Design and off-design performance analysis into industrial gas turbine

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ABSTRACT

This work has been undertaken to establish a frame work for evaluating two prevalent industrial gas turbine. These engines are simple cycle heavy duty inspired by GE-MS9001FA and intercooled aero-derivative gas turbine inspired by GE-LMS100. The engines have been modeled by in-house software developed in Cranfield University (TURBOMATCH) in order to verify the design point performance. Further investigation into the behavior of the engines over different ambient conditions, altitude and power setting has been also carried out. The engines have been tested over a wide range of ambient temperatures -5 °C up to 35°C. That's to say from -20 to +20K deviation from the design point. The ambient temperature variation was implemented with TET and power constant respectively. For both engines with constant turbine entry temperature, whenever the ambient temperature increase the required work by the compressors will increase as well. which consequently effects the engines output power. Therefore; the greater the ambient temperature for constant TET, the lesser the engines power output. The LMS 100 efficiency and power output are not severely affected compared to MS9001 FA model due to the presence of the intercooler. For constant power (useful work), the ambient temperature increase will reduce the engines thermal efficiency. The turbines have to compensate the work augmentation of the compressors as ambient temperature rises. The TET will experience a noticeable increase. Consequently, the fuel flow has to increase for the same amount of power output and so the exhaust temperature. For an engine such as lms100 the thermal efficiency reduction will not be significant at temperature less than 35°C. Further investigations of testing these engines for load and altitude variation scenarios have been considered in this research.

Keywords Turbine entry temperature, efficiency, useful work

1. Introduction

The electricity markets deregulation is sweeping all over the world; power plants and companies are intending to have the most efficient and profitable energy. This will likely influence the investors to select the proper gas turbine application which mostly convenient for their demand criteria.

In real life situation, the operation of any system is influenced by a variety of factors. Gas turbine is susceptible to be affected by the unit configuration, intensity of duty, maintenance and environmental stresses. The investors or the users of industrial gas turbine are interested in performance analysis of the equipment and its ability to work in different scenarios with minimum cost and technical penalty.

Two different categories of advanced classes of industrial gas turbines are to be considered in this work: aero derivative-intercooled engine and Frame engine (heavy duty gas turbine). Aero derivative turbine as the name suggests is a gas turbine derived from the gas turbine used for aircraft.

The work objective is to perform technical performance investigation of two different gas turbine engines: simple cycle gas turbine which represented by the heavy duty turbine frame 9 inspired by (GE9001Fa) and aero derivative intercooled gas turbine inspired by GE-LMS100Pa. These engines have been simulated in order to have the design point performance and to obtain clear understanding of the behaviour of each one under different conditions.
Cranfield University developed the TURBOMATCH scheme by S.M.Ein 1967[2] to facilitate design-point and off-design point gas turbine performance. This software has been used widely in this research to obtain the gas turbine engine performance and to test the limitation of each engine under different operational conditions. This work is an extension to a research thesis submitted to Cranfield University 2015[1].

2. Methodology: Engines modelling

The computer programming technology is available for researchers to make justifiable prediction of the engine performance which involves thermodynamic equations derived from the energy conservations physical laws. The simulation tool has been used in this work is TURBOMATCH which enables the engine models to be established. The engines components will be represented by “Bricks” [3] linked together to form the engine model. Input information has been stored in this Bricks.

2.1. Design point performance calculation

2.1.1. Single shaft engine design point performance

The industrial gas turbine engine allocated to be used for this research as simple cycle is a single shaft engine which scaled from GE-MS9001FA Heavy duty Gas Turbine introduced in the early 1950s [4]. Figure (1) shows a simplified arrangement of simple cycle gas turbine.

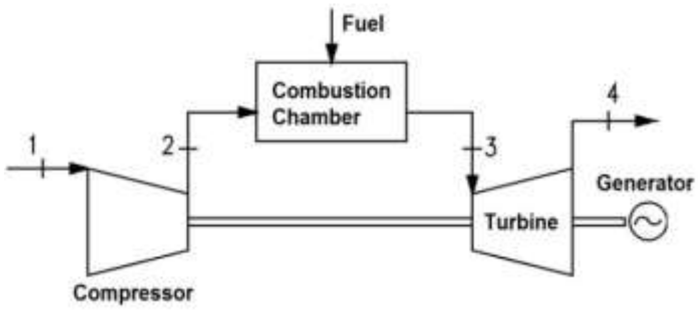


Figure 1 Simplification of single shaft gas turbine arrangement

The required input data has to be selected carefully to simulate the same conditions experienced by the real engine. The values used as input to the TORBOMATCH are stated in the table 1 below. About 10% of air extracted from compressor used for cooling purpose. The selected parameters values are chosen based on the assumption that this engine will be scaled from MS9001FA engine. The available parameters from engine producer and some literature study have been used to validate all these parameters as stated in the Table(1).

