Simulation of Gas Turbine Operations for Improved Performance

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Abstract— The response mode of some pre- specified parameters of gas turbine plant was studied and analysed using the scientific tool of simulation by varying the controlled variables, namely, flow rates, compressor inlet temperature and turbine inlet temperature. The results were achieved by following some steps which includes; determining the relationship that exist between components in the form of mathematical models, the equations from the mathematical models were solved on a visual C# environment. The results obtained showed that the control variables have major influence on the system; this was seen from the response mode of the pre- specified parameters when the control variables were varied. The optimum values of some of the pre-specified parameters were thus obtained. This research work can be applied in power generation companies and other companies that make use of gas turbines.

Index Terms— Efficiency, Gas Turbine, Performance, Power Generation, Simulation,

1 Introduction

THIS research tries to optimize the operating parameters of a gas turbine for improved performance. The operating parameters of a gas turbine play important roles in determining the performance of the gas turbine. Here, optimize means to make the gas turbine more efficient. The process of finding the requirement that gives the maximum or minimum values of a function is known as optimization. In thermal systems like a gas turbine, optimizing usually involves the use of simulation to simulate the performance over some operating conditions. Simulation was used to find the response mode of the state variables namely Turbine outlet temperature, Turbine work, Compressor work, Compressor exit temperature, Net work Output, Optimal Pressure ratio and the maximum Net work.

1.2 Statement of the Problem

The gas turbine engine is a major source of power generation in most industries in Nigeria. An improved Performance of the gas turbine system is key to efficient power generation. Sensitive parameters of the gas turbine engine have influence on the general operation of the gas turbine including its life span, power output and smooth operation without unnecessary shutdown. A study on the response modes of some pre-specified sensitive parameters will help to improve its performance

2 LITERATURE REVIEW

2.1 Early Development

Serious development of the gas turbine began not long before the Second World War with Shaft power in mind, but attention was soon transferred to the turbojet engine for aircraft propulsion. The gas turbine began to compete successfully in other fields only in the mid nineteen fifties (Cohen and others, 1996). But since then it has made a progressively greater impact in an increasing variety of applications. In 1791 a patent was given to John Barber, an Englishman, for the first true gas turbine. His invention had most of the elements present in the modern-day gas turbines. John Dumball envisioned a multistage turbine in 1808; unfortunately, his idea consisted only of moving blades without stationary airfoils to turn the flow into each succeeding stage (Giampaolo, 2006). Had he realized the need for a stationary stage between each rotating stage he would have originated the concept of an axial flow turbine. Najjar (1988) analysed the part load performance of the gas turbine cycle to estimate the equilibrium running line on the compressor characteristics for different running conditions of pressure ratio, performance calculations show that the maximum cycle temperature is relatively the most influential parameters hence operation along an isothermal equilibrium line gives the best performance. Lifson and others (1989) in their work on assessment of gas turbine vibration monitoring presented a basis for selecting and justifying vibration monitoring equipment for power generating gas turbines.

2.2 Recent Developments

Yasushi and others (2009) carried out a study on the optimal operation criteria for gas turbine cogeneration system based on the analytical solution of a linear programming model. It was shown that the optimal operation criteria successfully provided a direction for the system operation under the condition where the electric power output of the gas turbine was less than the capacity. Rahman and others (2011) investigated the effect of ambient temperature and operation conditions on the performance of gas turbine powerplant. It was observed that the thermal efficiency increases linearly with increase of compression ratio, the specific fuel consumption increases with increase in ambient temperature and lower turbine inlet temperature. Dempsey and others (2006) answered the question "where the most appropriate design space is, by showing the generalized performance trends of several four-port wave rotor-topping configurations in multidimensional space. A performance analysis and optimization of an open – cycle regenerator gas turbine was performed by lingen and others (2004), They optimized the power output by adjusting the mass-flow rate and the distribution of pressure losses along the flow path. Singh and Rajesh (2012), analysed the effects of the ambient air temperature (AAT) on various parameters of power plant namely power output of turbine,

efficiency and heat rate of gas turbine. The results of the analysis on 10MW power
plant showed that increase in AAT by 30 o C decreased the net power output by 18% and 11% decrease in mass flow rate of inlet air.

