

PAPER 35 – IMPACT OF THERMO-FLUID MODELLING AND SIMULATION FOR A TWO-SPOOL TURBOSHAFT GAS TURBINE CONFIGURATION

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ABSTRACT

Gas turbines built in the tropics for power generation are made for other climate regions, thus their performance tends to be affected. This research aims to present the impact of thermo-fluid modelling for gas turbines on performance simulations of a two-spool turboshaft power-generating gas turbine configuration. The variation of operating conditions (compression ratio, turbine inlet temperature (TIT), and ambient temperature) on the performance of gas turbine (thermal efficiency, shaft power delivered, specific fuel consumption (SFC), heat rate (HR) and fuel flow (FF)) was investigated. The analysis of the cycle has been carried out using GASTURB 14. The off-design simulation is carried out for ambient temperature between 288K to 318K and TIT between 1400K to 1600K. As the ambient temperature increases for a given TIT, the thermal efficiency, shaft power delivered, and FF decrease while the SFC and HR increase; this is due to a decrease in mass flow rate to the compressor as a result of lower air density and a higher compressor work. There is a loss of 4.3% in thermal efficiency at TIT 1400K as ambient temperature increases from 288K to 318K, this loss decreases to 1.3% at TIT 1600K, which reveals that, as TIT increases percentage loss in thermal efficiency decreases on increasing ambient temperature. In addition to this, it was observed that there was an increase of 0.05 kg/kWh in SFC at TIT 1400K when the ambient temperature rises from 288K to 318K which in turn decreased to 0.01kg/kWh. As the TIT increases for a given compression ratio (design point) or an ambient temperature (off-design point), the thermal efficiency, shaft power delivered and FF increase while SFC and HR decrease. The simulation results obtained were validated using industry data and those obtained from other experimental methods and they showed acceptable agreement.

KEYWORDS: Ambient temperature, compression ratio, design and off-design point, turbine inlet temperature.

1. INTRODUCTION

Operators' top priority is to make sure gas turbines function as efficiently as possible. Gas turbines are designed to compress air with the least amount of effort possible while maintaining high levels of efficiency and aerodynamic stability. Anything that boosts productivity and profit in the current economic context is welcome (Ibrahim *et al.*, 2011a). The International Standard Organization (ISO) conditions for a gas turbine are 1.013 bar of atmospheric pressure, an ambient temperature of 15°C, and relative ambient humidity of 60% (ASME, 2015). In a gas turbine power plant, the output is sensitive to the surrounding environment (Xiaojun *et al.*, 2010). The performance of a gas turbine can be categorized according to its thermal efficiency, power production, specific fuel consumption (SFC), and work ratio. Its performance is affected by several factors, including the compressor pressure ratio (PR), combustion inlet temperature (TIT) and other operational factors such as ambient temperature, elevation and relative humidity (Thamir and Rahman, 2010). The best effective way for determining a gas turbine power plant's operation is a mathematical modelling strategy that makes use of computer tools (Barsali *et al.*, 2015). In this respect, quantitative modelling of gas turbine power plants is necessary. The conditions at a gas turbine power plant's inlet and exit determine its performance in terms of power production, thermal efficiency, and specific fuel consumption (Khaliq and Dincer, 2011). Hot days have significantly lower air density, pressure ratio, airflow, and power output. As a result, as ambient temperature rises, power output declines and specific fuel consumption (SFC) rises. Performance of gas turbines is strongly impacted by changes in the ambient conditions (Thamir *et al.*, 2019). The ambient, which changes periodically, determines the gas turbine's performance (Nada, 2014). As the intake air temperature rises, the limiting air volume rises as well. As constant-volume engines, gas turbines continuously move the same volume of air at a specific shaft speed. Because combustion air in gas turbines is drawn directly from the atmosphere, weather conditions have a significant impact on how well they work (Saif and Tariq, 2017). The output power drops as the ambient temperature rises and rises with the turbine entry temperature (TET). To prevent early component failure and a shortened gas turbine's life, it is not possible to increase the TET indefinitely from a material standpoint (Nasir *et al.*, 2018). This research work investigates how operating conditions affect the performance calculations of gas turbines installed in Kogi State, central Nigeria with an altitude of more than 2000m above sea level. This research aimed to assess the impact of thermo-

fluid modelling for gas turbines on performance calculations, and this can be achieved through the following objectives:

- i. to create a model to calculate gas turbine performance based on a chosen set of measurable parameters.
- ii. investigating the operational factors (such as ambient temperature (AT)) that have an impact on gas turbine performance.
- iii. validate model results with measure gas turbine performance.

