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A Computational Study to Investigate the Effect of Altitude on Deteriorated Engine Performance

Koh, W. C.[1], **Mazlan, N. M.**[2], **Rajendran, P.**[3], **Ismail, M. A.**[4]

[1,2,3] School of Aerospace Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, MALAYSIA
[4] School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, MALAYSIA

Corresponding email: nmusfirah@usm.my

Abstract. This study presents an investigation on the effect of operational altitudes on the performance of the deteriorated engine. A two-spool high bypass ratio turbofan engine is used as the test subject for this study. The engine is modelled in Gas Turbine Simulation Program (GSP) based on an existing engine model from literature. Real flight data were used for the validation. Deterioration rate of 0.1% per day is applied for all turbofan components engine. The simulation is performed by varying the altitude from sea level until 9000m. Results obtained show reduction in air mass flow rate and engine thrust as altitude increases. The reduction in air mass flow rate is due to the lower air density at higher altitude hence reduces amount of engine thrust. At 1000m to 4000m, thrust specific fuel consumption (TSFC) of the engine is improved compared to sea level. However depleted in TSFC is shown when the aircraft flies at altitude higher than 4000m. At this altitude, the effect of air density is dominant. As a result, the engine is required to burn more fuel to provide a higher thrust to sustain the aircraft speed. More fuel is consumed hence depletion in TSFC is obtained.

1. Introduction

Commercial aviation is expected to grow significantly in the future. Demand in reliable and fast global transportation is increasing and has already set countless new standards for the aviation industry, at the same time, creating new possibilities and challenges in the field of science and technology. With the level of technology advancements today, the manufacturing of turbofan engines are usually of high quality and performance. However, once an engine is no longer a clean engine, deterioration of its performances occur. The phenomenon of deterioration is inevitable since every used engine will deteriorate over time. For aero gas turbines, the main mechanisms of deterioration are contributions of mechanical wear, thermal distress as well as abrasion, corrosion and erosion [1]. Deterioration will effect upon many aircraft operational parameters, which will impede the operations of aircrafts. In most cases, if the deterioration is beyond allowable limitations, it will cause losses in performance and economy to airline operators. Hence, in general, deterioration will cause more expenditure and is harmful to the environment.

This research was carried out to understand the effect of altitude on the overall performance specifically air mass flow rate, thrust and thrust specific fuel consumption (TSFC) of a deteriorated engine, aiming at helping aircraft operators saving expenditure on maintenance and fuel. An engine

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model within a simulation software was constructed and verified, as well as applying and performing the right conditions and configurations to simulate the research interest situations for the engine.

2. Literature Review

Most of the major propulsion systems for civil aircraft in service today are using gas turbine type of engines. Turbofan engines being the most widely used engine variant for short-to-medium and long range applications. Turbofan engines offers relatively good fuel efficiency and low noise levels compare to conventional turbojet engines [1]. In addition, turbofan engine has an efficient operation Mach number up to 0.85, which is an advantage compared to a turboprop engine [2]. Turbofan engines also has a medium to high bypass ratio direct drive turbofan engine, usually with two or three spool designs. These engines covers a conventional configuration with a large single-stage fan, a multi-stage low pressure compressor, a multi-stage high pressure compressor, an annular combustor, a multi-stage high pressure turbine and a multi-stage low pressure turbine as shown in Figure 1.

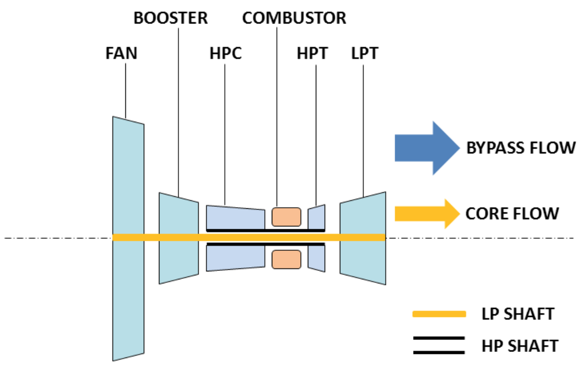

Figure 1. Typical two-shaft turbofan engine configuration [1]

Key parameters which describe the engine performance for an aircraft gas turbine engine is the net thrust (FN) and the specific fuel consumption (SFC) or sometimes thrust specific fuel consumption (TSFC). SFC is usually influenced by factors such as thermal efficiency, propulsive efficiency and combustion efficiency [3]. There are also three main design parameters of a turbofan engine. They are the turbine entry temperature (TET), overall pressure ratio (OPR) and bypass ratio (BPR). A change in these three parameters will significantly affect the engine thermal and propulsive performance.

