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OFF-DESIGN PERFORMANCE MODELING OF A GAS POWER PLANT IN NIGERIA

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Abstract

In this study, the performance characteristics of a gas power plant located in Rivers State Nigeria, operating at design and part load conditions was evaluated. Differences in part load performance, due to various factors in operation were investigated using EBSILON® Professional. Various part load operation strategies including variation in ambient temperature, variation of fuel and air flow, variation of expected output, variation in efficiency of components were considered while maintaining constant turbine exhaust temperature. The mass flow, air flow ratios under different load conditions (30% to 110%) nominal power was determined. Data were also collected from the power plant through direct observation from the monitoring screen of the human machine interface, log-books and manufacturer's manuals. The results showed that variation of temperature in different seasons of the turbine impacted performance, while lower temperatures increased air density and compressed mass flow and delivered more power. Variation in air ratio in the combustion chamber also enabled the regulation of the maximum temperature of the cycle and achieved specified power output. The results also showed that the power plant with higher design performance exhibited less efficiency degradation during part load operation. The efficiency of the turbine power plants was strongly affected by the pressure ratio, the air-fuel ratio, the ambient temperature, and the isentropic efficiencies.

Keywords: Modeling, Simulation, Off-design, Thermodynamic Performance, EBSILON®, Design Performance

1 Introduction

Global power generation from fossil fuels predominates till date [3]. The development of any economy, as well as standard of living of the general public depends on accessibility to, and availability of power. An increase in the use of power for commercial purposes is also important for sustainable development [9]. Therefore, the growing demand for non-renewable natural resources for power generation by the current energy conversion technologies, and the environmental impact due to global warming, waste disposal and flue gas emissions, has necessitated the need to improve the design and operation of energy systems, which prevents the release of substances capable of harming the environment.

The design of a gas turbine design is centered on certain distinguishing components, including the turbine geometry, flow rate, inlet and outlet pressures, dimensions, and performance [1]. However, alterations in power demands and turbine loses implies that turbines operate at reduced efficiencies. Hence, analysis and modeling of power generation system is of engineering interest and essential for the efficient utilization of energy resources. A simple gas turbine cycle (SGTC) is the most common cycle employed by most power plants for power generation. It is environmentally advantageous with short construction lead time and is characterized by low capital cost compared with steam power plants [9]. However, low efficiency due to limitations resulting from lower compression ratio and thermal properties of hot gas path limits the turbine inlet temperature. The problem of sustainability of energy has necessitated the need to improve on the existing gas turbine technology.

Sustainability in the use of gas turbines for power generation in gas turbines is a function of improved efficiency. Efficiency is very key because it affects other aspects of the sustainability of energy which includes cost value, efficient use of resources, enhanced design and analysis, energy security and a better environment. One way to improve the efficiency of a power plant is by combining gas turbine and a steam turbine to result in a combined cycle or combined with a steam generator to produce heat in a cogeneration plant, or combined heat and power (CHP) plant. A major setback to this, however, is the availability of space in already installed power plants. Carrying out modifications on the simple gas turbine cycle can improve its efficiency considerably. Some of the modifications which have been made on the SGTC are regeneration, reheating and intercooling. Apart from design efficiency, the off-design performance of gas turbines is equally important, since they ordinarily function at part load conditions for a significant portion of their lifetimes [5]. Regardless of gas turbine configurations, performance generally degrades with a reduction in power. For this reason, enhancing the part load performance for improving fuel economy, is paramount. Reports on off-design performance analysis of gas turbines have been previously reported [6], [8], [10], and [2].

Most power plants operate under off-design conditions as a result of variation in load or ambient conditions or both [7]. In comparison with design point performance, the understanding of part-load behavior is insufficient due to its complexity. In this study therefore, the part load performance characteristics of Omoku gas turbine was evaluated. Part load operation strategies included variations in ambient temperature, fuel, and air flow, expected output and efficiency of components, while maintaining constant turbine exhaust temperature. A model of the gas turbine cycle power plant was developed and simulated using EBSILON® Professional 13.0 software in design and part load operations.