2 THEORETICAL ANALYSES

2.1 Thermo-fluid Gas turbine component modelling

This dynamic thermo-fluid physics model, which consists of rotating and fluid elements, was developed as a starting point, using conservation principles and motion equations. Auxiliaries for the compressor, combustor, turbine, and engine are the gas turbine engine's key parts, and they all work together to produce the engine's total performance (Cohen *et al.*, 2017).

2.2 Modelling for Compressor

$$\dot{W}_c = \dot{m} \times h(T_{in}) - h(T_{out}) \quad (1)$$

$$PR_c = \frac{P_{out}}{P_{in}} \quad (2)$$

Equation (1), which reflects the compressor work but involves no heat transfer, is derived from energy conservation, equation (2) provides the compressor's pressure ratio relation (Thirunavukarasu, 2013).

2.3 Burner Modelling

$$\eta_b = \frac{1}{\dot{m}_f \times HV} (\dot{m}_{out} \times hT_{out} - \dot{m}_{in} \times hT_{in}) \quad (3)$$

The combustion chamber efficiency is defined by equation (3).

2.4 Turbine Modelling

$$\dot{W}_T = m \times (h(T_{in}) - h(T_{out})) \quad (4)$$

Turbine work is calculated by equation (4).

The rate of mass flow through the gas turbine is given as:

$$m = \rho v \quad (5)$$

$$\frac{dm}{dt} = \frac{d}{dt} (\rho v) \quad (6)$$

$$\dot{m} = \rho v \quad (7)$$

The density of the working fluid (air) has an inverse relationship with the temperature

$$\rho = \frac{k}{T_1} \quad (8)$$

Where T_1 is the ambient temperature, ρ is the density of air and k is the proportionality constant. The gas turbine's network (W_{net}) is computed:

$$W_{net} = W_T - W_C \quad (9)$$

$$P = \dot{m}_a \times (W_T - W_C) = \dot{m}_a \times W_{net} \quad (10)$$

$$P = \rho v \times W_{net} \quad (11)$$

$$P = \frac{k}{T_1} v \times W_{net} \quad (12)$$

The specific fuel consumption (SFC) is expressed by Equation (13).

$$SFC = \frac{3600 \times \dot{m}_f}{W_{net}} \quad (13)$$

The heat supplied is written as:

$$Q_{add} = C_{pg}(TIT - T_1(1 + \frac{\gamma-1}{\eta_c} \frac{PR^\gamma - 1}{\gamma})) \quad (14)$$

The efficiency of the gas turbine (η_{th}) can be calculated by Equation (15). It is the proportion of heat input to work performed by the turbine.

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \quad (15)$$

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 GasTurb 14

GasTurb 14 has been used to analyze the gas turbine cycle and evaluate the plant's performance. GasTurb 14 (GASTURB GMBH MELATENER STRABE 7052074 AACHEN, GERMANY) is professional software for gas turbine performance calculations.

3.1.2 The two-spool turboshaft

Interest is only in the two-spool turboshaft in this work since gas turbines used for power generation are the focus.

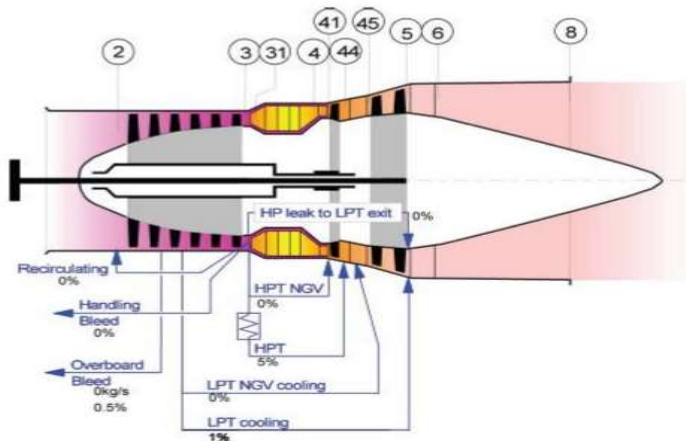


Figure 1. The state points in the GasTurb14 model of a two-spool turboshaft. The compressor entry (point 2), compressor outlet (point 3), high-pressure turbine entry (point 41), low-pressure turbine entry (point 45), and exhaust location (point 5) are the crucial points.