The maximum TET in an aero engine combustors is usually limited by the mechanical integrity of the combustion chamber and the turbine parts which are exposed to the highest gas temperatures in the whole engine. Apart from the materials available used for manufacturing, these highly thermal stressed engine parts can be applied with active cooling to ensure efficient operation. Hence, an engine which allows higher TET will normally yield greater thermal performance[4]. The overall pressure ratio (OPR) represents the relationship of the total pressure at the compressor exit and the total pressure at the engine inlet. This heavily depends on the number of compressors and the individual compressor design ie: the number of stages. Maximum overall pressure ratios in aero engines are usually limited by the maximum permissible engine weight and the operation ranges of the combustor and the turbines. The engine bypass ratio (BPR) is the ratio between air mass flow rate of air which bypasses the core of the engine to the air mass flow rate passing through the core engine. The air which passes through the core will be involved in the combustion process. Maximum engine bypass ratio is aero engines are usually limited by the size of the fan diameter or by the decrease in size of the core engine diameter. Extremely large fan will increase the aircraft total drag disproportionally as well as the weight of the fan section. Also, a larger fan requires a higher shaft speed. On the other hand, decreasing the size of the core engine is limited by compressor stages pressure ratio and the size of the combustion chamber. More detailed elaboration of the correlations between engine overall pressure ratio (OPR), bypass ratio (BPR) and the fan pressure ratio (FPR) with detailed analyses and diagrams can be found in Walsh, P.P. and P. Fletcher [3] and in Bräunling, W.J [4].

2.1. Gas Turbine Engine Deterioration

For a mechanical turbomachinery such as a gas turbine engine, substantial wear and tear over its service life is inevitable. Gas turbines are subject to gradual deterioration of engine performance with increasing time of operation [5]. In industrial gas turbines 70 – 85% of overall performance deterioration is estimated which causing by deposition [6]. Large particles causing the erosion can be removed from the fluid through proper filtration. However the remaining large fraction of small particles that causing deposition is difficult to be removed [7]. Unlike industrial gas turbines, deposition and erosion in aircraft engine superimpose each other thus making quantification of the individual effects from in-service data is a challenging task. Sallee [8] and Kramer and Smith [9] evaluated in-service data of the Pratt & Whitney JT9D and General Electrics CF-6 turbofan engines and found that one of the main factors causing performance deterioration of high-pressure compressor is surface finish degradation. Among compressor components, front stages being more affected than rear stages, and stators being more affected that rotors with the deposition of mass on stators was approximately twice as high as that on rotor [10]. Rapid roughness was estimated to build up within the first 1000 flight cycles and remain approximately constant afterward.

Deterioration in aircraft can be categorized as (1) On-wing recoverable performance deterioration which can be recovered by on-wing maintenance such as compressor washing, (2) Off-wing recoverable performance deterioration which can be recovered by off-wing maintenance such as disassembly and replacing or refurbish the damaged parts, and finally (3) Permanent performance deterioration which cannot be recovered at economically justifiable expenses. This is usually happen due to natural ageing which constitutes to an unavoidable process.

Engine degradation monitoring or Engine Health Monitoring (EHM) is an essential instrument for gas turbine operation. It is used to determine engine performance and also to allow a prognosis for future performance trends prediction and estimation [11]. Typically, the minimum data that is recorded for performance analysis consists of pressure and temperatures of the engine gas path as well as shaft rotational speed and fuel flow. In addition to those parameters, vibration data, engine oil temperature and pressure is also used for analysis. Apart from obtaining the parameters through sensors, visual inspection is also done either using direct visual such as the borescope or indirect visual methods such as non-destructive testing (NDT) [12]. The measurement of engine exhaust gas temperature (EGT) is a common measurement used to determine actual engine, which in turn allows the calculation of exhaust gas temperature margin (EGTM). This method is used by many major airline operators and has proven to give reliable results on the engine health. It is usually measured at locations after the high pressure turbine exit or at the first stages of the low pressure turbine.

