Nigerian Journal of Engineering, Vol. 29, No. 3, December 2022, ISSN (print): 0794 – 4756, ISSN(online):2705-3954.

Nigerian Journal of Engineering,
Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria
journal homepage: www.njeabu.com.ng

Performance Characteristics Exhibited by Different Gas Turbine Engine Configurations under Degraded Conditions

R. Agbadede[1], B. Kainga[2], I. Allison[3]

[1,2]Department of Electrical Engineering, Nigeria Maritime University, Okerenkoko Warri, Delta state, Nigeria
[3]Headquarters, Nigeria Army Engineers, Bonny Cantonment, Victoria Island Lagos, Nigeria
roupaagbadede@yahoo.com

Research Article

Abstract

Gas turbines which come in different configurations are employed for a wide range of applications. The various gas turbine configurations exhibit different performance characteristics when operated under degraded conditions. This study aims to establish the effect of degradation on the performance characteristics exhibited by the different engine configurations. Gasturb software was employed to model and simulate the performance of different gas turbine configurations, namely single and twin shaft engines. Also, the single and twin shaft variants of the SGT 300 Siemens gas turbines data were used to model the different engine configurations. Consequently, arbitrary values of flow capacity and compressor efficiency percentage reductions referred to as moderate and heavy degraded conditions were implanted, to separately simulate the single and twin shaft engine configurations. When the heavily degraded condition was considered for the two engine configurations under conventional operating mode , the results show that fuel flow increased by 0.6% for the single shaft engine; while fuel flow dropped by 4.9% for the two shaft engine. Similarly, thermal efficiency drop of 2.8% for the twin shaft engine is higher than the single shaft engine of 0.6% for the conventional operating mode. When heavily degraded case was considered under variable speed operating mode, the percentage drop in fuel flow for the single shaft engine is 14.7% as against 4.9% for the twin shaft engine

Keywords

Compressor Degradation; Engine Configuration; Heat Rate; Simulations; Thermal Efficiency.

Article History

Received: – April, 2022 **Accepted: –** December, 2022
Reviewed: – November, 2022 **Published: –** December, 2022

1. Introduction

Gas turbines which come in different configurations are employed for a wide range of applications. The various gas turbine configurations exhibit different performance characteristics when operated under degraded conditions. The degradation in the performance of gas turbines is unavoidable even when operated under the best possible conditions due to several degradation mechanisms. One of the main factors that contribute to degradation in gas turbine performance is compressor fouling. The phenomenon of fouling is caused by foreign particles contained in air that find their way through filter systems and stick to the surface of the compressor blades. These results in the development of surface roughness, changes to the shape of the aerofoil and/or inlet angles of the aerofoil, and decrease of throat area; thereby, causing a decrease in output power and thermal efficiency of the engine (Mund and Pilidis, 2006).

The impact of fouling/degradation on twin shaft engine operating at variable speed differs from a single shaft with a fixed speed. This is because of their different configurations and applications. For instance, most single shaft engines are used for electricity generation purposes because of the need for the gas generator to run at constant speed in order to maintain same frequency with the generator. While twin shaft engines on the other hand are suitable for driving compressors or pumps because of their variable speeds.

Najjar and Zaamout (1992) conducted an investigation to compare the performance of single shaft and twin shaft solar gas turbines. The power output and thermal efficiency of the operating variables over wide range were calculated using a specially designed computer program. The authors discovered that the twin shaft engine outperformed the single shaft engine over most of the operating range. Kurz et al. (2009) stated that single shaft engines operated at fixed speed will show different degradation behaviour from twin shaft engines operated at variable speeds. In addition, the authors stated that the impact of degradation on two shaft engines depends on the control mode in which the engine is operated. Meher-Homji and Bromley (2004) observed that multi-shaft engines are more susceptible to performance degradation than single shaft engines. Similarly, Tarabrin et al. (1998) reported that the twin shaft engines suffer more severe effect of degradation than single shaft engines. However, Kurz and Brun (2000) argued that this statement can only be correct if the degradation suffered by the two shaft engine leads to a reduction in gas generator speed. The authors further added that if a variable geometry is applied in the twin shaft engine, that the drop in speed caused by the effect of compressor degradation can be prevented by adjusting the geometry. Furthermore, the authors posited that the effect of compressor degradation on twin shaft engines installed with variable geometry is roughly similar to single shaft engines. Also, Kurz and brun (2001) claimed that effect of compressor degradation on engines run under temperature topping is less severe when compared with engines operated under speed topping.