4. RESULTS AND DISCUSSION

4.1 Off-design point simulations

Table 1. Simulated results of the effect of ambient temperature and different turbine inlet temperatures on thermal efficiency

TIT(K)	1400	1500	1600
AMBIENT TEMPT(K)			

288	0.29015	0.29757	0.29652
293	0.28408	0.29537	0.29458
298	0.27770	0.29273	0.29257
303	0.27044	0.28947	0.29073
308	0.26283	0.28529	0.28885
313	0.25504	0.28028	0.28660
318	0.24719	0.27503	0.28396

The difference in thermal efficiency with ambient temperature at various TIT and a 60% relative humidity in the air is displayed in Table 1. It is evident that as the temperature of the turbine inlet increases from 1400K K to 1600 K, thermal efficiency also rises for a given ambient temperature until the turbine inlet temperature reaches 1650 K, at which point a sharp decline in thermal efficiency is seen (Ibrahim and Rahman, 2010). However, it is also established that the thermal efficiency will decrease for all ranges of TIT under consideration if the temperature of the ambient rises from 288K to 313K. Thermal efficiency rises at lower temperatures, but as the temperature rises, its value somewhat declines (Nasir *et al.*, 2018). Given that higher air density is derived from a lower ambient temperature and less compressor effort, improved gas turbine performance—which then results in greater thermal efficiency—is produced. Higher ambient temperatures, on the other hand, result in less air density and more compressor work. In this study, compressor work predominates over turbine work, resulting in a decline in net work done and a potential reduction in thermal efficiency at higher ambient temperatures (Saif and Tariq, 2017).

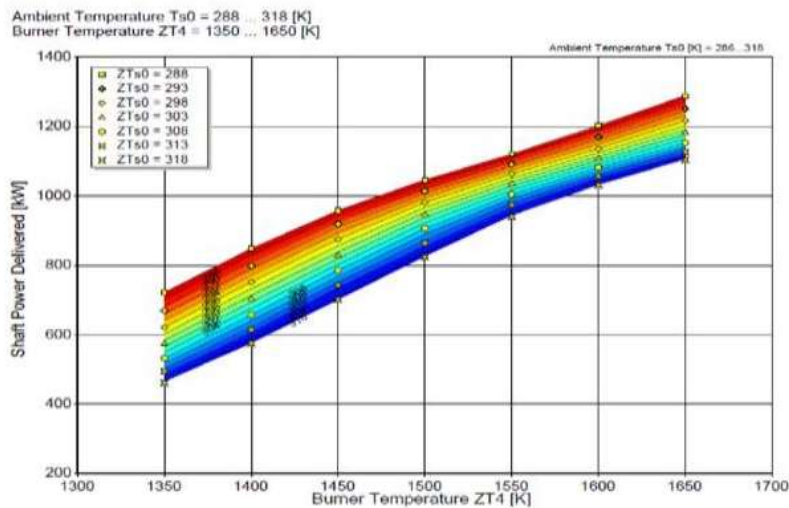


Figure 2. Shaft power delivered as a function of ambient temperature and TIT

The impact of the temperature of the ambient and TIT on shaft power is shown in Figure 2. It is clear that for a given ambient temperature, the shaft power provided increases when the TIT climbs from 1350K to 1650K (Nasir *et al.* 2018). However, it is determined that for all ranges of turbine inlet temperature being investigated, the shaft power provided decreases as the ambient temperature rises from 288K to 318K (Shi *et al.* 2010). At lower temperatures, the shaft power delivered is greater, but as the temperature rises, its value somewhat declines.