2. Materials and Methods

2.1 Study area

2.1.1 The Omoku gas power station

The 150 MW gas power plant used in this study is situated in Omoku community, Ogba/Ndoni/Egbema Local Government Area, with a total population of approximately 33,000 people in the northern part of River State, Nigeria. It is located in the south coastal area of Nigeria with geographic coordinates on Longitude: $6^{o}39^{'}24^{''}$E ad Latitude: $5^{o}20^{'}37^{''}$N. It is among the power stations under the National Integrated Power Project (NIPP) scheme, managed by the Niger Delta Power Holding Company. The community is not linked with the national power grid due to its remote nature, hence a 132 kV switchyard is being used for electricity distribution. Natural gas powers the power plant due to its proximity to raw materials, occasioned by the presence of oil multinational oil companies.

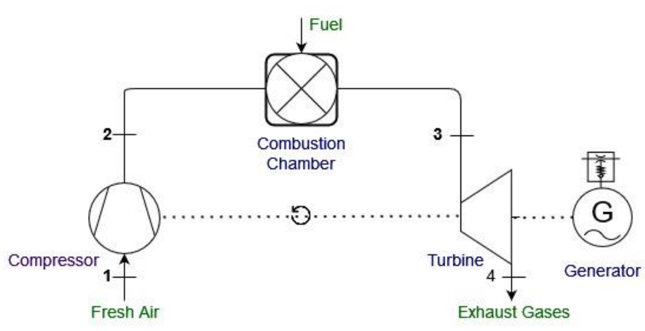
The plant has 6 generating 25 MW GE heavy duty gas turbines, with a combined installed capacity of 150 MW.

2.1.2 Data collection

Data were collected from the gas plant (GE FRAME 5—MS 5001 PA—Single Shaft) via direct observation from the monitoring screen of the human machine interface (HMI), log-books and manufacturer's documentation. Relevant plant and working fluid parameters were obtained from appropriate thermodynamic tables.

2.1.3 Omoku gas turbine cycle

The turbine is a simple cycle, single shaft gas turbine, made of an inlet, seventeen stages of axial compressor, two stages of axial turbine, combustion chamber which comprises 10 cans arranged in an annular order, exhaust, and support systems. Figure 1 shows the schematic and temperature-entropy (T-S) diagram.



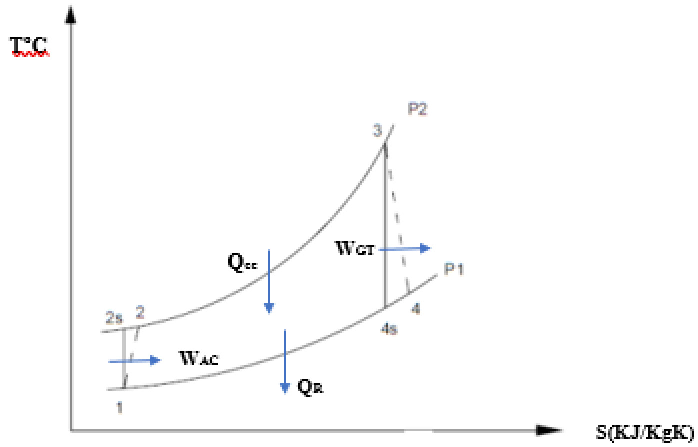


Figure 1 Schematic and T-S Diagram of Omoku Gas Turbine Power Plant

2.3 Energy balance for the simple gas turbine cycle

(a) ***Actual compressor work for the simple cycle gas turbine***

Turbines and compressors are steady flow devices. A balance between the energy in the fluid entering the compressor and that exiting the compressor will give the compressor work.

$$\dot{W}_{AC} = \dot{m}_a(h_2 - h_1) = \dot{m}_a c_{p,a}(T_2 - T_1) \quad (1)$$

Where $\dot{m}_a$ (kg/s) is mass flow rate of the air at the inlet of AC, T_1 is the compressor inlet temperature, $c_{p,a}$ is the specific heat capacity of air.

(b) Combustion Chamber

$$\dot{Q}_{CC} = \dot{m}_f H_f \eta_{cc} = \dot{m}_{fg} h_3 - \dot{m}_a h_2 \equiv \dot{m}_{fg} c_{p,g} T_3 - \dot{m}_a c_{p,a} T_2 \quad (2)$$

$$\dot{m}_{fg} = \dot{m}_f + \dot{m}_a \quad (3)$$

Where $\dot{Q}_{CC}$ is heat added into the combustion chamber, $c_{p,g}\left(\frac{KJ}{KgK}\right)$ is the specific heat capacity flue gas, η_{cc} is efficiency of the combustion process, $\dot{m}_{fg}$ and $\dot{m}_f$ are mass flow rate of flue gas and fuel respectively.