Tarabin et al. (1998) stated that compressors with low head (stage work) are known to be less sensitive to fouling when compared with the high head ones. Low head compressors are associated with low flow turning angles as well as solidity; therefore, they are less sensitive to fouling. While on the other hand, high head compressors are sensitive to fouling due increased flow turning angles and solidity.

Najjar (1998) compared the performance between single and twin shaft engines. The author observed that under part-load operation single shaft engine shows a higher drop in turbine entry temperature as against the twin shaft engine. Also, the author added that the exhaust temperature follows a similar trend to the turbine entry temperature. In addition, all the indicators used in ascertaining the engine performances show that twin shaft engine performs better under part-load condition than the single shaft engine.

McDonough (1960) conducted a study on the comparison of operating characteristics of a two-shaft gas turbine with a single-shaft gas turbine for gas line pumping application. The study demonstrates that the twin shaft engine configuration demonstrated better flexibility than the single shaft engine. Agbadede et al. (2022) investigated the effect of associated gas utilization on the creep life of a twin shaft gas turbine. Salilew (2022) presented an investigation to ascertain the effect of physical faults on the performance of a three-shaft gas turbine at full-load and part-load operation. Physical faults were implanted into the performance model to evaluate the performance characteristics of the gas turbine degradation at full and part-load operation. Nikolaidis et al. (2020, 2022) conducted an investigation into the off-design performance comparison of single and two-shaft gas turbine engines, to ascertain which of the gas turbine configurations provides a better thermal efficiency under part load condition. The authors reported that the single-shaft engine was found to provide a better thermal efficiency than the twin shaft engine under part-load conditions for the ideal case. However, when realistic component maps were utilized the contrary was the case. Najjar (1996) compared the performance of cogeneration systems associated with twin-shaft engines with those related to single-shaft engines over a wide range of loading conditions. The study showed that the twin-shaft cogeneration system proved to provide a superior performance under part-load conditions.

Salilew et al. (2022) simulated the effects of fouling and erosion in compressors and turbines of a gas turbine engine under full load full-load operation. The study showed that the measured component performance parameters deviated linearly from the clean state when the fault severity was increased. Najjar et al. (2020) presented a study on the degradation analysis of a heavy-duty gas turbine engine under full and part load conditions. Varying operating loads of 50%, 75% and 100% were tested under different ambient conditions. The authors reported that the relative losses in the polytropic efficiencies increased with loading where the highest level of performance degradation for both compressor and turbine was recorded at the full load operation.

In view of the foregoing, it is obvious that a lot of studies have been conducted to compare the performance between the single and twin shaft engines. Most of the studies conducted focused on comparison between the single and twin shaft engines performances at nominal and part load conditions. Another area investigated is the effect of degradation on single and twin shaft engines. In all these research works, there is no study which has investigated the effect of degradation between single and twin shaft engines, taking into account the modes at which these engines have been operated, and/or if the engines are similar in terms of design specifications. In most cases, the comparisons have been done while the engines are been on different control modes. For instance, the single shaft engines are often operated at constant speed, while for the twin shaft engines; the speed is allowed to vary. Based on these findings, the effect of degradation on single and twin shaft engines have been investigated under two different modes:

1. Conventional operating mode - Fixed speed for single shaft, while the twin shaft engines are operated under variable speed.
2. Both single and twin shaft engines are operated under variable speed.