Table 1 Trbomach input information for single shaft engine

Parameter	Value
Inlet temperature	288K
Inlet pressure	101.325Kpa
Compressor isentropic efficiency	88%
Compressor pressure ratio	15
Combustion chamber pressure loss	6%
Combustion chamber efficiency	99%
Turbine isentropic efficiency	89%
Inlet mass flow	265.8Kg/s
Turbine entry temperature	1561K

2.1.2. Intercooled engine design point performance

The engine selected to represent the intercooled gas turbine engine model is inspired by GE LMS100. Based on the concept, compressor work can be reduced by employing an intercooler between compressor stages the compression becomes nearly isothermal at the inlet temperature, which reduces the compressors work and hence increasing the power output [5]. Figure (2) simplifies this engine.

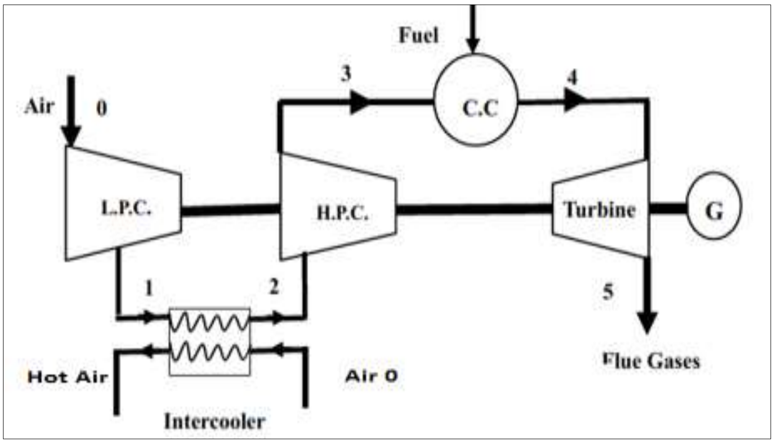


Figure 2 Simplification of intercooled gas turbine

The intercooler exit temperature has been calculated for this model outside the TURBOMACH code by using Excel sheet. The calculation is based on number of assumptions:

- The intercooler effectiveness (∈) 0.86
- The intercooler used is Air-Air.
- Intercooler effectiveness is given by the equation (3-1)

$\in= (T1 - T2)/(T1 - T0)$.خطأ! لا يوجد نص من النمط المعين في المستند-1

T0- Engine inlet temperature.
T1 -Compressor exit temperature
T2- intercooler exit temperature
Number of assumptions has been made to perform the simulation. Moreover some of input data was selected based on the available parameters provided by the producer. Table (2) shows some of these data.

Table 2 Intercooled engine input parameters

Parameter	Value
Inlet temperature	288K
Inlet pressure	101.325Kpa
LP Compressor isentropic efficiency	90%
HP compressor isentropic efficiency	90%
OPR	42 (3×14)
Intercooler Exit Temperature	305K Calculated
Combustion chamber pressure loss	5%
Combustion chamber efficiency	99%
Power Turbine isentropic efficiency	90%
Inlet mass flow	216Kg/s
Turbine entry temperature	1600K

2.2. OFF-design performance considerations

As stated previously the off- design consideration is a key answer to assist the engine capability to work over a wide range of conditions. Ambient temperature, altitude and part load are the main expected factors an engine can experience during its course of life.

2.2.1. Ambient temperature

Both engines have been tested over a range of ambient temperatures -5 C up to 35 C. That's to say from -20 to +20 K deviation of the design point. The ambient temperature variation was implemented with TET and power constant respectively. Number of observations has been highlighted.

2.2.2. Altitude

It is of high importance to simulate the engines at different altitude levels as the possibility of installing the Gas turbine in various countries around the world. Some places located at high altitude level such as Mexico 2230m and others at about 0m above the sea level like London [3]. Various ranges of elevation levels have been investigated from 0 to 3000m. It is commonly known that the ambient temperature and pressure decreases as the altitude gets higher, and from the Ideal Gas Low, the reduction in pressure leads to a drop in air density.

2.2.3. Part Load condition

It is curtail to test the engine with wide range of power values to observe the performance characteristic as the engine in real life has to follow the customer demand and the load change between day and night.

3. Engines performance simulation Results

3.1. Design point performance calculation results

By simulating the engines using the parameters in the table (3, 4) the results obtained are reasonable and similar to the manufacturer revealed data to some extent. The small difference in intercooled engine data is due to the fact that the real turbine provided by some advanced technologies and so the TORBOMACH does not has the ability to consider it with the available version. The tables 3 and 4 show some important simulation results of both engines respectively.