2.2. Previous study on the Effect of Engine Deterioration on Engine Performance

Unlike industrial stationary gas turbine, the impact of engine component deterioration on civil aero engines application has not been widely investigated or available in open literature. Igie et al [13] studied the effect of different level aero-engine compressor fouling on engine performance particularly at short and long-haul missions. Two different aircrafts with different two-spool engines were used. They observed increment in turbine entry temperature (TET) for both aircraft engines in order to maintain the same level of thrust as their clean condition. The highest TET is observed during take-off and climb when thrust setting is the highest.

Kellersman et al [14] performed numerical study in comparing the performance of a jet engine compressor front stage with Blade Integrated Disk (BLISK) geometry during a flight operation interval due to deterioration effects. BLISK is an arrangement of blades in which each stage cannot be changed during maintenance. Unlike conventional compressor front stage, deterioration effects will grow stronger in BLISK until part reaches its life limit. Results obtained from the numerical study shown increases in specific fuel consumption (SFC) and exhaust gas temperature (EGT), both having an influence on the On-Wing-Time of a jet engine and hence the maintenance intervals. However for the conventional blade rows, the blade can be arranged, so the coupled effects can be minimized and the performance can be restored. For a BLISK, the arrangement cannot be changed leading to mistuned stage hence drop engine performance and efficiency.

Jorgenson et al [15] utilized a computer tool in understanding the low pressure compressor and engine performance during an engine roll back event caused by ice accretion. Ice accretion can occurs in the fan low pressure compression system when the aircraft operates at high altitude in which ice water content is high. In general, air static temperature typically increases in fan and low pressure compression system. As ice crystals are ingested into the systems, a portion of the ice crystals melt due to the warmer air. This allows the ice-water mixture to stick to the metal surfaces of the compressor components. This will result to the blockage on stationary components such as the stator vanes hence resulted into the deterioration in performance of the compressor and consequently reduces engine thrust.

An experimental and analytical study was performed to investigate the influence of compressor deterioration on engine dynamic behaviour and transient stall-margin [16]. The analytical study was performed by modifying a two-dimensional, linear, compressible state-space analysis developed by Fuelner et al [17]. Unsteady pressure fluctuation forcing in the clade passages to account engine transients and deterioration were included in the latter model. Whilst the experiments were performed on large commercial aircraft engines in both undeteriorated and deteriorated states. Results showed losses in stall-margin of about 5% due to deterioration. Measurement on transient stall margin has yield to 12% losses for undeteriorated engine and 7% for deteriorated engine. This is because during acceleration transients the operating lines depart from the steady-state level toward the stall line, thus reducing instantaneous stall-margin.

All studies mentioned above observed deterioration effect of certain components on the engine performance. As far as author's knowledge, no study has been performed to investigate deterioration of all components in the engine on engine performance. Therefore this study is the first to analyse the effect of altitudes on engine performance when all components is assumed deteriorated.

3. Methodology

3.1. Modelling CFM56-3 Engine Design Point

This study used a two-spool high bypass turbofan type of engine, CFM56-3 which modelled in Gas Turbine Simulation Program (GSP). The configuration of the engine is shown in Figure 2. GSP is used to model design point and off-design condition for the engine. Within this study, design point of the engine is referred as clean engine where deterioration is absent. The engine is modelled based on the general configuration and characteristics obtained from previous study conducted by Radiaura and Rubio [44] who modelled the engine based on the CFM56-3 Correlation Test Report data [45].

The Correlation Test Report is a proprietary report, owned by the maintenance organization of TAP Portugal in collaboration with CFM International. Since the full report cannot be obtained, a partial informative report is found within the research of Ridaura and Julio Antonio Rubio [44]. From their study, performance data of a CFM56-3 on a test bed as well as their methodology on verifying the CFM56-3 model is obtained. Although the software they used to evaluate the engine performance is differed with the one used in this study, the calculation procedure however is similar and was applied to all engine performance simulation software. In addition, the results they achieved was verified through Kurzke's method [43] and results has been found to be satisfying. Engine parameters used in modelling the engine design point is shown in Table 1. This parameters were adopted in our engine design point model. The verification results are shown in Results and Discussion section.

