Performance Simulation of a Power Generating Gas Turbine in Off-design pointConditions

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ABSTRACT

We present an off-design point analysis of a power generating gas turbine based on a reference location in Isle of Man. The off design simulation is carried out at, up to, an altitude of 2km for ambient temperatures range of 1 to 19^{o}C. A parametric analysis for the altitude simulations shows that power output and cycle efficiency reduced with an increasing ambient temperature while fuel consumption increased. The altitude simulation also shows that power output and mass flow rate reduce as altitudes increase, while the cycle efficiency reduces with increasing altitude. Degradation simulation was attempted by using a reduced fraction of the clean engine data and results show that power output was lower even at a higher shaft speed for a constant turbine entry temperature.

Keywords: Degradation, Gas Turbine, Off-design point, Star plot.

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INTRODUCTION

Effective gas turbine performance diagnostics strongly depends on accurate engine performance models close to chosen nominal diagnostic operating condition, like the design operating condition. Any noticeable performance deviation as a result of degradation of engine could result inmisleading diagnostic results. Toobtain accurate engine models, two steps are used:*design point simulation* and *adaptation*. Adaptingthe engine fulfilsthe design point performance of the engine. Afterwards,the satisfying of the performance away from full power conditions, or design conditions becomes paramount.The design point of a gas turbine is not enough to give all the variables in which the machine should be tested for performance as some of these variables are not attainable at the point or area of operation. The need to satisfy the performance of the machine means that the machine will have to be simulated using off design point data. Important off design point data for the simulation are different altitudes and operating (ambient) temperatures. Relevant off-design techniques have beenintroduced [1-8]. All the techniques placed emphasis on the assumption that design point analysis is accurate. An elaborate insight will be to look into the aforementioned referrals to have a better insight into off design adaptation. Gas turbine off design adaptation performance techniques for gas path diagnostic purposes has been explored by many researchers [1-8]. Stamatis et al [1, 2]introduced modification factors (MF)and used a non-linear generalized minimum residual method to optimise the MF's. The introduction of MF's greatly improved offdesign predictions. But limitations owing tonottooaccurate optimisation resulted tothe introduction of a weighted error function and alsothe usage of polytope algorithm to optimise the MF's by Lambaris et al [3]. This technique greatly improved the optimisation of the modification factors and achieved better accuracy compared to the method introduced byStamatis et al [1, 2]. Despite the merits of the polytope algorithm technique,the adaptation error was quite large, leading to the evolution of other methods to improve adaptation.

Recently, Mohammed et al [9] carried out a design point simulation and adaptation of GE LM2500+ gas turbine engine installed at the Isle of Man, UK [10]. The design point chosen was based on the assumption that when engine runs steadily at operating point and close to the nominal design condition, it achieves an optimal result. They used PYTHIA for the design point simulation, and obtain very high deviation for the targeted performance parameters such as pressure deviations at the turbine, and the compressor and temperature deviations at the turbine and compressor. Due to high level of percentage deviation, an adaptation was carried out. The adapted values gave a deviation that is within tolerance of ± 1%.There is therefore a need to perform an off-design point simulations and degradation to establish the performance of the turbine at otheroperating conditions.

For a modern gas turbine engines operating close to the engine design point operating condition, the turbines and the nozzle with high total pressure ratios are nearly choked and these alters slightly the performance of the nozzles, burners, turbines, and the secondary flows with a massive alteration in the behaviour of the compressors [11]. In the off design analysis, the ambient temperatures and altitude were altered to cover a large envelope with corresponding off design parameters (turbine power output, mass flow and cycle efficiency) measured. This paper presents the off-design point simulation and degradation model to satisfy off design performance predictions; the degradation performances are also presented using star plots.

METHODOLOGY

The gas turbine used is an industrial GE LM2500+ gas turbine engine installed at the Isle of Man, UK by Manx Electricity Authority (MEA). It has two LM 2500+ engines, each producing 29 MW at the dry mode. It drives a combined cycle power plant with two once-through steam generators and a steam turbine producing 20-25 MW [10]. It has an additional stage zero blisk on the high pressure compressor (HPC), a new stage and variable guide vane. It also has a higher power output rated at about 25-29 MW at ISO condition with specific fuel consumption of 235 g/kWh. An accessory gear box located on the axial compressor frame takes the HP shaft power. The compressor is made up of a 17 stage axial compressor with a fully annular combustor with externally mounted nozzle which is bolted to the compressor and wrapping around the turbine stages.