The single and twin shaft engines modeled were derived from engines of similar design specifications, so as generate engines of two different configurations with similar design specifications. Note that single shaft engines are rarely used driving mechanical loads at varying speeds. But for the purpose of this study, single shaft engine has been simulated at variable speed in order to produce similar mode of operation with the twin shaft version.

2. Materials and Methods

2.1 Gas Turbine Performance Simulations

GASTURB performance simulation software is employed to model and simulate the single and twin shaft engines separately under design and degraded conditions. GasTurb simulation Software employed in this study utilizes predefined engine configurations, thus allowing for an immediate start of calculations. GasTurb is designed for easy evaluation of the thermodynamic cycle both for design and off-design performances of the gas turbine. In addition, the software utilizes basic gas dynamic principles where thermodynamic equations such as gas, conservation of mass, conservation of momentum etc. were incorporated, to carry out the evaluation of the gas turbine performance.

In this study, single and twin shaft engines inspired from Siemens SGT300 class of engines were modeled for the purpose of the investigation. For the purpose of comparison, the single and twin shaft engines were modeled to generate similar engine design parameters. Table 1 shows the experimental and simulated data for the single and twin shaft engines.

The two engine models were created by selecting single and twin shaft engine configurations separately from the software interface and consequently implanting design specification data obtained from open domain, which are similar to the proposed engine models. Few of the data such as component efficiencies and turbine entry temperature were altered to arrive at the expected design engine specifications. Consequently, different fouling levels referred to as light (3% flow capacity and 1% Isentropic Efficiency reductions) and heavy degradations (8% flow capacity and 1% Isentropic Efficiency reductions) respectively, found in Seddigh and Saravanamuttoo (1990), were implanted to simulate the effect of fouling on the the single and twin shaft engines separately. Similarly, Razak (2007) used 3% loss in flow capacity and 1% loss in component efficiency to represent moderate degradation of gas turbine component.

To carry out the simulations of fouling effect on the single and twin shaft engines, the mode of operation of the engines were put into two categories, namely conventional and variable speed modes as mentioned earlier.

The first case referred to as conventional operating mode, was carried when the single shaft engine is operated at fixed speed, while twin shaft engine is operated variable speeds. For the second scenario referred to as variable speed condition, both single and twin shaft engines were assumed to have been operated at variable speed. Hence, both single and twin shaft engines were simulated separately under variable speed operating conditions.

The compressor flow capacity and isentropic efficiency reductions used as input to simulate the fouling effect on the single and twin shaft engines separately are presented in Table 2. While Figures 1 and 2 depict the single and twin shaft gas turbine engine configurations respectively, employed for the study.

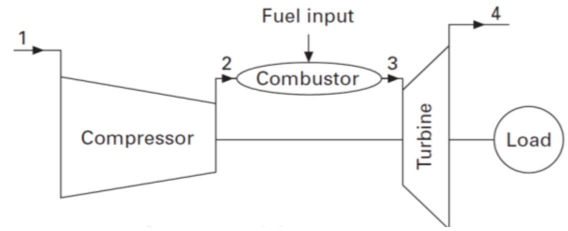

Figure 1: Single shaft engine configuration

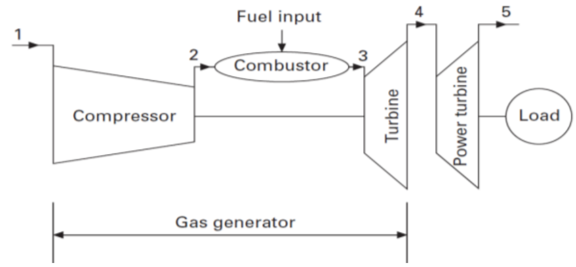

Figure 2: Twin shaft engine configuration

3. Results and Discussion

Figure 3 shows the plot of fuel flow against degradation levels for the two different engine configurations operated under conventional mode. As can be seen in Figure 3, fuel flow reduced with increased degradation levels for the twin shaft engine. The reduction in fuel flow with increased degradation levels for the twin shaft engine can be attributed the pressure ratio-flow relationship in the compressor, as the operating point remains unchanged.