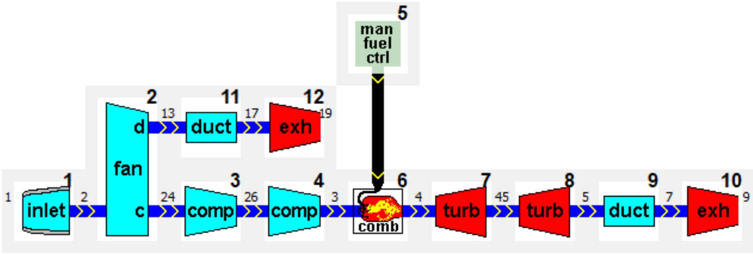

Figure 2. GSP11 CFM56-3 configuration

Table 1. Input parameters for CFM56-3 modelling

Input Parameter	**Value**
Ambient Temperature, T1 (K)	288.15
Ambient Pressure, P1 (kPa)	101.325
Intake Pressure Ratio	0.99
Inner Fan Pressure Ratio	1
Outer Fan Pressure Ratio	1.714
Intermediate Compressor (Booster) Pressure Ratio	2.237
High Pressure Compressor Pressure Ratio	10.672
Design Bypass Ratio	5.294
Burner Exit Temperature (K)	1636.99
Burner Design Efficiency	0.9995
Fuel Heating Value (LHV) (MK/kg)	43.38

To evaluate the effect of operational altitudes on performance of deteriorated engine, using the settings in the first case study as the base, the ambient conditions is manually varied using the altitude, with intervals of 1000m starting from sea level altitude to the average cruising altitude of similar engine aircraft of 9000m. The pressure and temperature of the respective altitudes are all based on the International Standard Atmosphere. Table 2 shows the respective pressure and altitude used for each altitude.

Table 2. Pressure and temperature at respective altitudes

Altitude (m)	**Pressure (bar)**	**Temperature (K)**
Sea Level	1.01	288.15
1000	0.89	281.65
2000	0.79	275.15
3000	0.70	268.65
4000	0.62	262.15
5000	0.54	255.65
6000	0.47	249.15
7000	0.41	242.65
8000	0.36	236.15
9000	0.31	229.65

4. Results and Discussion

4.1. Verification of CFM56-3 Gas Turbine Engine Model Design Point

Table 3 shows percentage difference between the engine simulation performed in GSP 11 and Correlation Test Data for several engine parameters. It is shown that the percentage difference between GSP11 and Correlation Test Data for all engine parameters are below 10% except for the bypass duct pressure (PT17) which is slightly higher than 10%. The results obtained are considered acceptable and the engine model is verified and reliable to be used for further case analysis study.

Table 3. CFM56-3 design point verification results

Performance Parameter	GSP11 Results	Correlation Test Data	Deviation (%)
IPC Temperature, TT26 (K)	387.18	372.70	3.88
HPC Pressure, PT3 (kPa)	2599.43	2371.01	9.63
HPC Temperature, TT3 (K)	787.17	786.19	0.12
Bypass Duct Pressure, PT17 (kPa)	193.80	167.59	15.64
Thrust Specific Fuel Consumption, TSFC (kg/kNs)	0.0109	0.0110	0.91
Exhaust Gas Temperature, EGT (K)	1168.05	1064.65	9.71

4.2. Off-Design Conditions Model Verification

The off-design conditions for CFM56-3 engine modelled in GSP11 is validated by comparing the engine performance with a real flight data of a CFM56-7B24 provided by a local airline. Within this study, the engine used for the validation will be referred as Engine X. Since there is limited data available from the local airline operator, the only comparable parameter for off-design verification is the takeoff exhaust gas temperature (EGT). The CFM56-3 model in GSP11 is set to simulate at the same ambient conditions of Engine X at an ambient pressure of 0.95bar and ambient temperature of 284.25K.

Error! Reference source not found. shows the EGT of Engine X for its first 30 days since new (clean engine). It shows that the engine has operated for almost 200 flights in 30 days. The number of daily flights of Engine X (the number of times the engine being used every day) is different each day for the period of 30 days hence varies the EGT. Additionally, the engine flies at different locations every day thus inconsistency in air humidity, ground temperature, weather etc will influence the fluctuation of EGT. However for simplification an average value of EGT is calculated by considering that the aircraft flies only once a day.

