Open Journal of Energy Efficiency, 2022, 11, 88-107
https://www.scirp.org/journal/ojee
ISSN Online: 2169-2645
ISSN Print: 2169-2637

Off-Design Modelling of a Turbo Jet Engine with Operative Afterburner

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How to cite this paper: Ighodaro, O.O., Aburime, E.I. and Erameh, A.A. (2022) Off-Design Modelling of a Turbo Jet Engine with Operative Afterburner. *Open Journal of Energy Efficiency*, **11**, 88-107.
https://doi.org/10.4236/ojee.2022.113007

Received: April 11, 2022
Accepted: September 16, 2022
Published: September 19, 2022

Abstract

Gas turbines are considered as one of the leading internal combustion engines in modern air transportation due to its favourable power to weight ratio and its continuous combustion process. Recent research focus has been concerned with performance improvements aimed at reduced fuel consumption and hence reduced impact on the environment. This study is aimed at using theoretical and computational methods to model the operation and performance a turbojet gas turbine engine. The commercial software GasTurb13 was used for the theoretical simulation while Microsoft Excel was used for the analytical study. GasTurb13 solved the model using pseudo-perfect gas models *i.e.* component maps since the specific gas ratio could not be inputted into the solver. The effect of changes in the Mach number and altitude on the engine performance was studied. Also the effect of changes in the compressor pressure ratio, the turbine inlet temperature and the afterburner exit temperature were also studied. Results obtained showed the optimum pressure ratio at maximum thrust constraint to be 16.78 for the turbojet engine operating at Mach number (Ma) = 0.8 and altitude = 10,000 m, Turbine inlet temperature (TIT) = 1200 K and Afterburner exit temperature = 1800 K.

Keywords

Turbo Jet Engine, Modelling, Simulation, Off-Design

1. Introduction

Gas turbines are among the leading internal combustion engines in the transportation industry. They are used mainly for aviation and stationary electricity generation purposes. They play an important role in the aviation industry due to their high power to weight ratio, are lighter and smaller than comparable engines and are cost-efficient in operation [1]. More and more attention is been paid on optimizing fuel consumption of these engines while reducing their noise level.

Gobran [2] studied the off-design performance of solar centaur-40 gas turbine engine. A Simulink model was used in simulating the off-design running for the single shaft Centaur 40 gas turbine engine used for power generation. The off-design modelling was done in two phases, initially, the engine was operated at speeds ranging between 65% to 100% at no load conditions, subsequently, the engine was loaded at a constant speed of 100%. The results obtained from this test were compared with the actual operation results of the turbine to check the validity of the Simulink model. He then went to investigate the effect of ambient temperature on engine performance at engine design conditions.

Lazzarettoand Toffolo [3] used neural network models for their studies on gas turbine. Both design and off-design simulations were carried out. The results obtained from their analytical studies were used in training the neural network model, they further studied the capability of using the developed neural network model to predict the performance of the turbine.

The predicting of off design performance of gas turbine engines using graphical analysis was carried in studies conducted by Shapiro and Caddy [4] and Wittenberg [5]. In the absence of manufactures component maps, gas dynamic relations were used in the analysis. The results obtained were far from accuracy due to the many assumptions used in the analysis.

Sellers and Daniels [6] used the software DYNGEN for the dynamic simulations of both jet and turbofan engine dynamic, they obtained poor results due to the software's numerical stability issues and its poor user interface.

The so called "hot end method" used in predicting the steady state performance of LM-600 gas turbine engine has been used by a number of authors [7] [8]. The method is based on using simplified matching equations on the condition that the low pressure turbine is chocked (fixed high pressure turbine operating point). The solution method starts from hot end down to the compressor entry point.

Najjar and Balawneh [9] carried out optimization studies on turbojet engines. Initial results showed that the specific thrust from the engine depends heavily on the turbine inlet temperature and consequently on the specific fuel consumption (SFC) of the engine. They work rigorously in achieving minimal specific fuel consumption for a maximum thrust and after optimizing the turbojet cycle, they found the optimal pressure ratio for minimal specific fuel consumption.