(c) Gas Turbine

$$\dot{W}_{GT} = \dot{m}_{fg}(h_3 - h_4) = \dot{m}_{fg} c_{p,g}(T_3 - T_4) \quad (4)$$

Where $\dot{W}_{GT}$ is the work done by the turbine.

(d) Heat Rejected

$$\dot{Q}_R = \dot{m}_{fg} c_{p,g} T_4 - \dot{m}_a c_{p,a} T_1 \quad (5)$$

Net Work, $\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{AC}$ (6)

Thermal Efficiency, $\eta_{therm} = \frac{\dot{W}_{net}}{\dot{Q}_R}$ (7)

Heat rate, , $HR = \frac{3600}{\eta_{therm}}$ (8)

2.3 Modeling and simulation with EBSILON® professional

Ebsilon, an abbreviated form of Energy balance and simulation of the load response of power generating or process controlling network structures, is a mass and energy balance calculation program for thermodynamical cycles. It is based on standard components, which are used for modeling common power plants; and programmable components used for modeling complex power plants processes with user-defined behaviour.

The basic control elements and tool bars (Figure 2) are the standard toolbar, component bar for selecting a component from a category, component wizard bar for accessing components classified by numbers, Ebsilon bar for starting simulations, and zoom bar for zooming in the model and finding objects.

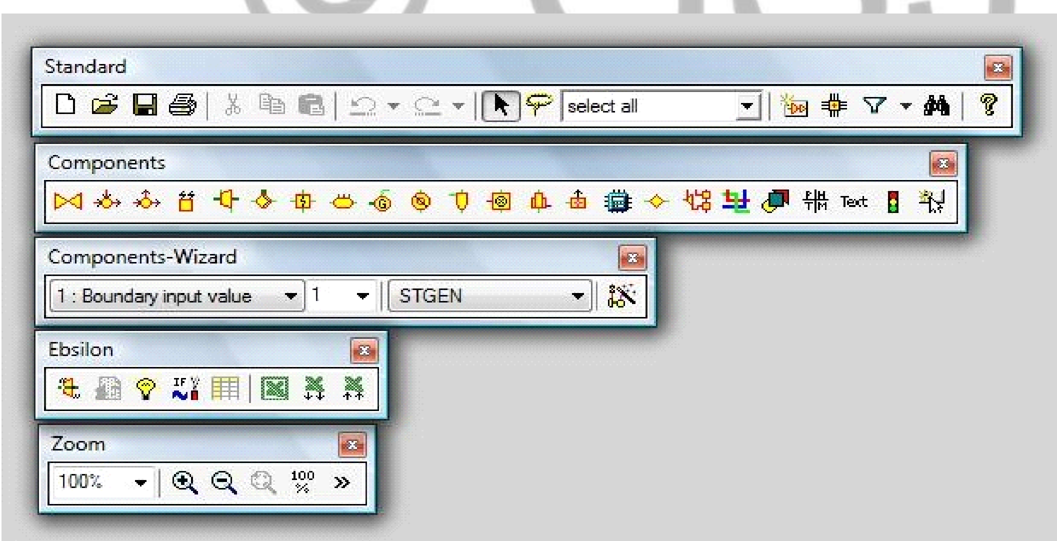


Figure 2 The basic control elements and tool bars of Ebsilon Software

2.4 Gas turbine GE MS 5001 in off-design

Off-design performance refers to the performance of an engine other than the design point [2]. Temperature, fuel and air flows were selected for the off-design performance of the gas plant. The following assumptions, according [4] were made:

i. The kinetic and potential energy losses were neglected in the system.

ii. The system operated under a steady state and steady flow condition.

iii. Combustion taking place in the combustion chamber was complete.

iv. Fuel and air were ideal gases.

v. The composition of air at the inlet of the compressor were 79 % N_2 and 21 % O_2.

vi. Air compressors and gas turbines operated at adiabatic condition.

2.4.1 Variation of ambient temperature

The variation of ambient temperature produced a change in the turbine behaviour because the air entering the turbine changed its properties, such as density, humidity, and flow rate. In this study, a 5% variation in humidity was assumed when the temperature changed; while variations in density and air flow for different cases (10^{o}C, 20^{o}C, 30^{o}C, and 40^{o}C) were considered.
As example, the calculations for the case at 40^{o}C is described below:

Table 1 Density values obtained in each case are as shown.