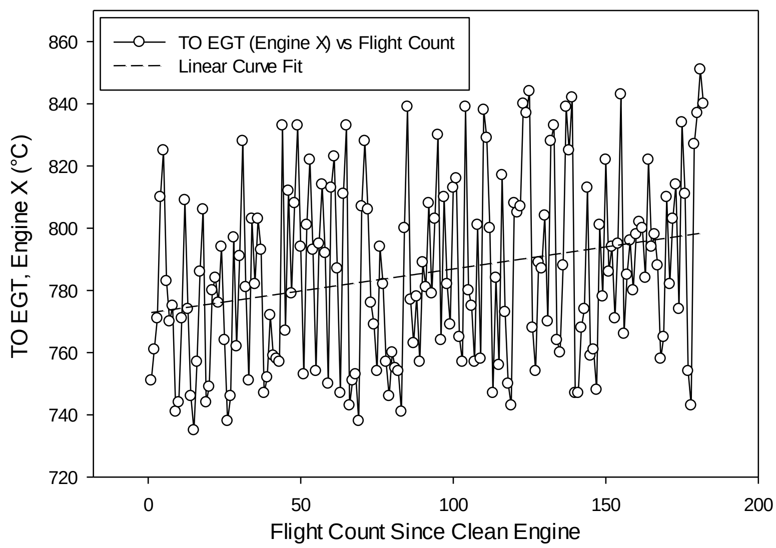

Figure 3. Takeoff exhaust gas temperature against flight count since clean engine [Source: Local airline operator]

The average value of EGT per day is presented as straight line as shown in Figure 4. This value will be used as comparable data with EGT value obtained from simulation.

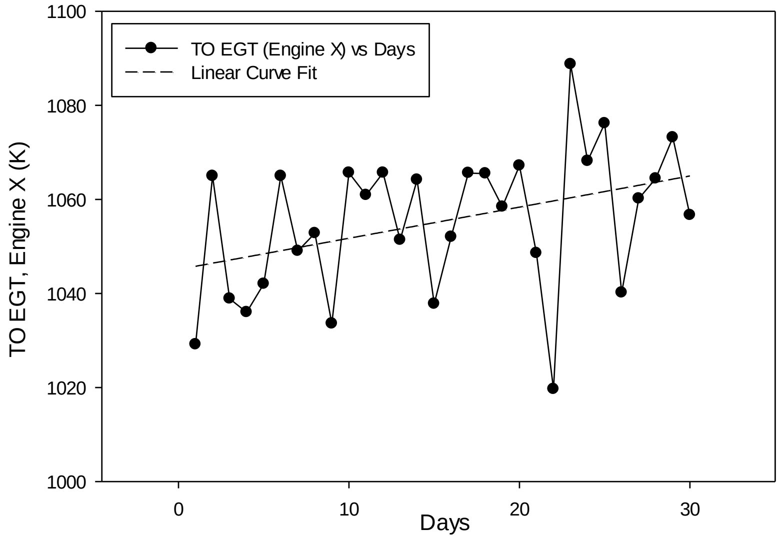

Figure 4. Average takeoff exhaust gas temperature against days since clean engine

The GSP11 modelled engine is applied with deterioration effect where the fan, booster (low pressure compressor), high pressure compressor, high pressure turbine and low pressure turbine are all assumed to have a deterioration rate of 0.1% per day. The results are shown in Figure 5.

It can be noticed that EGT changes when 0.1% deterioration effect was applied and the value increases with the number of operation days. Similar trend is observed as Engine X although absolute values are different. This is due to the fact that Engine X (CFM56-7B24) and CFM56-3 are not the same engine thus those deviations are expected. However considering that both engines are being in the same family, the difference in absolute value is not the main issue, the trend in results obtained are considered more representative than the absolute value. As far as the trend is concerned, the trend similarity between the engine model and real data obtained from local airline shown in the graph is validated and can be used for further analysis.