3 SYSTEM CONFIGURATIONS

Table 3.1 System Configuration

DESCRIPTION	DATA
COMPRESSOR	
Type	Axial
Number of stages	12
Compression ratio	12.5:1
Speed	14 944 rpm
COMBUSTION CHAMBER	
Type	Annular
Ignition	Torch
Number of fuel injectors	12
TURBINE	
Type	Reaction
Number of stages	3

3.1 Solution Methods

The problem was identified; this was related to the physical system
The schematic of the physical system illustrating the component relationships was drawn. As shown in figure 3.1a
A mathematical model of the physical system was obtained
Some assumptions were made to simplify the process which includes:

I. The working fluid is air with specific heat constant C_p, 1.005(kJ/kgK) and specific heat constant ratio k, 1.4 (-)
II. Negligible heat transfer to the ambient
III. Pressure at compressor exit P_2, equals pressure at the combustor exit, P_3
IV. The chemical composition and properties of the air remains constant throughout the cycle.

Data was collected both in primary and secondary form.
Codes were written in visual C# environment to solve the numerical equations as well as to run the simulation; the codes are in the Appendix. Gas turbine simulation software developed in visual C# environment by Saturday was also used to run the simulation and the results obtained were presented in the following chapter

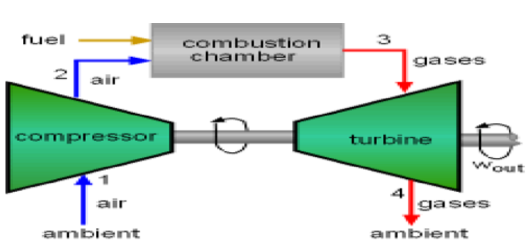

Figure 3.1 schematic of a gas turbine system

3.2 Equation Formulation

Compressor work:

$$\dot{W}_C = \dot{m}_a c_p (T_2 - T_1) \quad (1)$$

$$\dot{W}_C = \dot{m}_a c_p T_1 \left(r^{\left(\frac{k-1}{K}\right)} - 1 \right) \quad (2)$$

Where:
$\dot{m}_a$ is mass flow rate of air entering the compressor
c_p is the Specific Heat Capacity at constant pressure
r is the pressure ratio
k is the ratio of specific heat capacity
T_1 is the compressor inlet temperature
T_2 is the compressor exit temperature

Compressor Exit Temperature

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}} \quad (3)$$

$$T_2 = T_1 \left(r^{\left(\frac{k-1}{k}\right)} \right) \quad (4)$$

P_1 and P_2 is the compressor inlet and exit pressure respectively

Heat addition and removal from the Combustor (combustor Model)

Heat addition to the working fluid is given by

$$\dot{Q}_{IN} = \dot{m}_a c_p (T_3 - T_2) \quad (5)$$

$$\dot{Q}_{IN} = \dot{m}_a c_p T_2 \left(\frac{T_3}{T_2} - 1\right) = \dot{M}_f H_f \quad (6)$$

Where:
T_3 is the turbine inlet temperature
$\dot{m}_F$ is the fuel flow rate
H_f is the fuel Heating Value

The quantity of heat removed from the working fluid is given by

$$\dot{Q}_{OUT} = \dot{m}_a c_p (T_4 - T_1) \quad (7)$$

T_4 is the turbine exit temperature

Power output of the turbine

$$\dot{W}_T = \dot{m}_a c_p (T_3 - T_4) \quad (8)$$

$$\dot{W}_T = \dot{m}_a c_p T_3 \left(1 - r^{\left(\frac{k-1}{k}\right)}\right) \quad (9)$$

Turbine exit temperature

$$T_4 = T_3 \left(r^{\frac{k-1}{k}} \right) \quad (10)$$

Net work output of the plant

$$\dot{W}_{NET} = \dot{W}_T - \dot{W}_C = \dot{m}_a c_p T_3 \left(1 - r^{\frac{k-1}{k}}\right) - \dot{m}_a c_p T_1 \left(r^{\frac{k-1}{k}} - 1\right) \quad (11)$$

$$\dot{W}_{NET} = \dot{m}_a c_p T_1 \left(1 - r^{\frac{k-1}{k}}\right)(T_3 - T_2) \quad (12)$$