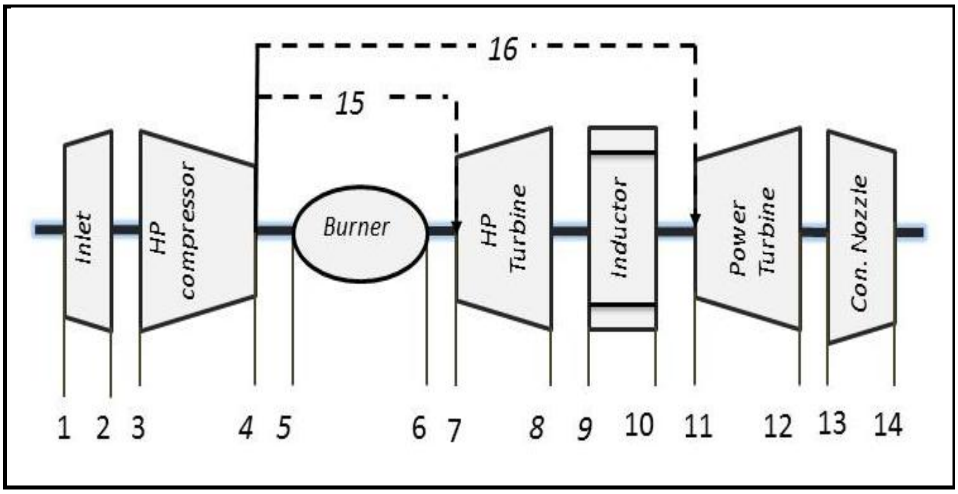

Fig. 1. Schematic of Pythia model [9]

Fuel injection is done through atomising nozzles located at the rear of the combustor chamber. The power turbine has 6 stages, which drives the load operated over a cubic curve for mechanical drive. The engine and its configuration at sea level are detailed in previous work. Fig. 1 shows a Pythia representation of the turbine and the details of its operations are provided in previous publication [9].

Off DesignPerformanceSimulation

Inthe operating conditions close to the engine design pointfor the modelled gas turbine engines, the turbines and the nozzle with high total pressure ratios are nearly choked and the performance of the nozzles,burners, turbines, and the secondary flows usually alter slightly, while the behaviour of the compressors could alter massively [11]. In the off design analysis, the ambient temperatures and altitude were altered to cover a large envelope with corresponding off design parameters measured.

Star Plots-Degradation Simulation

To confirm the stability and accuracy of engine model over a wide degradation range, degraded simulation was done on the engine model. The importance of star plot tests is that data and analysis from star plots might be useful for diagnostic purposes.

Star plots are tools that could be used to understand the effects of degradation on measurable parameters, likewise, they aid in the prediction of the behaviour of the engine and the validation of the engine model.

RESULTS AND DISCUSSIONS

Off Design Performance Simulation

EffectofAltitude

The effect of altitude is shown in Fig.s 2, 3 and 4 below. The results shown that thereisa systematic drop inpoweras altitude increased (Fig. 2).This is because of the decline in the ambient temperature, pressure and the density in the troposphere. Decline in the density subsequently results in the mass flow drop due todirect variationas could be denoted in the expression$\rho \alpha m$,which led to the decline in power output at constant speed (Fig. 3). But since the ambient temperature (T_1) reduces athigh altitude,$\frac{N}{\sqrt{T_1}}$increases and shifts up the pressure ratio. Therefore the workproduced for same turbine entry temperature (TET) increment is at agreater rate compared to the drop in the ambient temperature in the troposphere. Though, mass flow reduction predominates later on. In the stratosphere, $T_1$and$\frac{N}{\sqrt{T_1}}$remains constant and the power output falls due to a reduction in the mass flow and subsequently, the fuel flow rate. Equally, for the specific fuel consumption (sfc),the increment in the temperature ratio$\frac{TET}{T_1}$and the pressure ratio (PR)predominates. This leads to an increment in the thermal efficiency and a subsequent lowering of the sfc as shown in Fig. 4.

