from GTs in various industries; GT power has also been used in other power-driven activities such as driving of loads generators, propellers, process compressors, and pumps (Bade & Santanu, 2015; Ibrahim et al., 2019). Initially, GT evolved as a relatively simple engine but has recently become a complex and dependable prime mover with high-efficiency. 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. 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 % (Ibrahim et al., 2019).

Classification of Gas Turbines

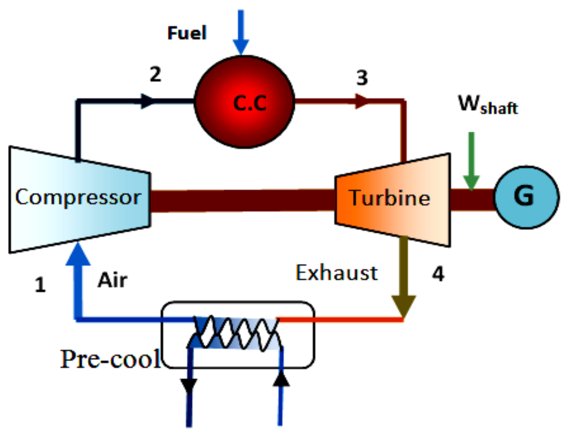
Different arrangements of the GT components have developed in the past. Some of these arrangements are appropriate for power generation and the others used to mechanically drive applications such as compressors and pumps (Razak, 2007; Ibrahim et al., 2019). In this section, GT was classified based on the working cycle, components arrangements, and the field of application as follows:

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 (Ibrahim et al., 2019). 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) (Ibrahim & Rahman, 2013; Ibrahim et al., 2019). 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. 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) (Ibrahim et al., 2019).



(a) Open cycle



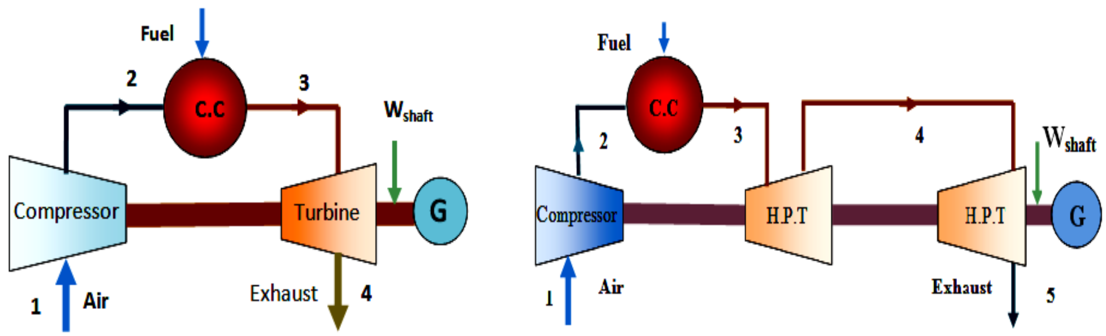
(b) Close cycle

Figure 2: Simple gas turbine cycles
Source: Ibrahim et al. (2019)

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 (Ibrahim, 2015; Ibrahim et al., 2019). 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 (Najjar, 1996; Ibrahim et al., 2019). In this arrangement, the rotational speed of both shafts may vary to ensure a large extent of load control flexibility (Kim & Ro, 2000; De Sa & Sarim, 2011). 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. 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 (Haglind, 2011). On entering the turbine of the GT, the hot gas expands and get expelled to the immediate environment via a chimney (Figure 3 (a)) (Ibrahim et al., 2019). About 60 % of the turbine power output from a GT plant is utilized by the compressor while the rest is used to either power the generator or lost to the environment with the expelled gases (Ibrahim et al., 2019).

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) (Ibrahim et al., 2019). 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. 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.



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

Figure 3: The schematic representation of simple gas turbines
Source: Ibrahim et al. (2019)

Criterial For Open Cycle Gas Turbine (OCGT) Adoption

With the growing popularity of natural gas for power generation, it is not startling that people keep inquiring about Open Cycle Gas Turbine (OCGT) and Combined Cycle Gas Turbine (CCGT) systems. As with all products, each of these systems has its advantages and disadvantages. The OCGT have a rather straightforward operation that starts with fresh ambient air entering the compressor and ends with power generation. This simplicity gives to OCGT some advantages over CCGT. Conversely, this cycle has some shortcomings that may deter its application in certain situations. It would be worthwhile to compare the open cycle gas turbine (OCGT) and combined cycle gas turbine (CCGT), based on efficiency, economics and environmental effect:

Efficiency

CCGT technology remains the choice for most power plants that rely on natural gas. Efficiency of this system is its driving force, and it seems to be getting even better. Recent developments have allowed for higher efficiency (to the tune of over 60%). Analysts in the sector are already forecasting that efficiency will have hit the 64% mark by 2020.