Table1: Experimental and simulated design specification data for single and twin shaft engines

Parameters	**Single Shaft Engine**			**Twin-Shaft Engine**		
	Experimental	Simulation	Margin (%)	Experimental	Simulation	Margin (%)
Power output (MW)	7.9	7.9	0.0	8.4	8.48	0.95
Gross Efficiency (%)	30.8	33.1	6.9	35.3	35.6	0.84
Heat Rate(kJ/kWh)	11704	10875	7	10204	10096	1.06
Pressure Ratio	13.7	13.7	0.0	13.5	13.5	0.0
Exhaust Temperature(°C)	543	503.47	7.27	490	488	0.4

Table 2: compressor flow capacity and isentropic efficiency reductions for different operating conditions

Different Operating Conditions	**Flow Capacity Reduction (%)**	**Isentropic Efficiency Reduction (%)**
Clean Condition	0.0	0.0
Moderate Degradation	3.0	1.0
Heavy Degradation	8.0	1.0

Thus, from the simulations, it can be observed that fuel flow reduced with increased degradation levels. The reduction in fuel flow with increased degradation leads to a drop in engine mass flow, which results in reduced power output for the two shaft engines. Though, the gas generator speed increased with degradation for the twin shaft engine. However, the magnitude of percentage increase in gas generator is relatively low compared to the reduction in mass flow. Hence, the increased gas generator speed could not compensate for the effect of mass flow reduction due degradation. For the single shaft engine, fuel flow increased with degradations levels. This is due to the fact that the single shaft engine is operated at a fixed speed; hence, under degraded condition, the fuel flow as well as the turbine entry temperature is increased to maintain the given load demand.

For instance, when the heavily degraded condition was considered for the two different engine configurations, the plots show that fuel flow increased by 0.6% for the single shaft engine. While for the twin shaft engine, the fuel flow dropped by 4.9%.

As can be seen in Figure 4, it is obvious that heat rate increased with degradation levels for the two engine configurations. The increased heat rate experienced for the twin shaft engine under increased degradation can be caused by the reduction in power output which results from reduced gas mass flow rate. Similarly, the heat rate for the single shaft engine also increased with degradation levels. The increased heat rate with degradation for the single shaft engine can be attributed to the increased fuel flow as can be seen in Figure 3. With reference to heavily degradation condition, when heat rate of single and twin shaft engines are compared, it can be seen that the heat increased by 0.6% for the single shaft engine as against 2.5% for the twin shaft gas turbine.

For thermal efficiency plot shown in Figure 5, it can be seen that the thermal efficiency for both single and twin shaft engines reduced with increased degradation levels. The reduction in thermal efficiency for the twin engine can be attributed to the fact that power output reduced with increased degradation; while for the single shaft engine, the reduction in thermal efficiency can be ascribed to increased fuel flow, which signifies that much energy is been expended to generate the required load demand. Also, when the reduction in thermal efficiency was compared for the two engines, it shows that degradation in thermal efficiency of 2.8% for the twin shaft engine is higher than the single shaft engine of 0.6%. These findings agree with that of (Tarabrin et al., 1998) which states the effect of degradation on twin engines more severe than a single shaft engine.

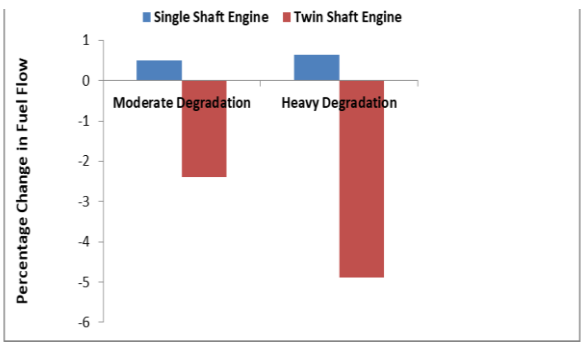

Figure 3: Fuel flow against levels of degradation under convention operating conditions