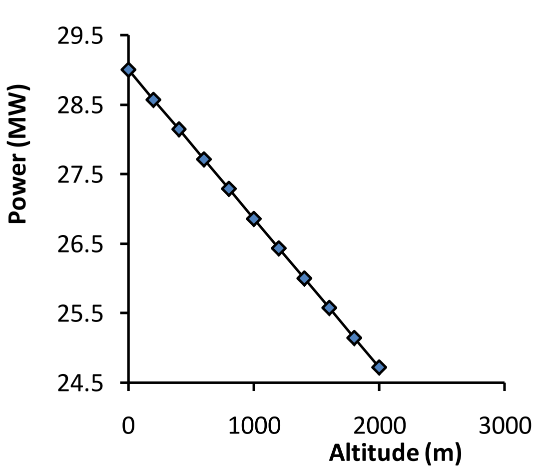

Fig. 2. Effect of altitude on power output

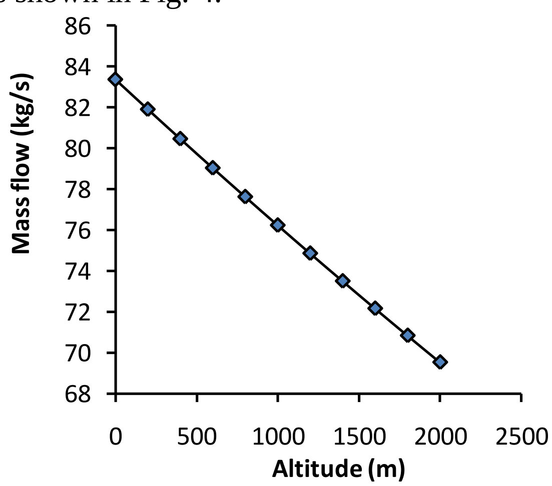

Fig. 3. Effect of altitude on mass flow rate

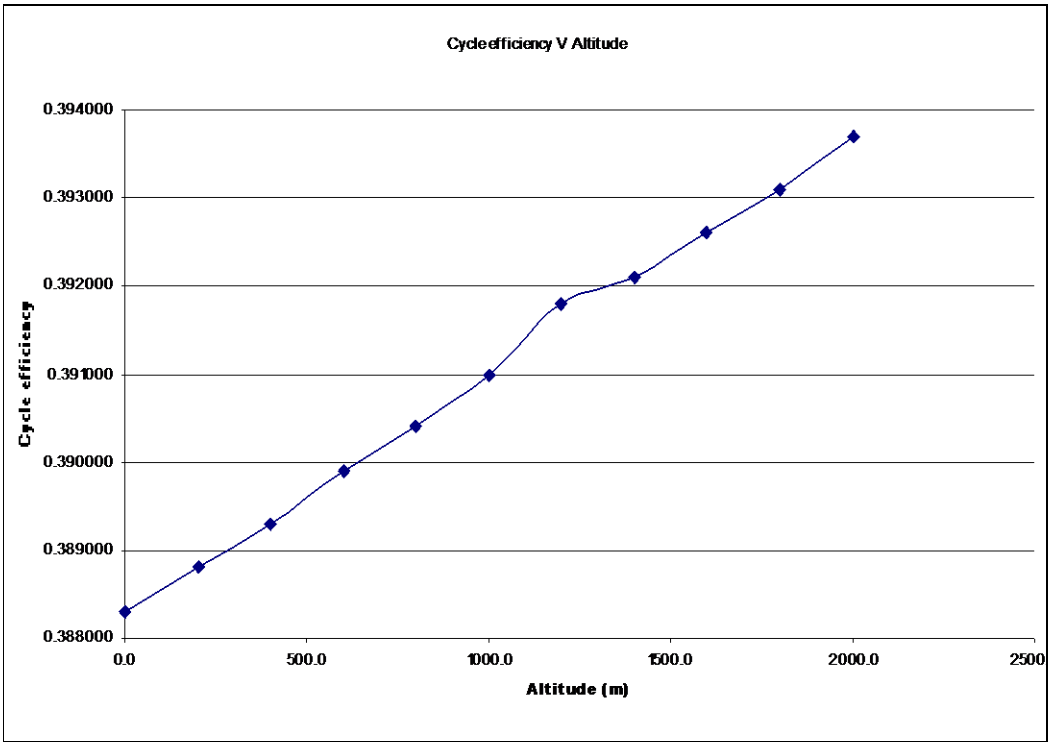

Fig.4.Effect ofaltitude on cycle efficiency

Effectof Ambient Temperatures

The effect of ambient temperature is shown in Fig. 5, 6 and 7 below. Itcanbe deduced that the ambient temperature significantly affects the performance of the gas turbine.The values of power (Fig.6) and efficiency (Fig. 5) decreases with a corresponding rise in fuel flow (sfc) (Fig.7),as ambient temperature increases from design point ambient temperatureof 6.9^{0}C to37^{0}C(310K). This is due to the fact that it is far more difficult to compress hot air, which results to an increment in the work required by the compressor to achieve compression. Equally, onahotter day, the gas turbine will function at a higher non-dimensional speed$\frac{N}{\sqrt{T_1}}$,whichwill subsequently result toa lower pressure ratio and thus,reduced shaft power output [11,12].