Table 3 Single shaft engine design point performance result

Parameter	Value
Power output	100MW
Fuel flow	6.3Kg/s
Thermal Efficiency	36.4%
Exit pressure	102Kpa

Table 4 Intercooled engine design point performance result

Parameter	Value
Power output	100MW
Fuel flow	5Kg/s
Thermal Efficiency	45%
Exit pressure	102Kpa

3.2. Off design point performance results and observations

The results of testing the selected engines for various conditions are stated bellow along with some important observations.

3.2.1. Ambient Temperature change with constant TET

When TET kept as constant, any increase in ambient temperature will increase the required work by compressor. The turbine has to produce more work for compressor which consequently, affects the power output of the engines. That’s to say that the greater ambient temperature for constant TET will reduce the gas turbine power output. Fuel consumption is concerned. By fixing the TET, the temperature difference between the combustor inlet and outlet will not be significant as the ambient temperature increases. Therefore the fuel flow which proportional to the amount of heat input will decrease. Moreover; the power decreases rabidly compared to the fuel flow reduction. For intercooled engine, Power and Thermal efficiency are not severely affected by high temperature because of the presence of the intercooler. Inlet temperature to the second compressor will be relatively low, which means less work is required by HP compressor. The figures 3and 4 explain the pervious observations.

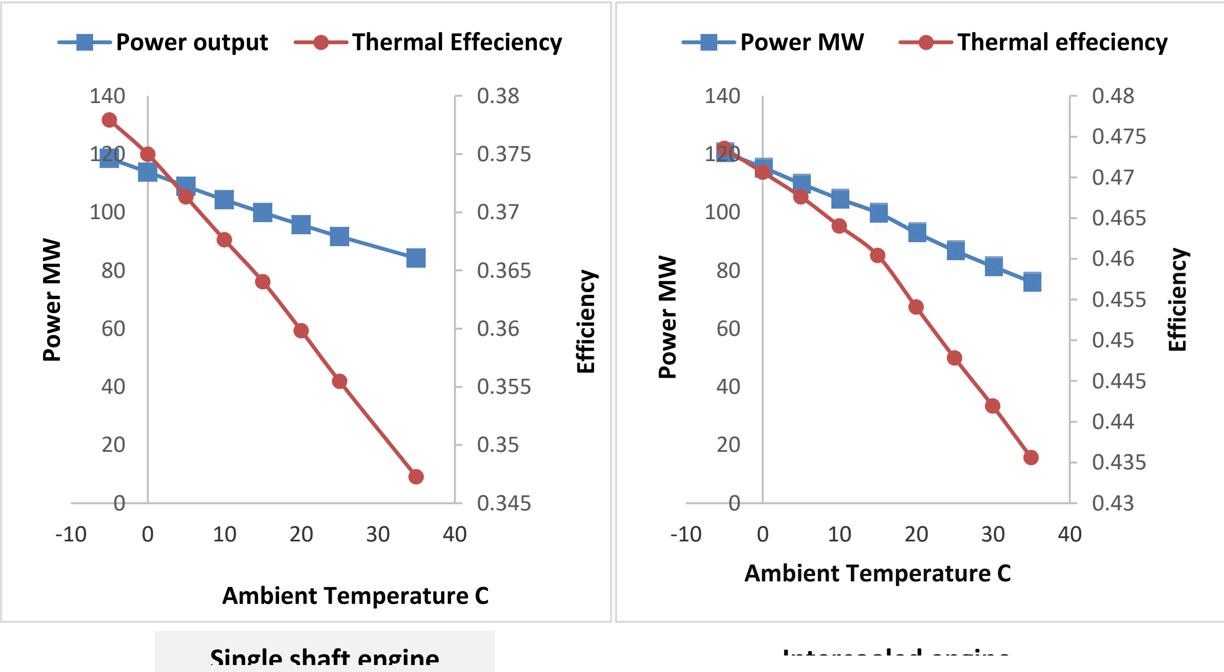


Figure 3 Ambient temperature with constant TET VS (Power output & Thermal efficiency)