T_{amb} (◦C)	ρ (kg/m^3)	φ (%)
10	1.246	120
20	1.204	110
30	1.163	100
40	1.127	90

At 40^{o}C, we get a mass of air of 118.63kg/s, which is smaller than in nominal conditions of 122.319kg/s. The new air flow must be set at the compressor entrance using the "boundary value input" as we explained earlier. The temperature has to be changed also.
In every case of partload we will now have new conditions of temperature and mass flow. Ebsilon calculates by itself the amount of fuel which has to be burnt in the combustion chamber. The parameter which determines the amount of fuel is the air ratio.

The air ratio (called ALAM in Ebsilon and represented in tables as λ) is a parameter in the combustion chamber which enables the regulation of the maximum temperature of the cycle. The air ratio is defined as the ratio between the mass of air and the stoichiometric mass of air for a known fuel flow. By changing the air ratio, an order is given to the combustion chamber to accept more or less fuel. This means that the maximum temperature of the cycle, after the combustion chamber changes also. This creates a measure to achieve either higher or lower temperatures by varying the air ratio. If the air ratio is increased, more air is accepted in reference to the stoichiometric air and the maximum temperature of the cycle decreases. The exhaust temperature of the turbine decreases as well. If the air ratio decreases, the temperatures increase.

Variation of fuel and air flows

When an amount of power smaller than in nominal conditions is enough for satisfying the demand, the gas turbine can work in partload as well. First, the pursued objective is to determine how much power is needed. Then to achieve a variation in power, taking into cognizance the aim of keeping the exhaust temperature of the gas turbine constant; basically, for the benefit of a heat recovery steam generator to be coupled at the exhaust of the gas turbine unit. To adjust the exhaust temperature, the air ratio is varied.

In this case the criteria followed establishes a constant exhaust temperature while the range of power is between the 50 % of the load and nominal conditions. To obtain a constant exhaust temperature, the air ratio was varied in the same way that we have already explained when the gas turbine works in an ambient with changing temperatures. To obtain the required power, the mass of air has to be changed as well, taking into account that the smaller amount of air the less power is delivered. Depending on the required power, Ebsilon calculates by itself the amount of fuel necessary for ensuring that the gas turbine delivers exactly that amount.

For 80% load case:

The amount of power obtained in nominal condition is 26.809 MW. In this case we need the 80% of the nominal power, which is 0.8 × 26.809 = 21.447 MW. To reach that amount, the air ratio and the mass of air entering the compressor was varied. That also implies variation in mass of fuel, and the value at 80% load case was obtained. This value is represented as P_{aprox} and the ratio P_{aprox}/P_o represents the ratio with which the delivered power is obtained. If the P_{aprox}/P_o coincides with the partload needed, then the delivered power is exactly the required amount. In the case of 80%, the ratio P_{aprox}/P_o is exactly 80%, which means that the numbers obtained are correct.

In Figures 3 and 4, the model of the gas turbine working at nominal conditions of GE MS 5001 in design conditions and 80% nominal power are shown.