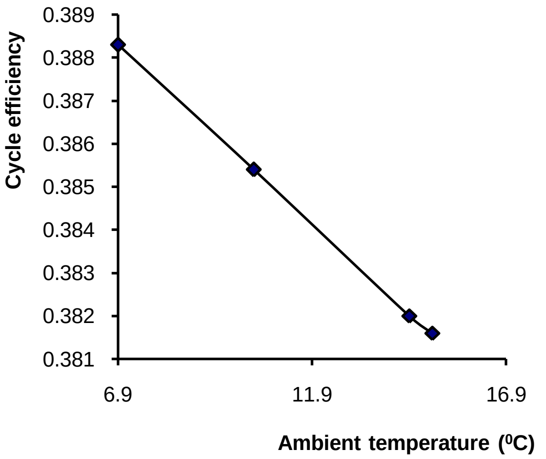

Fig. 5. Effect of ambient temperature on cycle efficiency

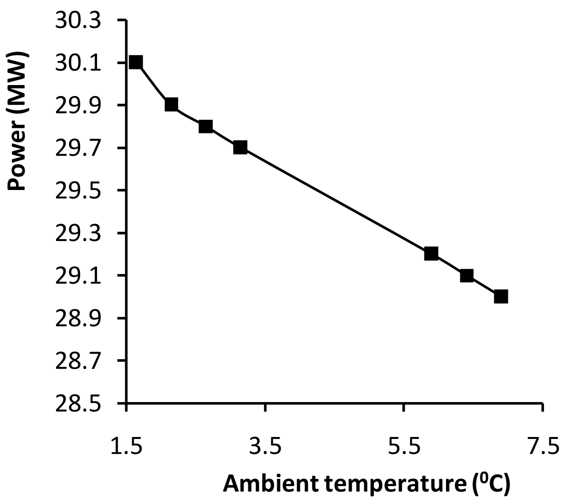

Fig. 6. Effect of ambient temperature on power output

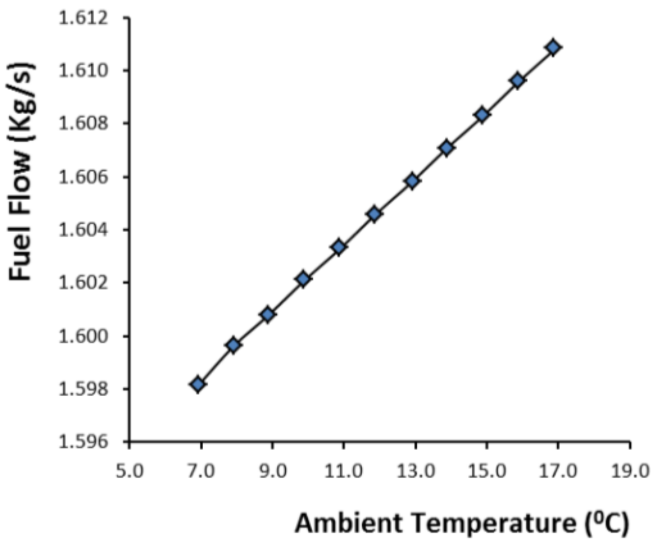

Fig. 7. Effect of Ambient temperature on fuel flow

Degradation Simulation

Fig. 8 and 9show the various star plots obtained from simulating the degradation of the engine model. -2.0% drop in efficiency (Fig.8) and 0% drop in capacity (Fig. 9) is considered as degradation on the compressor with key measurable parameters being observed. Variations in the performance parameters were then evaluated in percentage deviation with design point values taken for clean engine measurements. The percentage changein the dependentparameters such as fuel flow, power output, the compressor discharge pressure (CDP)and the compressor discharge temperature (CDT)are plotted against the degradationof -2.0%on compressorefficiencyand the capacities respectively.