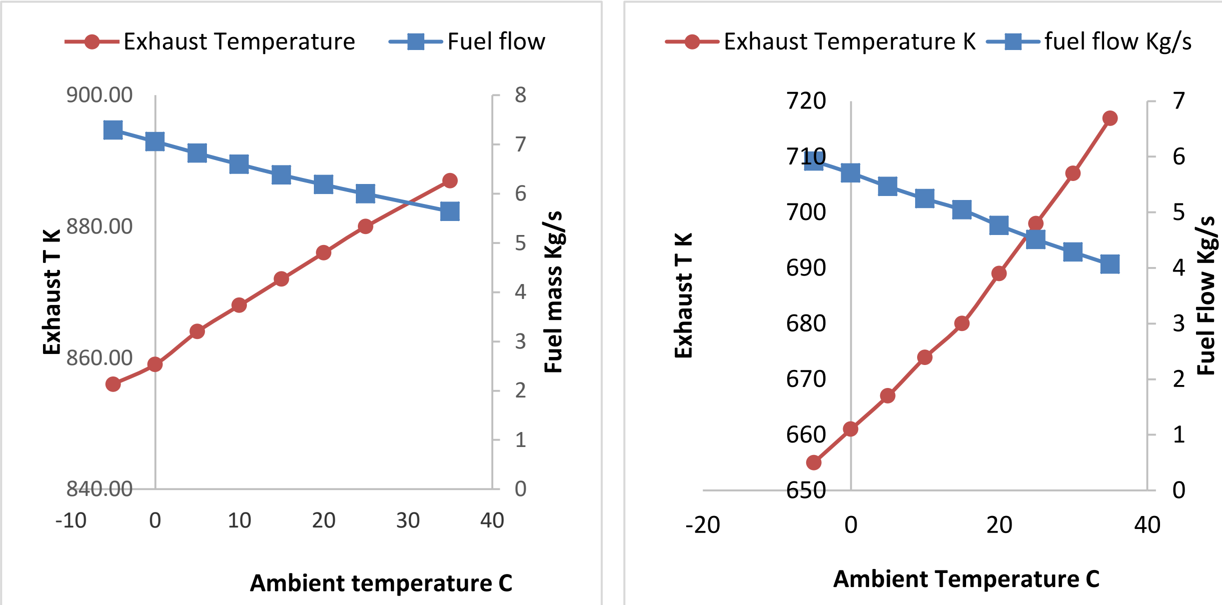
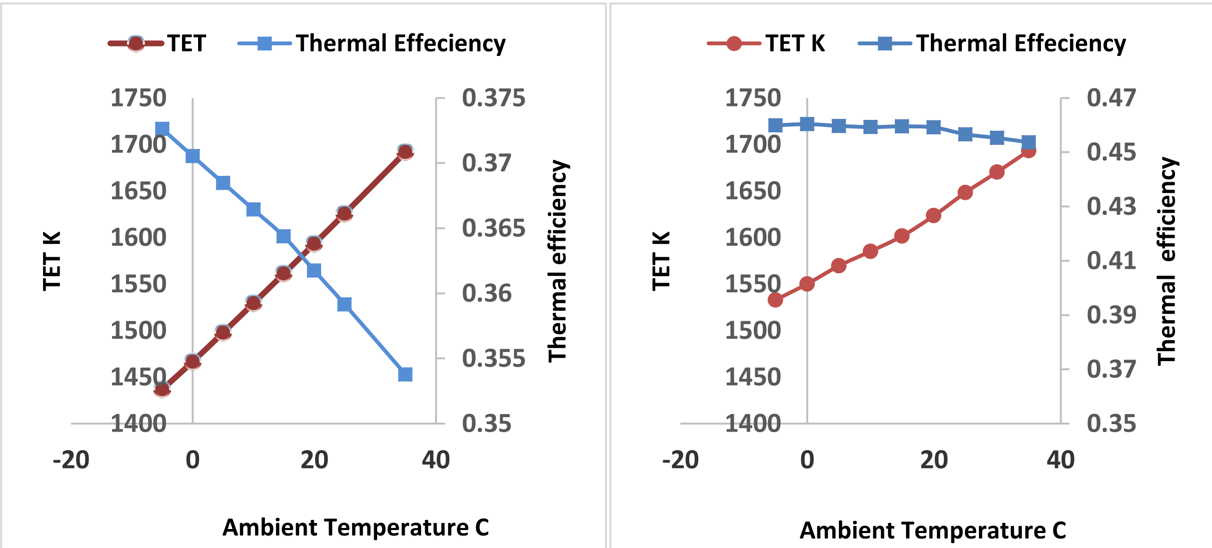


Figure 4 Ambient temperature with constant TET VS (Exhaust temperature & Fuel flow)

3.2.2. Ambient temperature change with constant power output

In this time the engines simulated at constant power and the ambient temperature is changed. Lower the ambient temperature, higher the engine thermal efficiency. As the engines inlet temperature increases, for constant power (useful work), the turbine has to compensate the work augmentation of the compressor results from ambient temperature increment. Therefore the TET will experience a noticeable increase. Consequently, the fuel flow has to be increased for the same amount of power output and so the exhaust temperature will increase. More details are in the Figures (5&6)



Single shaft engine

Intercooled engine

Figure 5 Ambient temperature with fixed power output Vs (TET& Thermal efficiency)