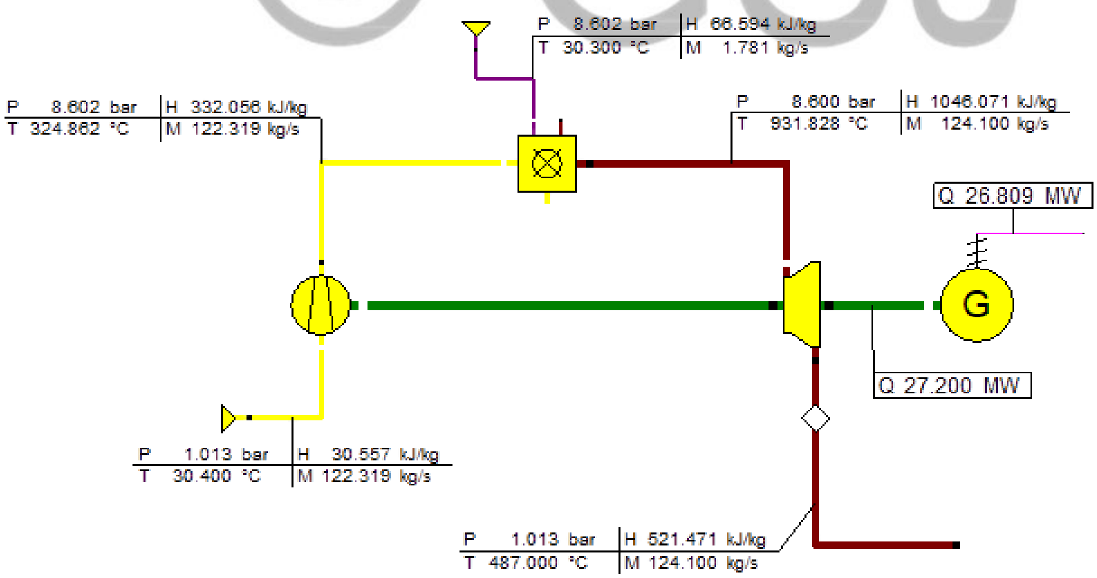


Figure 3 Model of GE MS 5001 in Design Conditions

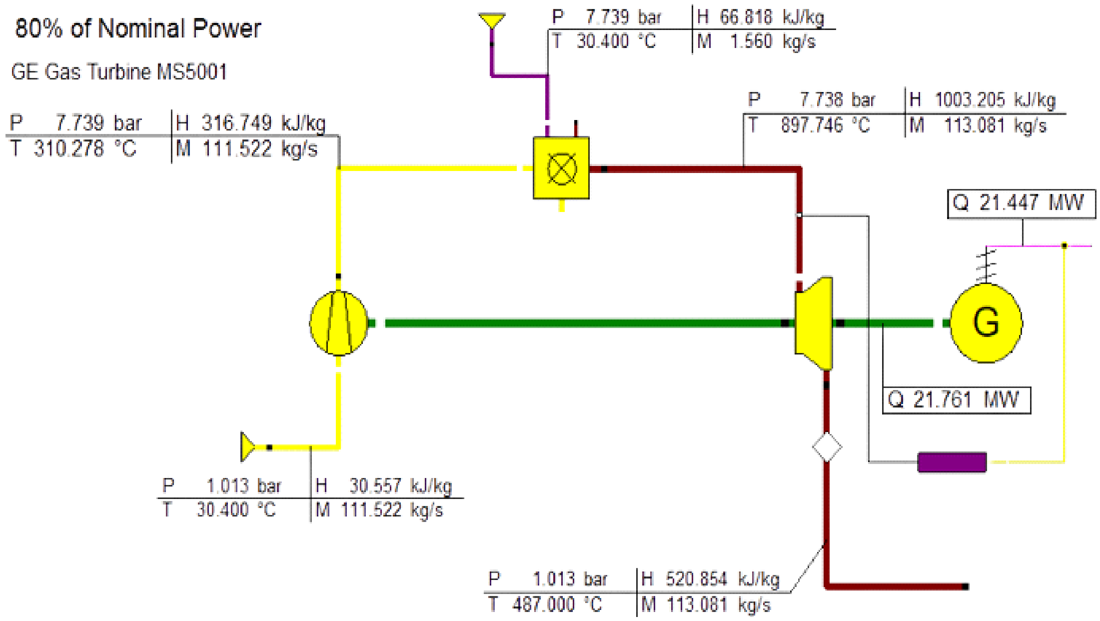


Figure 4 Gas Turbine working at 80 % of Nominal Power

Result and discussions

Temperature simulation in off-design

Table 2 and Figure 5 show the simulation of the exhaust and inlet temperatures of the gas turbine according to the criteria followed for establishing the temperatures in off-design. As shown in Tables 4 and 5, the power of the gas turbine is higher when the ambient conditions are colder due to the fact that a bigger amount of gas is expanded in the turbine and the pressure ratio is higher than in nominal conditions. That makes the gas turbine power output higher in rainy seasons, while in dry season it decreases. In the analysis, an average of 2.73 MW drop in power output for 10^{o}C increase in ambient temperature is obtained. The power of the gas turbine is higher when the ambient conditions are colder due to the fact that a greater amount of gas is expanded in the turbine, and the pressure ratio is higher than in nominal conditions. This makes the gas turbine power output higher in rainy seasons, while in dry seasons, it decreases. In the analysis, an average of 2.73 MW drop in power output for 10^{o}C increase in ambient temperature is obtained.

In a combined cycle power plant, the energy in the exhaust gases of the gas turbine is transferred to the steam cycle by using a HRSG. The exhaust gases of the gas turbine have a large amount of energy when they are leaving the turbine with a temperature of over 487 ˚C. The parameters which define the HRSG are set for the design case that means that the surfaces of the heat exchangers are designed according to these conditions. At other conditions, they are of course constant. For adequate performance of a combined cycle power plant the conditions of the steam cycle should remain constant. In consequence the outlet temperature (TOT) of the gas turbine should be as constant as possible independent of the ambient temperature.