Itwasobserved thatwhen the efficiencies (Fig.8) and capacities (Fig.9) declined with constant power, there was a decrease in the fuel flow rateand the compressor discharge pressure. The compressor shaft speed though went up, with a slight increment in the compressor discharge temperature due to the degradation. Likewise, when the TET was kept constant, with a drop in capacity and efficiency, the fuel flow rate, the shaft power and the CDPallwent downwith a simultaneous increment in the shaft speed and the CDTdue to the effect of the degradation.

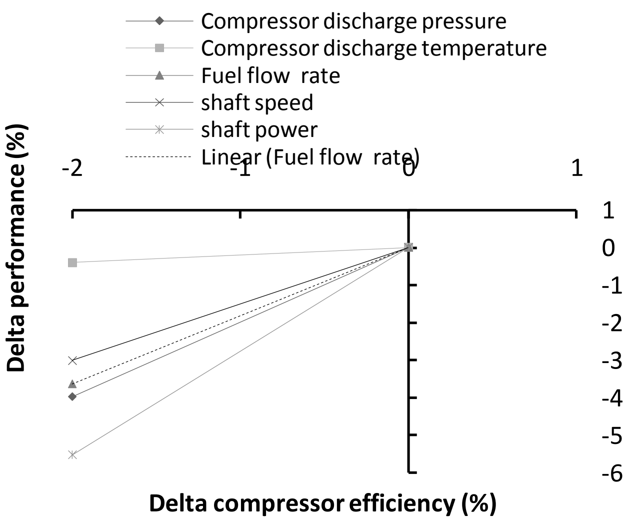

Fig.8. Compressor efficiency degradation on performance

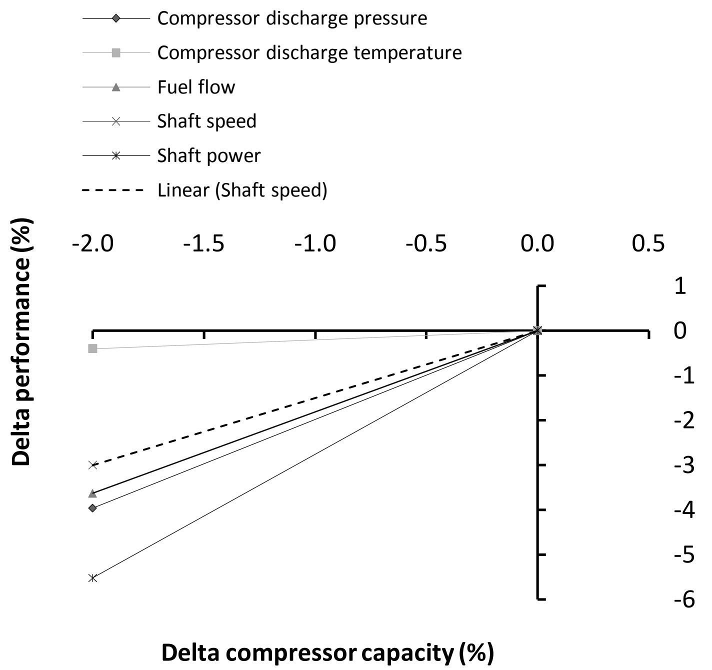

Fig.9. Compressor capacity degradation on performance

CONCLUSION

An off-design point studies has been conducted on an industrial GE LM2500+ gas turbine engine, with two LM 2500+ engines and each producing 29 MW at the dry mode. The off design performance of the Gas turbine engine was achieved by checking the effect of ambient temperature and altitude of the turbine power output, mass flow and cycle efficiency. Star plot was used to simulate the degradation of the compressor capacity. The effect of altitude shows a decrease in power output and mass flow as altitude increases, and cycle efficiency increases with increasing altitude. The power output and cycle efficiency also decreases with increasing ambient temperatures.

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