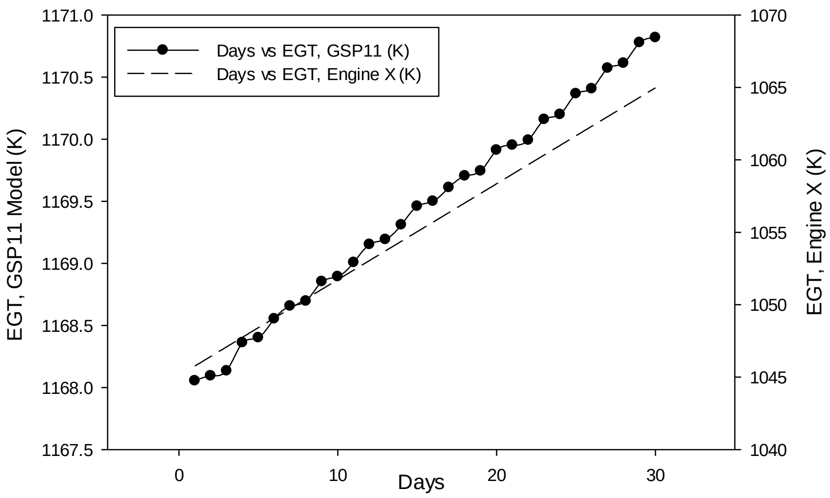

Figure 5. Exhaust gas temperature against day between GSP11 model and Engine X

4.3. The Effect of Altitude on Air Mass Flow Rate, W1

In this study, the effect of altitude on air mass flow rate of the deteriorated engine is observed (Figure 6). Very small changes in air mass flow rate is observed for all 30 days of engine operation is noticed. Furthermore, the deterioration trend is similar for all altitudes. In comparison to sea level, as the altitude increases, the air mass flow rate decreases. This is because as altitude increases, the air density decreases, hence reducing the amount of air goes into the engine.

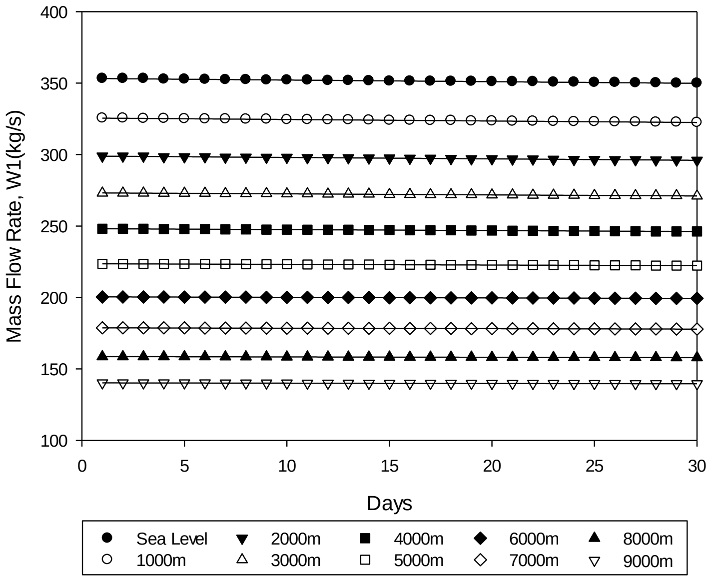

Figure 6. Effect of operation altitude on air mass flow rate

4.4. Effect of altitude on engine thrust, FN

The effect of altitude on engine thrust is depicted in Figure 7. It can be seen that the trend of the graph is similar with the effect of altitude on air mass flow rate. As for turbofan engine, amount of thrust generated by the engine comprises of a combination of thrust generated from the fan and thrust generated from the core engine. Thrust generated from the fan contributes about 80% of total thrust. Therefore decreases in the amount of air bypassing the fan will contribute to the reduction in total thrust of the engine. As for air mass flow rate, as the altitude increases, the air density decreases hence reducing the amount of air entering the fan. For that reason, the amount thrust generated by the engine reduces. As number of operation day increases, reduction in engine thrust is observed and it is consistent with all altitudes.