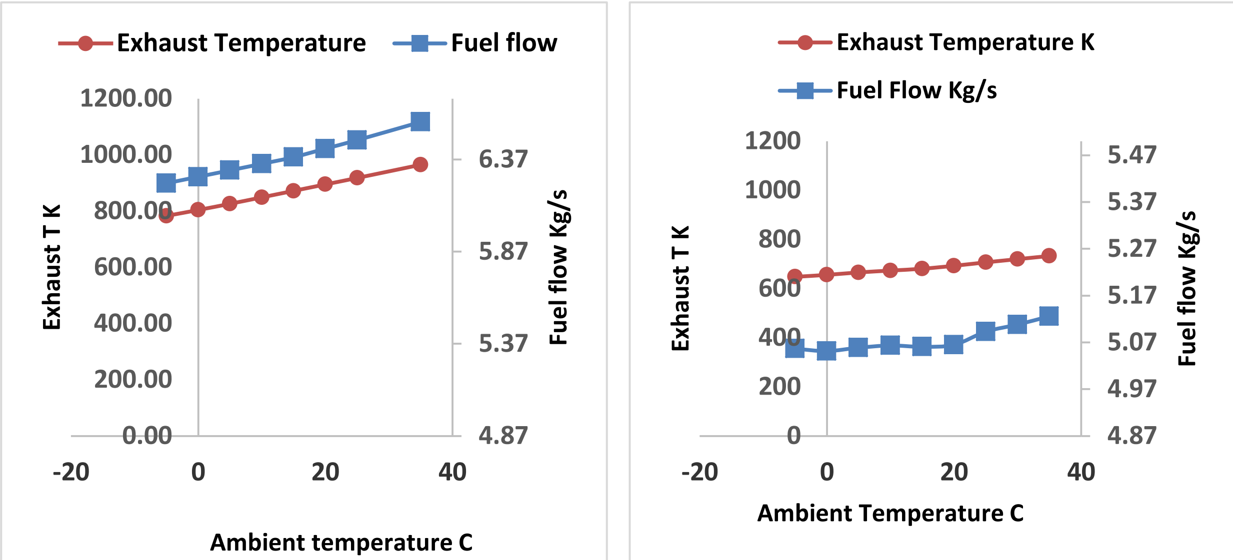
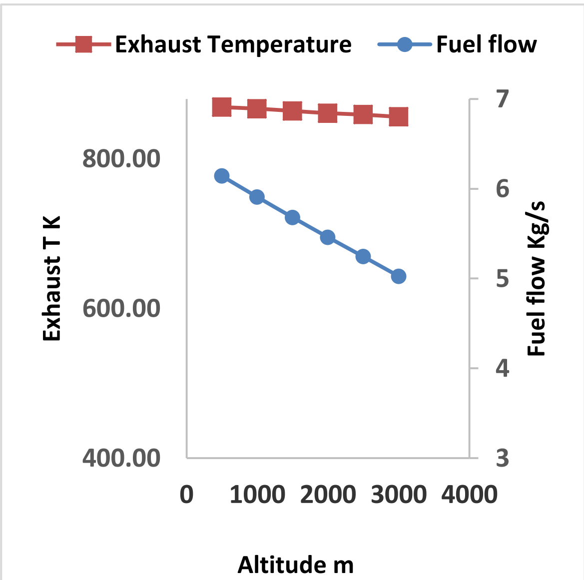


Figure 6 Ambient temperature with fixed power output Vs (Exhaust TK& fuel flow)

3.2.3. Altitude

3.2.3.1. Altitude change with TET constant

When TET remains constant, the higher the altitude the lower the power output and the thermal efficiency increase. The reduction in air density by elevation will reduce the air mass flow. Fuel to air ratio should remain constant thus fuel mass flow decreases and power output of the engine falls down. Heat input decreases faster than the reduction in power output. Hence, the thermal efficiency increase. This can be shown in figures (7&8).



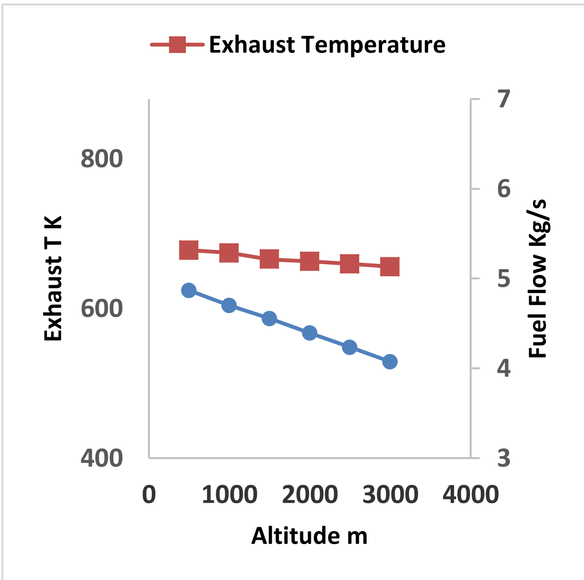


Figure 7 Altitude with constant TET VS (Fuel flow & Exhaust TK)