Bakalis & Stamatis [10] developed a small model of turbojet engine which was well calibrated and tried to calculate for the efficiency which proved to be inadequate for producing reasonable values. They suggested the possible reasons for the inadequacy were due to ignoring the heat transfer occurring in the turbine casing and errors when taking measurements. The analytical calculations carried out for the turbine inlet temperature (TIT) and the turbine exit total pressures deviated significantly from the predictions. In trying to resolve the differences, the model was recalibrated to use static pressure instead of total pressure measurements in the turbine exit, the recalibration produced much more reasonable results both for predicting measured parameters and for the turbine efficiency, their research concludes that for small engines, static pressure measurements at hot regions produces more reliable results than total pressure measurements. Wood & Pilidis [11] also investigated a jet engine based on a variable cycle for a supersonic short take-off vertical landing (ASTOVL) aircraft. They analysed the on-design and off-design parameters for the engine

Najjar & Al-Sharif [12] carried out a study to develop and find the effect of using and combining four cycle design variables to reduce the specific fuel consumption (SFC) of a turbofan engine. In the study, the bypass ratio (B), the fan pressure ratio, the overall pressure ratio and turbine inlet temperature (TIT) were selected as the variables. The SFC was reduced without any constraint in the minimum thrust. Afterwards, a minimum specific thrust constraint was used. The study discovered that the first condition of no constraint in thrust resulted in a two-dimensional optimisation problem whereas when the thrust constraint was introduced, it became a three-dimensional problem. Sensitivity analysis was also carried out on the optimised cycle, results showed that there was little or no deviations in SFC from design values and that the SFC were more sensitivity to TIT and FRP. The study revealed that the By-pass ratio no longer the limiting factor, as it is now a three-dimensional (B, FPR, TIT) problem, however the overall pressure ratio remained the limiting factor in all the cases studied.

In order to study and overcome the shortcomings of energy loss caused by compression heating in compressed air energy storage technology, Xin He *et al.* [13] proposed a novel constant pressure pumped hydro system. Their study adopted an off-design model so as to make the study close to reality. The model was used to calculate and analyse the effect of key parameters on system thermodynamics performance

In the analysis carried out by Hiromasa Suzuki *et al.* [14] they opted for experimental analysis to study the effect of an under expanded jet radially discharging from a circular slit nozzle which consists of two cylinders, the aim was to study the frequency of the noise emitted from the jet when different nozzle pressure ratios and different cylinder diameters were used.

At higher altitudes, a wrong configuration of the operating parameters of a jet engine could result to a reduced optimal propulsive efficiency. This could cause the engine to consume more fuel than normal and produce a much lesser thrust than capable. Najjar and Al-Sharif [12] conducted a research study on the reduction of the specific fuel consumption on a turbofan engine while Najjar and Balawneh [9] focused on finding the optimal pressure ratio for various design variables. However, not much work has been done on determining these factors when using an afterburner. Thus, the aim of this study is to evaluate the performance of a turbojet engine with and without afterburner for different combinations of design choices and operating conditions and to determine an optimal configuration of the cycle for optimal operation.

2. Methodology

The major objectives of this study are: 1) to model a turbojet engine with an afterburner and validate the model using realistic data 2) determine the influence of ambient temperature on performance of design point 3) optimize the cycle for minimum specific thrust with and without minimum thrust constraint, these are achieved by modelling the process using commercial softwares and analysing the results.

2.1. Modelling

Modelling of the engine was conducted in two parts: Analytical modelling using Microsoft Excel and Computer modelling using GasTurb 13.

2.1.1. Developing the Model in Microsoft Excel

Governing Equations

The different processes and Equations (1) and (7) in the engine are outlined below:

1) Intake/Diffuser

The total temperature at the diffuser outlet depends on the diffuser efficiency, η_d .The outlet pressure and temperature will be given by

$$P_{02} = P_a\left(1+\eta_d\frac{\gamma_c-1}{2}Ma^2\right)^{\gamma_c/\gamma_c-1} \tag{1}$$

$$T_{02} = T_a\left(1+\frac{\gamma_c-1}{2}Ma^2\right) \tag{2}$$

2) Compressor

From the diagram in Figure 1(a), the state 2-3 represents the adiabatic compression process, the compressor isentropic efficiency, η_c is a determinant factor. The outlet conditions are given by:

$$P_{03} = P_{02}\pi_c \tag{3}$$

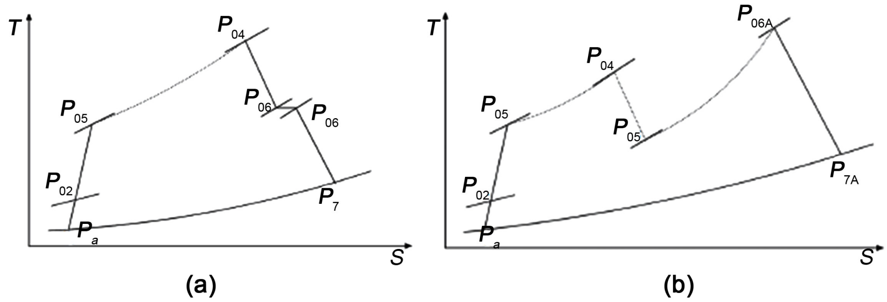

Figure 1. (a) T-S diagram of Turbojet Engine with an inoperative afterburner; (b) T-S diagram of Turbojet Engine with an operative afterburner.