Table 2. Effect of ambient temperature and TIT on specific fuel consumption (kg/kWh)

AMBIENT TEMPT(K)	TIT(K)		
	1400	1500	1600
288	0.28772	0.28054	0.28154
293	0.29386	0.28263	0.28339

298	0.30062	0.28518	0.28533
303	0.30868	0.28839	0.28714
308	0.31762	0.29261	0.28901
313	0.32733	0.29785	0.29127
318	0.33772	0.30353	0.29398

Table 2 illustrates the change of ambient temperature and varied TIT on SFC. It has been found that when the turbine inlet temperature increases from 1350K to 1600K the significance of the specific fuel consumption decreases until the turbine inlet temperature of 1650K, where an abrupt rise in the value of the SFC is noticed. However, for a particular TIT, the value of a particular fuel consumption rises as the ambient temperature rises (Ibrahim and Rahman, 2010). This is because a change in ambient temperature produces an increase in the mass flow rate of air at the compressor's input (Saif and Tariq, 2017).

4.2 Model validation

The model developed in this study is validated by the actual data obtained from the gas turbine power plant. In this study, a GE LM6000pc gas turbine plant unit with an installed capacity of 45MW was selected for the study. The plant is owned by Dangote Cement Plc-Obajana Plant, Obajana, Kogi State, Nigeria. Operating data for the gas turbine unit were collected from the control room log sheet. A summary of the operating parameters of the GE LM6000pc used for this study is presented in Table 3.

Table 3. Operating parameters of GE LM6000pc

Time range	Ambient temperature (K)	Power output (MW)
04:00	295.4	38.87
06:00	295.4	36.76
08:00	297.1	31.17
10:00	297.1	31.08
12:00	297.6	37.99
14:00	298.2	37.86
16:00	299.8	37.25
18:00	299.8	32.78
20:00	299.3	33.41
22:00	295.9	39.33
24:00	295.4	38.88

The parameters considered in this study for the gas turbine engine during simulation are ambient temperature and turbine inlet temperature.

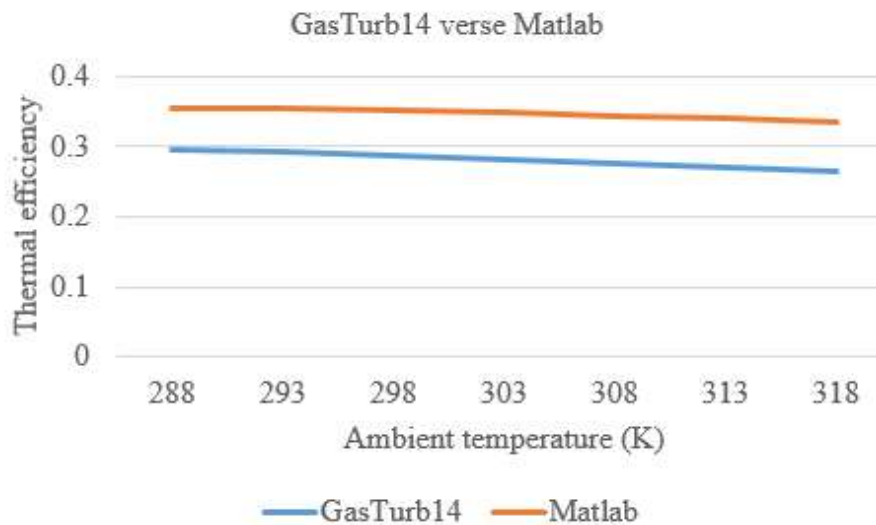


Figure 3. Comparison of the effect of ambient temperature on thermal efficiency

Figure 3 is a comparison between the results from the present study and that of previous work (Ibrahim *et al.*, 2016) and it reveals an acceptable agreement. It shows the effect of ambient temperature on the thermal efficiency of the gas turbine. As the ambient temperature increases for a given turbine inlet temperature, the ratio of the temperatures; $\frac{TIT}{T_1}$ reduces and this forces the thermal efficiency to decrease.

5.0 CONCLUSIONS

As the TIT increases for a particular ambient temperature (off-design point), the thermal efficiency and shaft power delivered increase while the SFC decreases. For a particular turbine inlet temperature at higher ambient temperatures (other than ISO conditions), the thermal efficiency and shaft power delivered decline while the specific fuel consumption rises. Lower air density and more compressor effort were the results of greater ambient temperature. The mass flow rate reduces because gas turbines are machines with a constant volume. The results of this study have been highlighted, but other areas of performance calculations should be carried out for other configurations of gas turbines.

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