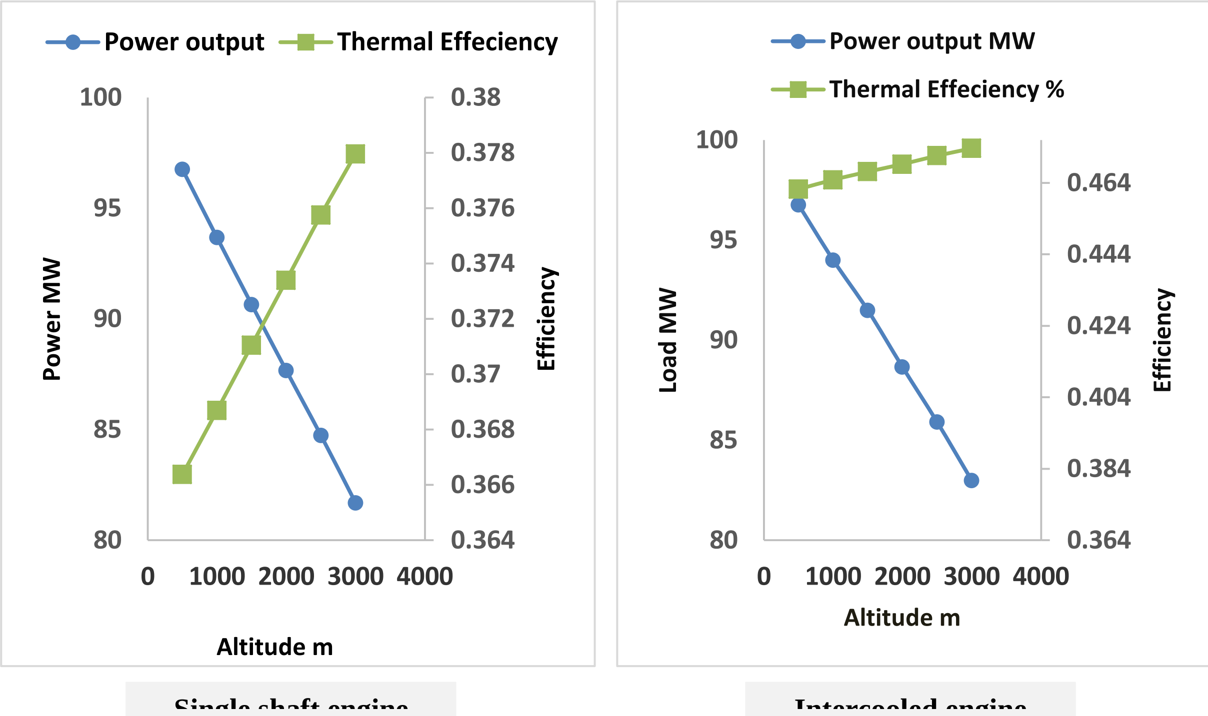


Figure 8 Altitude with constant TET VS (Efficiency & power output)

3.2.3.2. Altitude change with constant power output

As stated before the most significant effect of elevation is the mass flow reduction. This time the output power will keep constant. To gain the same power with high altitude the inlet and outlet of combustor temperature difference should increase to compensate the mass flow decrease. That requires increasing the TET and therefore the exhaust temperature will rise. The air mass flow and fuel flow decrease for constant power output causes reduction in the heat input which results in thermal efficiency increase. The reduction of fuel flow by elevation is faster than the required fuel addition to increase the TET. Therefore the trend of fuel reduction is not significant.