Table 2 Temperature variation in Off-design

Tamb **(◦C)**	***λ***	***TIT*** **(°C)**	***TOT*** **(°C)**
20	3.773	968.21	447.0
30	3.890	968.15	487.0
40	4.004	618.56	487.0
50	4.178	543.98	487.0

Table 3 Mass flows in Off-design

Tamb **(◦C)**	$\dot{m}_{air}$ **(kg/s)**	$\dot{m}_{fuel}$ **(kg/s)**	$\dot{m}_{gas}$ **(kg/s)**
20	101.35	1.588	102.91
30	106.29	1.585	107.88
40	111.28	1.612	112.90
50	116.99	1.645	118.64

Table 4 Parameters obtained in Off-Design

Tamb **(◦C)**	***λ***	**Power (*MWe*)**
20	3.773	32.328
30	3.890	29.588
40	4.004	26.809
50	4.126	24.119

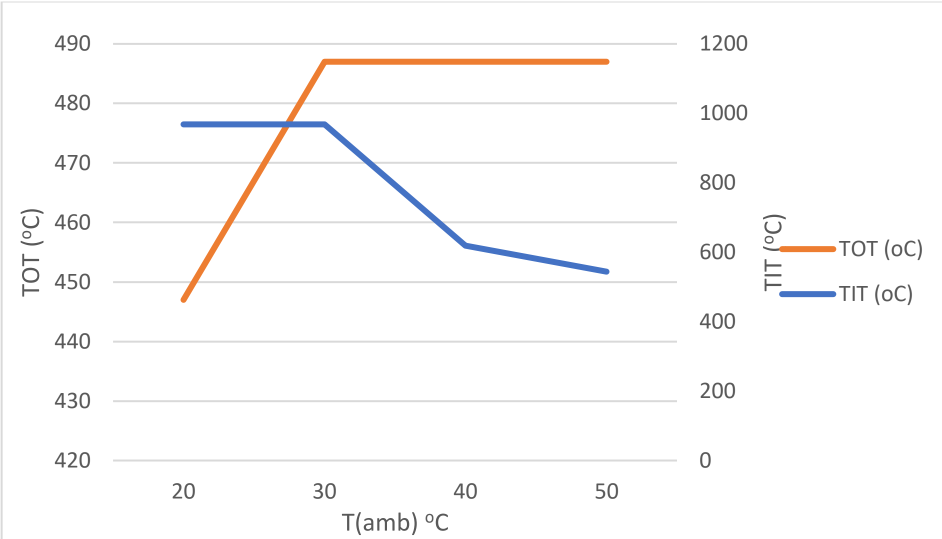


Figure 5 Temperature Simulation in Off-design

Variation of fuel and air flows

Figure 6 shows the simulation of the gas flow and exhaust temperature when the performance of the gas turbine varies from 30 % to 110 % of the nominal power.

- The ratio M_{gas}/M_{gas0} represents the variation of the gas flow with regards to the nominal gas flow.
- The ratio T_{exh}/T_{exh0} represents the variation of temperature with regards to the exhaust temperature in design conditions.

In Table 5, the different values obtained for every parameter are shown in each case of the off-design:

- The parameter Off-design represents the ratio between the necessary power and the nominal power.
- The parameter P_{aprox} is the power that in reality is obtained in the turbine in each case.
- The ratio P_{aprox}/P_0 represents how close we are at obtaining the off-design percentage necessary.

Off-design	P_0 **(MW)**	P_{aprox}**(MW)**	$\dot{m}_{air}$**(kg/s)**	$\dot{m}_{fuel}$**(kg/s)**	$\dot{m}_{gas}$**(kg/s)**	λ	***Texh*** **(◦C)**
110.00%	27.500	27.500	116.921	1.744	118.664	3.890	487.0
100.00%	25.000	25.003	106.292	1.585	107.877	3.890	487.0
90.00%	22.500	22.500	101.739	1.487	103.226	3.970	487.0
80.00%	20.000	20.000	96.865	1.385	98.250	4.057	487.0

70.00%	17.500	17.500	74.404	1.110	75.514	4.240	487.0
60.00%	15.000	15.000	63.775	0.951	64.726	4.343	487.0
50.00%	12.500	12.500	53.146	0.793	53.938	4.459	487.0
40.00%	10.000	10.000	42.517	0.634	43.151	4.592	450.0
30.00%	7.500	7.500	31.887	0.476	32.363	4.749	432.0

Table 5 Variation of Parameters in Off-design when the power is specified

From Table 5, the amount of fuel is decreasing at the same time as the amount of air. The fuel decreases slower compared with the variation of air flow. The decrease of the amount of air entering the compressor leads to a constant outlet turbine temperature, can be seen in Figure 6.