The recent development in the power augmentation platform must be exciting power plant owners, especially those that manage combined cycle power plants. Leading open cycle turbine manufacturers are trying hard to enhance the efficiency of these products, but the figures attained so far are much lower than the 60%-plus of CCGT.

Economics

When choosing the CCGT, you must look at the fiscal factors keenly. The technologies for setting up a combined cycle power plant are complex and high as compared to the OCGT.

Environmental effect

Power plants may affect the environment during both construction and operation. Effects include taking up space, pollutant emission and use of water resources. Furthermore, the height of the facility can be a hindrance to aviation activities. While any power plant can have effects on the environment, most people prefer the combined cycle power plant to the open cycle gas turbines. US power plants that have gone this route are reporting fewer emissions. The significant reduction is reported for pollutants such as sulfur dioxides (SO_2), carbon dioxide (CO_2) and nitrogen oxides (No_2). The open cycle gas turbine discards waste heat into the atmosphere, something that can have adverse effects on the environment. The Combine Cycle Power Plant does not feature such a concern because it reuses waste heat to generate more power.

Recent development in Power Generation

Recently, gas turbines play a major role in power generation in the world. The main focus on gas turbine developments over the past years has been on its efficiency i.e. identifying the relationship of efficiency to the cost of electricity (Breeze, 2014). Currently research and development are being carried out by organizations and gas turbine manufacturers to improve the efficiency, emissions in relation to the power output and cost of electricity and equipment. Some more recent works on both the open gas turbine and the combine cycle gas turbine have being done in recent years. This review have brought in some very interesting line of thoughts in the turbine technology industry. Mukesh and Raj (2015) analyzed the performance of an open cycle gas turbine power plant using the concepts of exergoeconomics which basically involves the use of Second law of thermodynamics and assigns monetary values to the thermodynamic quantity known as exergy. Analyses based on exergoeconomic criteria were done for the open cycle gas turbine power plant turbine. The methodology was illustrated using the example of a 25 MW open cycle gas turbine power plant. Optimization was done for the open cycle gas turbine power plant as tradeoffs between the unit product cost of the compressor and combustion chamber as functions of compressor pressure ratio and unit product costs of combustion chamber and gas turbine as functions of turbine inlet temperature.

Khan and Tlili (2018) conducted a parametric analysis to optimize the performance of combined cycle which involves the bypass valve. The result shows that gain in network output is about 45% when the temperature at the inlet of the turbine of topping cycle increases from 1000K to 1400K. The gain in net efficiency of the cycle is from 15% to 31% when the temperature at the inlet of the turbine of topping cycle increases from 1000K to 1400K. They suggested that the bypass valve should be opened for small compression ratio and closed for high value of compression ratio. Janusz and others (2016) came up with a calculation methodology of isentropic efficiency of a compressor and turbine in a gas turbine installation on the basis of polytropic efficiency characteristics. A gas turbine model was developed into software for power plant simulation. There were shown the calculation algorithms based on iterative model for isentropic efficiency of the compressor and for isentropic efficiency of the turbine based on the turbine inlet temperature. The isentropic efficiency characteristics of the compressor and the turbine were developed by means of the above-mentioned algorithms. The gas turbine development for the high compressor ratios was the main driving force for this analysis. The obtained gas turbine electric efficiency characteristics show that an increase of pressure ratio above 50 is not justified due to the slight increase in the efficiency with a significant increase of turbine inlet combustor outlet and temperature.

Conclusion

Gas turbines are used as fixed power plants to produce electricity as stand-alone units, or in concurrence with steam power plants. The high temperature exhaust gas emanating from the gas turbine serves as the heat source for steam generation in a combined-cycle gas turbine power plant. The purportedly waste exhaust heat associated with gas turbine operation has necessitated the need for Combined-Heat and Power (CHP) application for better fuel economy. This would render gas turbine cycles environmentally-friendly, and a lot more economical.

Declaration of Competing Interest

The author declares not to have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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