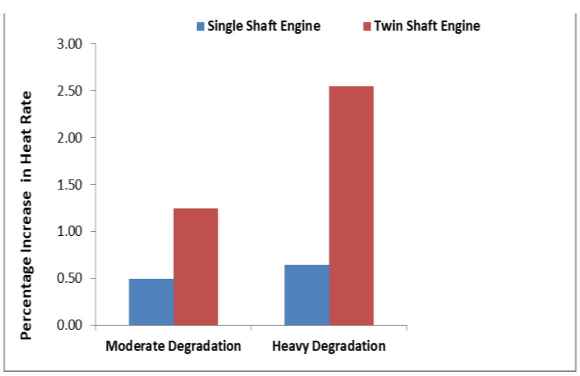

Figure 4: Heat rate against levels of degradation under convention operating conditions

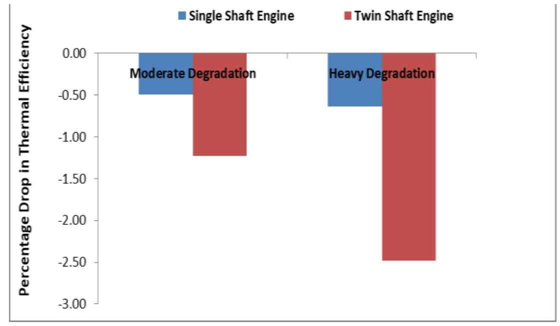

Figure 5: Thermal efficiency against levels of degradation under convention operating conditions

The section below depicts plots of the effect degradation on single and twin shaft engines operated variable speed. The single and twin shaft engines were simulated under variable speed condition so as to establish if the mode of operation contributes to the performance characteristics exhibited by the engines with different configurations. Conducting the simulations of the different engine configurations under variable speed operating mode is acceptable, as the twin shaft engines are usually operated at variable speed condition because they are mostly used for mechanical drive applications. In the case of the single shaft gas turbines, the authors are aware of the fact that they are rarely used for driving mechanical loads at varying speeds. But for the purpose of this study, both the single and twin shaft engines have been simulated at variable speed so as to establish if the mode of operation contributes to the performance characteristics exhibited by the engines of different configurations.

Figure 6 shows the plot of fuel flow for the single and twin shaft engines operated at variable speed under degraded conditions. As can be seen from the figure, fuel flow reduced with increased degradation levels for the two engine configurations investigated. When heavily degraded case was considered, the percentage drop in fuel for the single shaft engine is 14.7% as against 4.9% for the twin shaft engine. Similar to the trends of fuel flow plots, the percentage reduction in thermal efficiency from the clean to the heavily degraded condition for the single shaft engine is 6.7% as against 2.5% for two shaft engine (see Figure 7).

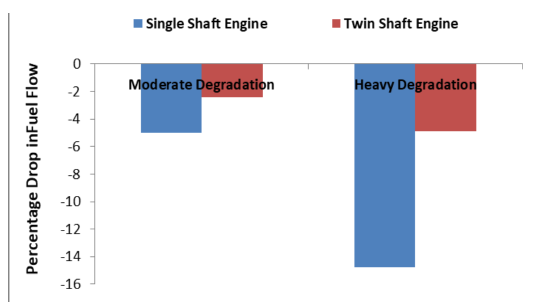

Figure 6: Fuel flow against levels of degradation under variable speed operating conditions

Unlike the plots of thermal efficiency and fuel flow, the plots heat rate increased with the degradation levels. As can be seen in Figure 8, when the single and twin shaft engines were compared under the heavily degraded condition, it can be observed that heat rate increased by 7.2% for the single shaft engine as against 2.5% for the twin shaft engine.