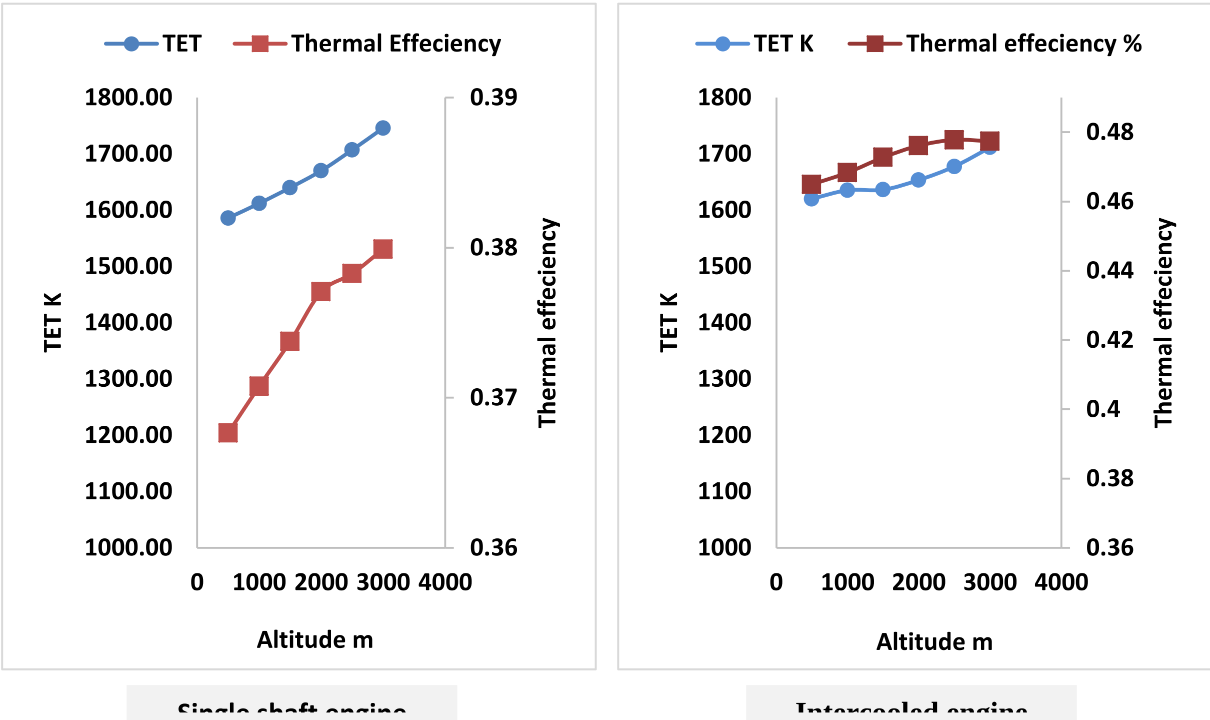


Figure 9 Altitude with constant power VS (Efficiency &TET K)

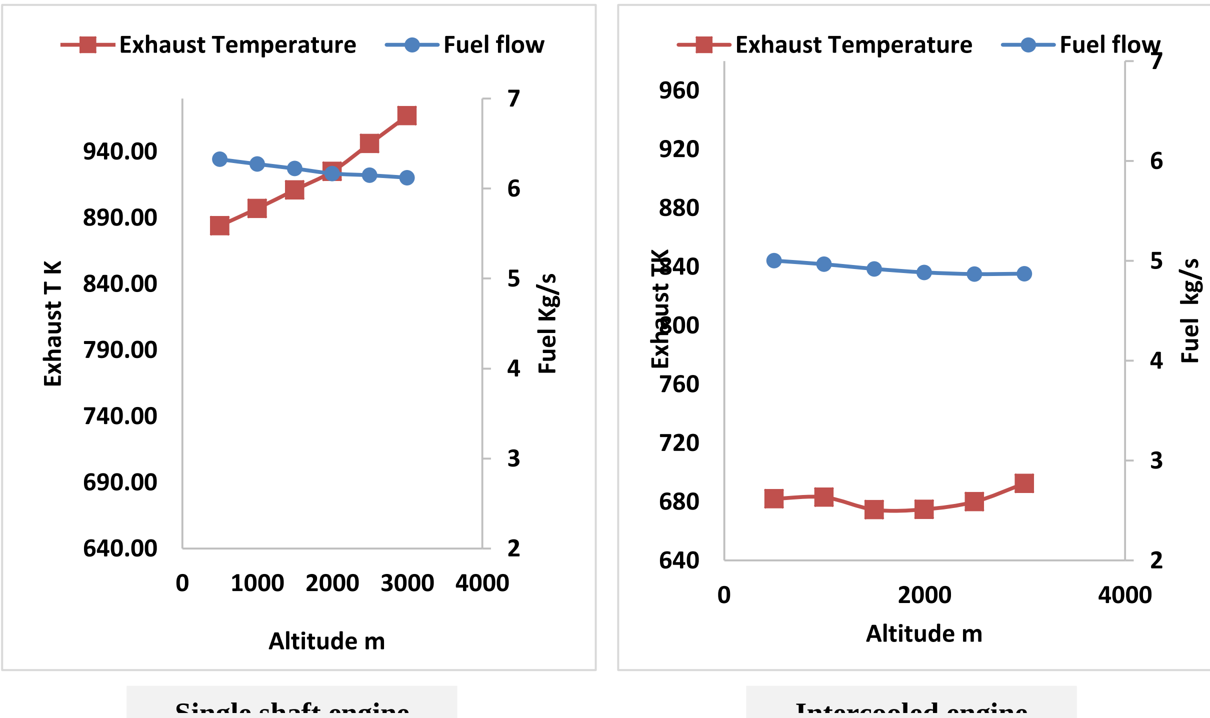


Figure 10Altitude with constant power VS (Fuel flow& Exhaust TK)

3.2.4.Part load condition observations

TET will increase and hence the fuel flow also rises. However the gain in power will be stronger. The unit thermal efficiency will experience a noticeable increase. Furthermore; the exhaust temperature and TET have similar trend. One of the advantageous of the intercooled gas turbine is the ability to work at different power sitting with high efficiency. The figure (11) lustrates that the simulated LMS100 engine can work efficiently at 50% power output. This engine produces half of its rated power with efficiency better than most of conventional gas turbines. Moreover, TET and Exhaust temperature having almost similar trend.