4.5. Altitude Effect on Thrust Specific Fuel Consumption, TSFC

Figure 8 shows the effect of altitude on the thrust specific fuel consumption at altitude ranging from 1000m to 9000m. Sea level depicted design point of the engine model. It can be seen that at 1000m to 4000m, TSFC of the engine is improved (low TSFC) compared to design point. However TSFC of the engine started to increase (depleted TSFC) when the aircraft flies at altitude higher than 4000m. TSFC of the engine is worst at altitude of 9000m. It is known that at high altitude air density decreases thus provide lower drag for the aircraft. The lower drag causing the engine to consume less fuel in providing enough thrust hence lower TSFC is observed. Meanwhile after 4000m (the altitude becomes much higher), pressure and density drops much quicker than temperature so that the effect of air density is much dominant. Reduction in pressure ratio causes the fuel flow decreases. This is required to maintain the proper fuel-air ratio in the engine. At this condition, thrust of the aircraft reduces. However, since TET of the engine is set to be constant in the beginning. As a result, for the engine to maintain the constant turbine entry temperature (TET) at higher altitudes, the turbofan engine needs to burn more fuel to provide a higher thrust to sustain the aircraft speed, hence after 4000m, the turbofan engine burns more fuel with a higher TSFC.

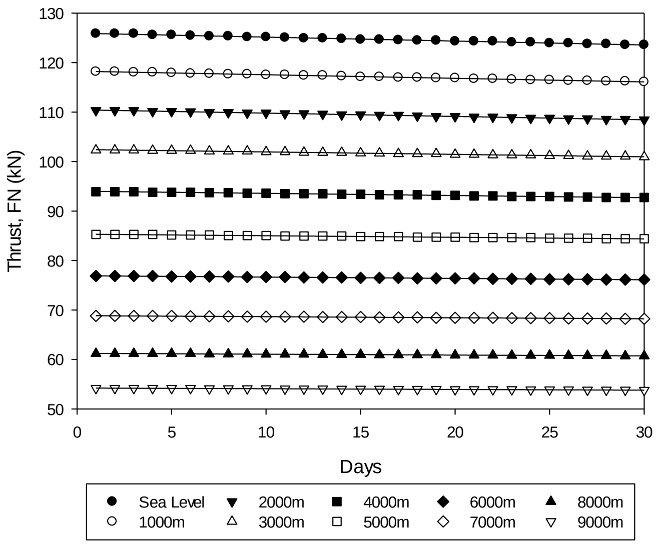

Figure 7. Effect of operation altitude on thrust

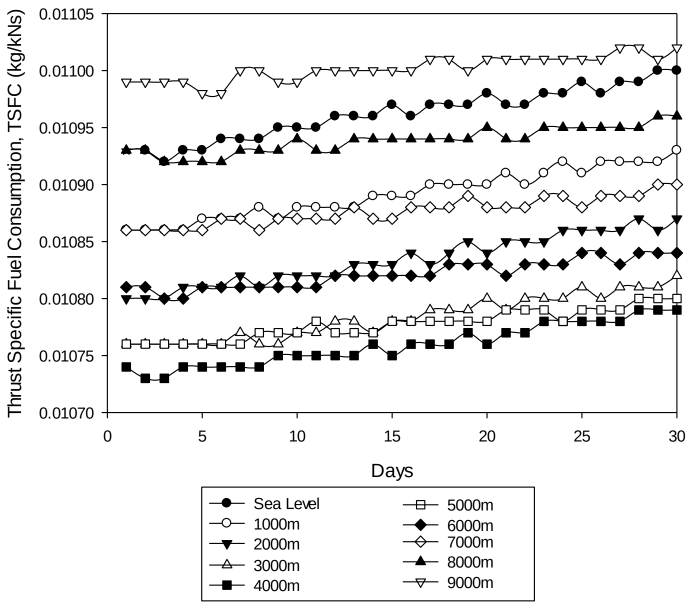

Figure 8. Effect of operation altitude on thrust specific fuel consumption

5. Conclusion

This study is performed to examine the changes in engine performance when all components in the engine is deteriorated. A two-spool high bypass turbofan engine was modelled in Gas Turbine Simulation Program (GSP) based on engine parameters obtain in literature. The model was validated with real flight data obtained by local airlines.

The effect of altitude on engine performance particularly air mass flow rate, thrust, and thrust specific fuel consumption was analysed by ranging the altitude from 1000m to 9000 m. The simulation was performed for 30 days on operation. As altitude increases, reduction in air mass flow rate is observed. This reduction contributes to the reduction in engine thrust due to small amount of air bypassing the fan. TSFC of the engine improved when the aircraft flies from 1000m to 4000m. However TSFC depleted when aircraft flies more than 4000m. The effect of air density is more dominant at higher altitudes. Therefore in order to maintain the same turbine entry temperature and velocity required by the aircraft, the engine has to burn more fuel thus increases TSFC.

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