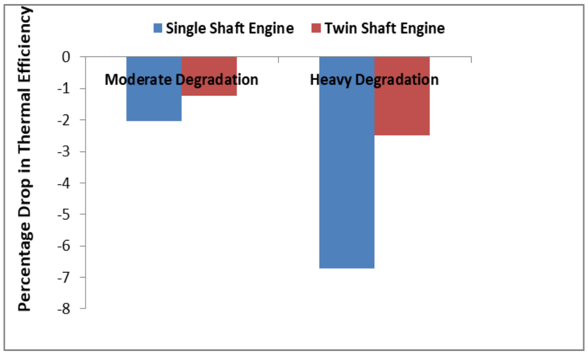

Figure 7: Thermal efficiency against levels of degradation under variable speed operating conditions

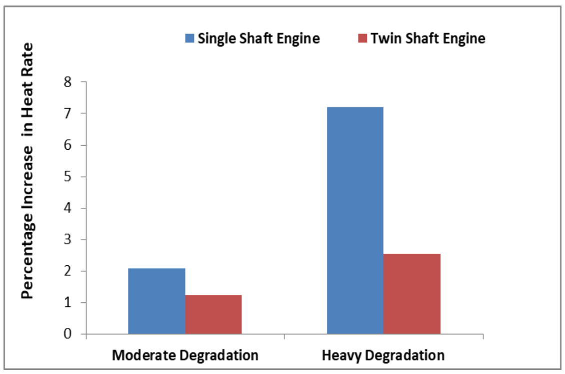

Figure 8: Heat rate against levels of degradation under variable speed operating conditions

4. Conclusion

The study presents the investigation of the degradation effect on the performance characteristics exhibited by the different engine configurations. GASTURB performance simulation software was employed to model and simulate the single shaft and twin shaft engines separately under clean and degraded conditions. The single and twin shaft engines inspired from Siemens SGT300 class of engine were modeled for the purpose of the investigation.

Two cases were considered for the investigation of fouling effect on the behavior of single and twin shaft engines. The first case referred to as conventional operating mode, was carried when the single shaft engine was operated at fixed speed, while that of twin shaft engine the speed was varied. For the second scenario referred to as variable speed condition, both the single and twin shaft engines were assumed to be operated under variable speed condition. Hence, both the single and twin shaft engines were simulated separately at variable speed conditions. Different degradation levels referred to as moderate and heavy obtained from literature were implanted to simulate the effect of fouling on the behavior of the single and twin shaft engines separately.

For conventional operating mode, when the heavily degraded condition was considered for the two engines with different configurations, the plots show that fuel flow increased by 0.6% for the single shaft engine; while fuel flow dropped by 4.9% for the two shaft engine. Similarly, thermal efficiency drop of 2.8% for the twin shaft engine is higher than the single shaft engine of 0.6% for the conventional operating mode.

When heavily degraded case was considered under variable speed operating mode, the percentage drop in fuel flow for the single shaft engine is 14.7% as against 4.9% for the twin shaft engine. Also, study shows that thermal efficiency under heavily degraded condition reduced by 6.7% and 2.5% for the single and two shaft engines respectively. When heat rate for the single and twin shaft engines were compared under degraded condition, the heat rate increased by 7.2% for the single shaft engine as against 2.5% for the twin shaft engine.

Finally, the study concludes that impact of degradation on either the single shaft engine or twin shaft gas turbine depends on the control mode operation, especially twin shaft engines.

5. Acknowledgement

The authors wish to express their gratitude to the Faculty of Engineering, Nigeria Maritime University for providing technical assistance.

References

Mund, F. C. and Pilidis, P. (2006) “Gas turbine compressor washing: Historical developments, trends and main design parameters for online systems,” Journal of Engineering for Gas Turbines and Power 128:344-353.

Najjar, Y.S.H. and Zamout, M. S. (1992) “Comparison of Performance of Single and Twin Shaft Solar Gas turbine Systems.

Kurz, R. and Brun, K. (2009) “Degradation Effects on Industrial Gas Turbines”, Trans ASME Journal of Engineering for GasTurbines and Power, Vol.131, pp 62401

Meher-Homji, C. B. and Bromley, A. (2004) “Gas turbine axial compressor fouling and washing," 33rd Turbomachinery Symposium, Houston, TX, pp. 163.