The Optimum pressure ratio

$$r_{opt} = \left(\frac{T_3}{T_1}\right)^{\frac{K}{2(K-1)}} \quad (13)$$

The Maximum Net Work Output of the Plant

$$\dot{W}_{NET,W_{max}} = \left(\dot{m}_a c_p \left\{T_3\left[1-\left(\frac{T_3}{T_1}\right)^{-\frac{1}{2}}\right] - T_1\left[\left(\frac{T_3}{T_1}\right)^{\frac{1}{2}}-1\right]\right\}\right) \quad (14)$$

The Thermal Efficiency

$$\eta_{th} = 1 - r^{\left(\frac{K-1}{K}\right)} \quad (15)$$

$$\eta_{th} = \frac{\dot{W}_{Net}}{\dot{Q}_{IN}} \quad (16)$$

3.3 Method of Data Collection:

Primary Data was collected from the plant log book as recorded from the Data acquisition interface of the power plant and the other data were gathered from performance catalogue

4 RESULTS AND DISCUSSION

Table 4.1 Summary of the data collected and used in simulation

Description	Value
Compressor inlet temperatures T_1 (K)	298.7, 300.4 and 302.1
Turbine inlet Temperature T_3 (K)	1611.3
Turbine Exit Temperature T_4 (K)	783
Power Factor (-)	0.86
Air flow rate $\dot{m}_a$ (kg/s)	3.30
Pressure ratio	12.5
Heat rate (kJ/kWh)	11430
Fuel flow rates $\dot{m}_f$ (kg/s)	0.0699, 0.0744 and 0.0703
Efficiency (%)	31.5
Fuel Heating value (mJ/kg)	47.121
Power (kW)	
At Compressor inlet temperatures	
298.7(K)	1804
300.4(K)	1693
302.1(K)	1703

The results obtained from the simulation are presented and analysed. The compressor inlet temperature (T_1), the turbine inlet temperature (T_3) and the flow rates (Air flow rate ($\dot{m}_a$) and Fuel flow rate ($\dot{m}_F$)) was determined to have effects on some chosen parameters listed below

The Compressor exit temperature (T2), Turbine exit temperature (T_4), Compressor work ($\dot{W}_C$), Turbine work ($\dot{W}_T$), Net work output ($\dot{W}_{Net}$), Maximum net work output ($\dot{W}_{Net,Max}$), Optimal pressure ratio (r_{opt}), and Combustor Heat input ($\dot{Q}_{IN}$**).**

Table 4.2 Simulation result obtained at fixed T_3 = 1611.3(K) and $\dot{m}_a$ = 3.30(kg/s) and varying T_1

T_1 (K)	T_2 (K)	T_4 (K)	$\dot{W}_C$ (kW)	$\dot{W}_{Net}$ (kW)	$\dot{W}_{Net,Max}$ (kW)	$\dot{Q}_{IN}$ (kW)
298.70	**614.66**	**783.02**	**1047.90**	**1699.09**	**1732.84**	**3305.34**
300.40	**618.16**	**783.02**	**1053.86**	**1693.13**	**1725.40**	**3293.74**
302.10	**621.66**	**783.02**	**1059.82**	**1687.16**	**1718.00**	**3282.14**
310.00	**637.92**	**783.02**	**1087.54**	**1659.45**	**1684.08**	**3228.22**

It can be seen from the results in table 4.2 that increasing the compressor inlet temperature leads to an increase in the compressor exit temperature; the turbine exit temperature remains constant and the net work reduces. the compressor work increases as compressor inlet temperature increases, and the net work output decreases as compressor inlet temperature increases. The maximum net work output that could be obtained from the system also decreases and the turbine work remained constant as compressor inlet temperature was varied. It is important to note that the first three compressor inlet temperatures are the real operating temperatures of the system from the control panel.

the plot profile of figure 4.1, shows that Increasing the compressor inlet temperature leads to an increase in the turbine inlet temperature, but the increment is not directly proportional as can be seen from the result of the simulation for example increasing the compressor inlet temperature from 300.40(K) to 302.10(K), the turbine inlet temperature increased from 1611.30(K) to 1614.80(K) this is an increment of 3.5(K) as against 1.7(K) increment in the compressor inlet temperature.