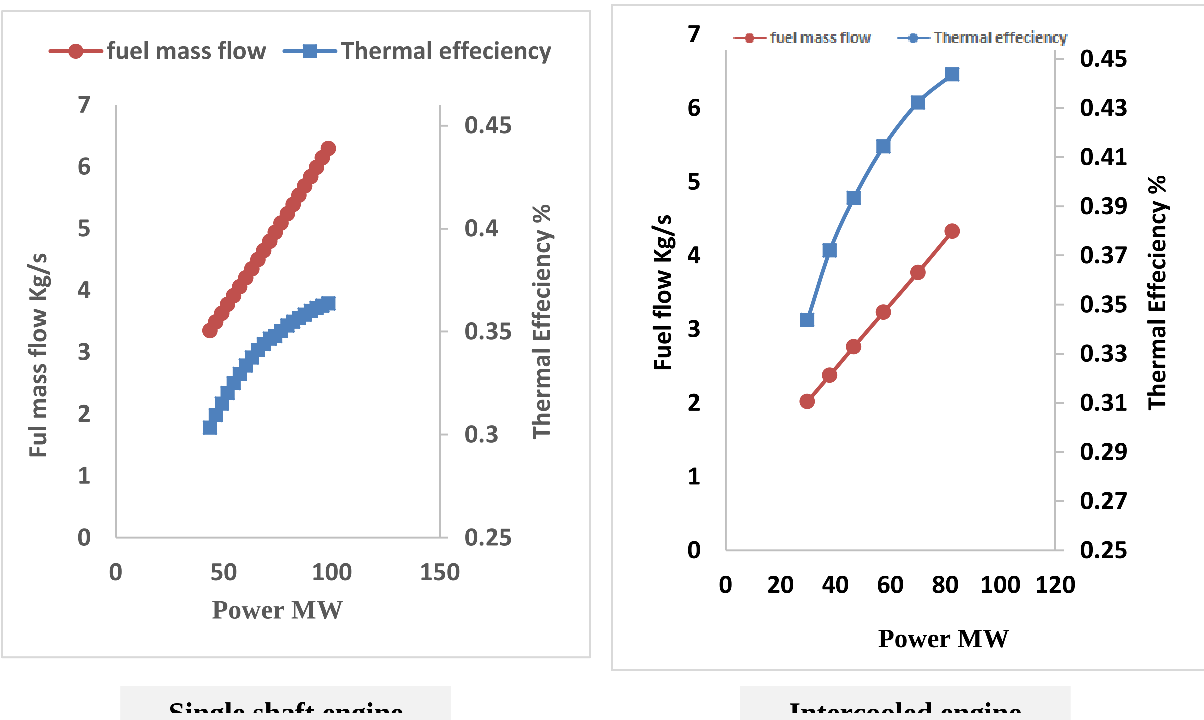


Figure 11 power variation VS (Fuel flow & Thermal efficiency)

4. Conclusion

This work contains in particular, a developed framework of technical evaluation of two prevalent gas turbine categories. These engines are: Simple cycle heavy duty gas turbine inspired by GE-MS9001FA and Aero-derivative gas turbine GE- LMS100. The design point of the engines has been examined by using Torbomach software. The thermal efficiency predictions for the simulated engines were 36%for the frame –class and 45% for the aero-derivative engine. The prediction results showed an increase in ambient temperature would result in air density reduction which consequently led to decline in mass flow and hence the power output. The presence of the intercooler in the intercooled engine made it less susceptible to be effected by temperature increment because the compression work

split between two compressors with an intercooler to reduce the LPC exit temperature and hand it to the HPC at relatively low value.
The elevation caused a reduction in mass flow therefore the output power reduced as well. For constant TET; the efficiency had upward trend with altitude increased because of the fast reduction of heat input compared to power output drop. When the power output assumed to be constant, for the same volume of air, the low dense air led to mass flow drop. The TET should increase to counterbalance the mass flow loss. The reduction of fuel flow by elevation is faster than the required fuel addition to increase the TET. Therefore; the reduction in fuel flow is not significant.
From power sitting prospective It can be seen clearly that The GTs could work more efficient at high power sitting. Furthermore; the intercooled engine efficiency remains relatively high at about 50% power output.

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