Table 6 Relative parameters in off-design

***Paprox/P*0**	***Mgas/Mgas*0**	***Texh/Texh*0**
110.0%	99.6%	101.0%
100.0%	100.0%	100.0%
90.0%	95.7%	100.0%
80.0%	91.1%	100.0%
70.0%	86.1%	100.0%
60.0%	80.7%	100.0%
50.0%	74.6%	100.0%
40.0%	67.7%	92.4%
30.0%	60.4%	88.7%

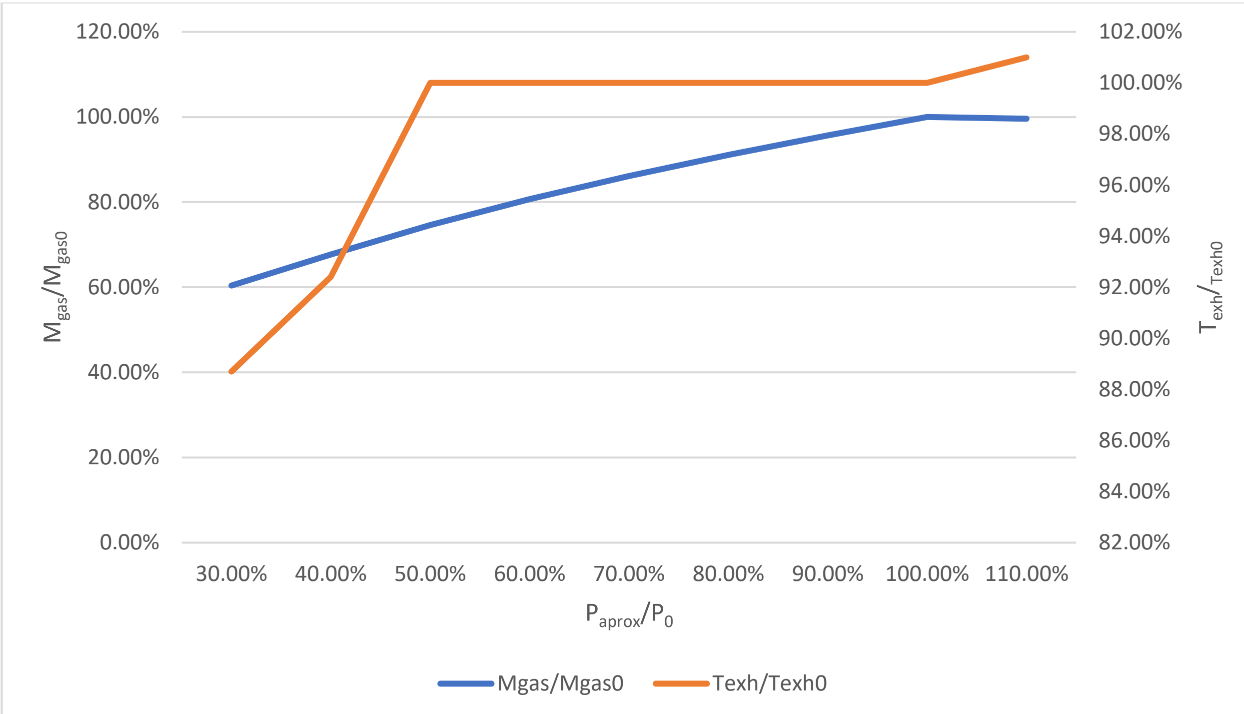


Figure 6 Temperature and Mass flow behaviour in off-design for a specific power

As shown in Figure 7, less mass goes through the turbine when we move into off-design operation, which implies that, the air flow, and the fuel flow decreases.