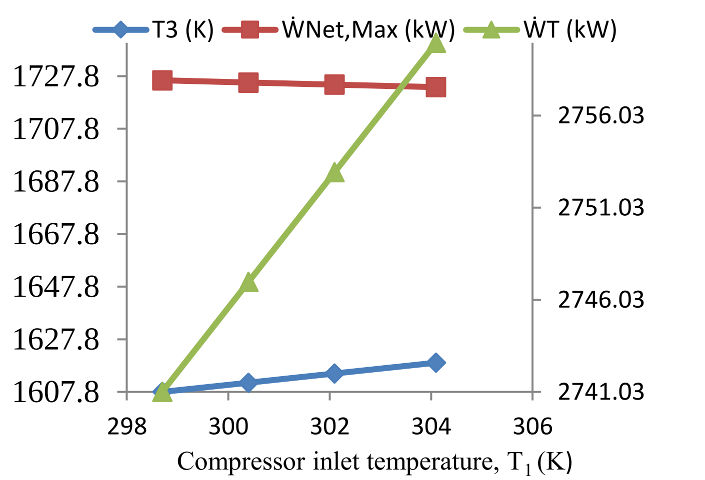

Figure 4.1: A plot of turbine inlet temperature (T_3), maximum net work output ($\dot{W}_{Net,Max}$**)** and turbine work ($\dot{W}_T$**)** against compressor inlet temperature (T_1)

In figure 4.2, turbine work and air flow rate increase with increase in heat input in the combustor. The maximum net work that could be obtained at the various air flow rate also increases as the air flow rates increase. The optimal pressure ratio for the system was observed to remain constant at 19.09 at the different air flow rate.

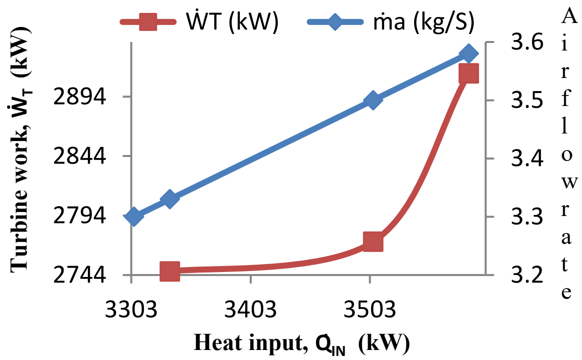

Figure 4.2: A plot of Turbine work, ($\dot{W}_T$) and Air flow rate, ($\dot{m}_a$) against Heat input, ($\dot{Q}_{IN}$)

the simulation result obtained when the turbine inlet temperature was kept constant and both the compressor inlet temperature and air flow rate are varied. Shows that the compressor exit temperature increases as compressor inlet temperature increases, turbine exit temperature remains unchanged; figures 4.3, shows that the optimal air flow rate that gives the lowest compressor work is at 3.29(kg/s). Compressor work is highest with the lowest compressor inlet temperature and highest air flow rate combination and lowest with medium compressor inlet temperature and lowest air flow rate combination

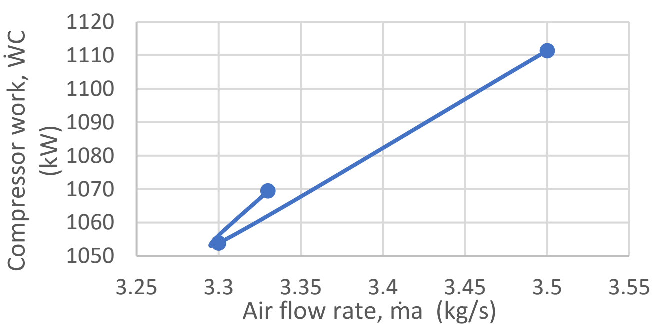

Figure 4.3: A Plot of Compressor work, $\dot{W}_C$ against Air flow rate, $\dot{m}_a$

5.1 Conclusion

The result of this research work showed that varying the compressor inlet temperature, the flow rates (Gas and the working fluid) and the turbine inlet temperature has major influence on the overall performance of the gas turbine.
The Gas turbine usage at Total E & P has been for a long time and as such alot of maintenance are in place to ensure that it operates at its best performance. One of such methods is gas turbine crank wash. It would be suggested that a research be carried out on the thermo-economic analysis of gas turbine crank wash as a maintenance process. Also suggested is research on best ways possible to reduce the excess level of vibration on a gas turbine system

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