Tarabrin, A. P., Schurovsky, V. A., Bodrov, A. I. and Stalder, J. P. (1998)“Influence of Axial Compressor Fouling on Gas Turbine Unit Performance Based on Different Schemes and With Different Initial Parameters,” ASMEPaper No. 98-GT-416.

Kurz, R. and Brun, K. (2000) “Degradation in Gas Turbine Systems,” ASME International Gas Turbine and Aero-engine Congress, Munich, Germany, ASME Paper No. 2000-GT-345.

Kurz, R. and Brun, K. (2001)"Degradation in gas turbine systems", Journal of Engineering for Gas Turbines and Power, vol. 123, no. 1, pp. 70-77, 2001.

Najjar, Y.S.H. (1998) “Comparison of Modelling and Simulation Results for Single and Twin Shaft Gas turbines, International Journal of Power and Energy Systems, Vol. 18, pp.29-33, 1998.

McDonough, M. J. (1960) “Comparison of Operating Characteristics of Twin Shaft Gas turbine with Single Shaft Gas Turbine for Gas Line Pumping, ASME Gas

Turbine Power and Hydraulic Conference, Houston Texas, March 6-9,1960.

Seddigh, F. and Saravanamuttoo, H. I. H. (1990) "Proposed method for assessing the susceptibility of axial compressors to fouling", International Gas Turbine and Aero-engine Congress and Exposition, Vol. 113, 11-14 June 1990, Brussels, Belg, ASME, New York, NY, pp. 595-601.

Razak, A. M. Y. (2007) "Industrial Gas Turbines: performance and operatability", Published by Woodhead Publishing Limited, Abington Hall, Abington, Cambridge CB21 6AH, England.

Agbadede, R., Kainga, B., Allison, I. (2022) "Effect of associated gas utilization on the creep life of gas turbines employed for power generation application", Results in Engineering, Volume 17,2023, 100865

Salilew, W. M., Abdul Karim, Z. A., Lemma, T. A., Fentaye, A. D. and Kyprianidis, K. G "The Effect of Physical Faults on a Three-Shaft Gas Turbine Performance at Full- and Part-Load Operation" Sensors 2022, 22, 7150. https://doi.org/10.3390/s22197150

Nikolaidis, T., Pellegrini, A., Saravanamuttoo, H. I. H., Aslanidou, I., Kalfas, A., and Pilidis, P. (2022) "Off-Design Performance Comparison Between Single and Two-Shaft Engines Part 1—Fixed Geometry." ASME. J. Eng. Gas Turbines Power. August 2022; 144(8): 081006. https://doi.org/10.1115/1.4054749

Nikolaidis, T, Pellegrini, A, Saravanamuttoo, HIH, Aslanidou, I, Kalfas, A, & Pilidis, P. (2020) "Off-Design Performance Comparison Between Single and Two-Shaft Engines: Part 1 — Fixed Geometry." Proceedings of the ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition. Volume 8: Industrial and Cogeneration; Manufacturing Materials and Metallurgy; Marine; Microturbines, Turbochargers, and Small Turbomachines. Virtual, Online. September 21–25, 2020. V008T17A003. ASME. https://doi.org/10.1115/GT2020-14500

Najjar, Y. S. H (1996) Comparison of Performance for Cogeneration Systems Using Single or Twin-shaft Gas Turbine Engines, Applied Thermal Engineering, vol. 17, No. 2, pp. 113-124

Salilew W. M., Abdul Karim Z. A., Lemma T. A., Fentaye A. D. and Kyprianidis K. G. Predicting the Performance Deterioration of a Three-Shaft Industrial Gas Turbine. Entropy (Basel). 2022 Jul 31;24(8):1052. doi: 10.3390/e24081052. PMID: 3601071

Najjar, Y. S. H., Alalul, O. F. A. and Abu-Shamleh, A. (2020) "Degradation analysis of a heavy-duty gas turbine engine under full and part load conditions" International Journal of Energy Research, pp. 1-14. DOI: 10.1002/er.5229