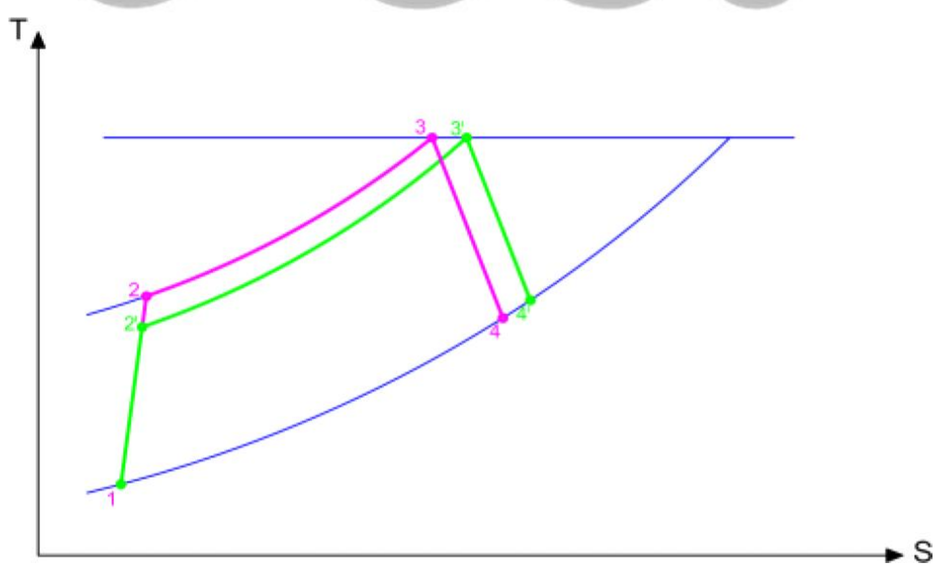


Figure 7 Comparison between the T-S diagrams for the gas turbine accepting less air

In the Figure 7, the cycle 1-2'-3'-4' represents the gas turbine working with less air. In the graphic, we can see that when the air flow is small the compression process is shorter, and the combustion is longer until reaching the maximum temperature in the cycle. This new "longer" combustion in process 2'-3' means that the amount of fuel burnt is bigger than in process 2-3. Technically, the mass of air entering the compressor is controlled by changing the orientation of the blades at the entrance (inlet guides vanes).

Variation of efficiency in components

As earlier mentioned, the gas turbine efficiency depends only on the pressure ratio and the nature of the working fluid. Working in off-design conditions means changes in the pressure ratio of the gas turbine and in its power output. But also, the other components of the gas turbine working in off-design suffer a change in their performance which has to be taken into account in the overall efficiency of the gas turbine.

In Ebsilon, compressors and turbines have an established default value of isentropic efficiency. The isentropic efficiency in a compressor or a turbine is a comparison between the real power obtained or consumed and the isentropic case. The default isentropic efficiency for turbines is 0.9 and for compressors is 0.85 and in off-design these values are defined by some correction curves. The variation of isentropic efficiency is directly proportional to the change of mass flow which is going through the compressor or turbine.

Conclusion

EBSILON Professional software was employed to model and simulate the Omoku gas turbine model. Modeling was done for both design and off-design scenarios to offer parameters that gas turbine model manufacturers would often not provide. The generated model validation results was in good agreement. Additionally, the data gathered will be beneficial for the installed gas turbine model thermodynamic and environmental evaluations. From the analysis, it was deduced that the power of the gas turbine is higher when the ambient conditions are colder due to the fact that a bigger amount of gas is expanded in the turbine and the pressure ratio is higher than in nominal conditions. This makes the gas turbine power output higher in rainy seasons, while in dry seasons it decreases. The power outputs at different ambient temperatures were simulated, indicating a drop in power output with increase in ambient temperature. An average of 2.73 MW drop in power output for 10◦C increase in ambient temperature was obtained.

The mass flow, air flow ratios under different load conditions (30% to 110% of nominal power simulation) show a decrease in the amount of fuel and air. However, fuel decreases slower compared with the variation of air flow at an average of 0.115 to 5.393 respectively. The decrease of the amount of air entering the compressor led to a constant outlet turbine temperature with variation in load case between 100% to 40%. Also, with less mass (air and fuel flow) going through the turbine when in off-design operation, the compression process is shorter, and the combustion is longer until reaching the maximum temperature in the cycle. This implied that more fuel is burnt. Technically, the mass of air entering the compressor can be controlled by changing the orientation of the blades at the entrance (inlet guides vanes). The results also showed that gas turbines with higher design performance exhibit less efficiency degradation during off-design operation. The efficiency of Gas Turbine power plants is strongly affected by the pressure ratio, the air-fuel ratio, the ambient temperature, and the isentropic efficiencies.

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