$$T_{03} = T_{02}\left[1+\frac{\pi_c^{\gamma_c-1/\gamma_c}-1}{\eta_c}\right] \quad (4)$$

3) Combustion Chamber

A reduction in stagnation pressure across the combustion chamber is expected due to the effect of fluid friction. The outlet pressure from the combustion chamber is defined as

$$P_{04} = P_{03}\left(1-\Delta P_{cc}\%\right) \quad (5)$$

The combustor outlet temperature is limited by the turbine metallurgical considerations. The fuel-to air ratio is defined as

$$f = \frac{Cp_g T_{04} - Cp_a T_{03}}{\eta_b Q_R - Cp_g T_{04}} \quad (6)$$

4) Turbine

From the diagram in Figure 1(b), the state (4)-(5) defines the turbine expansion which accounts for the power required by the compressor and mechanical losses, thus the outlet temperature from the turbine is defined

$$Wt = \frac{Wc}{\eta_m} \quad (7)$$

$$Cp_g\left(T_{04}-T_{05}\right) = Cp_a\left(T_{03}-T_{02}\right)/\eta_m \quad (8)$$

$$T_{05} = T_{04} - Cp_a\left(T_{03}-T_{02}\right)/\eta_m Cp_g \quad (9)$$

While its outlet pressure is expressed as

$$\frac{P_{05}}{P_{04}} = \left[1-\frac{1}{\eta_t}\left(1-\frac{T_{05}}{T_{04}}\right)\right]^{\gamma_g-1/\gamma_g} \quad (10)$$

5) Afterburner

a) *Inoperative afterburner*

A pressure drop within the afterburner is defined, the drop is due to presence of drag and skin friction in the flame holders. The expression is defined as

$$P_{06} = P_{05} - \Delta P_{ab} \quad (11)$$

Since no afterburning is carried out, thus the temperature is constant in the afterburner duct.

$$T_{06} = T_{05} \quad (12)$$

b) *Operative afterburner*

Additional fuel is burnt in the afterburner, this leads to a rise in the output temperature. The maximum temperature in the cycle is now given as

$$T_{06A} = T_{\max} \quad (13)$$

The afterburner fuel-to-air ratio is defined as

$$f_{ab} = \frac{(1+f)\left(Cp_g T_{06A} - Cp_g T_{05}\right)}{\eta_{ab} Q_R - Cp_g T_{06A}} \quad (14)$$

6) Nozzle

The critical pressure is used in determining if the nozzle is choked.

Inoperative afterburner

The critical pressure is defined as

$$\frac{P_{06}}{P_c} = \frac{1}{\left[1 - \frac{1}{\eta_n}\left(\frac{\gamma_g - 1}{\gamma_g + 1}\right)\right]^{\gamma_g - 1/\gamma_g}} \tag{15}$$

where η_n is the efficiency of the nozzle. For unchoked nozzles, the outlet pressure from the jet is equal to the ambient pressure, therefore the jet speed is defined as:

$$V_7 = \sqrt{2Cp_g\left(T_{06} - T_7\right)} \tag{16}$$

However, if the nozzle is choked, the outlet temperature is defined as

$$\frac{T_{06}}{T_7} = \frac{\gamma_h + 1}{2} \tag{17}$$

The jet speed is then defined as

$$V_7 = \sqrt{R\gamma_g\left(T_7\right)} \tag{18}$$

a) ***Operative afterburner***

In the presence of an afterburner, the critical pressure is defined as

$$\frac{P_{06A}}{P_c} = \frac{1}{\left[1 - \frac{1}{\eta_n}\left(\frac{\gamma_g - 1}{\gamma_g + 1}\right)\right]^{\gamma_g - 1/\gamma_g}} \tag{19}$$

For unchoked nozzles, the jet speed is defined as

$$V_{7ab} = \sqrt{2Cp_g\left(T_{06A} - T_7\right)} \tag{20}$$

When it is choked, it is expressed as

$$V_{7ab} = \sqrt{R\gamma_g\left(T_7\right)} \tag{21}$$

The specific thrust of the engine is therefore defined as

$$\frac{T}{\dot{m}_a} = \left[\left(1 + f + f_{ab}\right)V_7 - V\right] + \frac{A_7}{\dot{m}_a}\left(P_7 - P_a\right) \tag{22}$$

While the thrust-specific fuel consumption (TSFC) is expressed as

$$\text{TSFC} = \frac{\dot{m}_f + \dot{m}_{fab}}{T} \tag{23}$$

For an inoperative afterburner, the same equation was used but $\dot{m}_{fab}$ and f_{ab} is equal to zero.

2.1.2. Developing the Model in GasTurb13

Gasurb13 is incorporated with pre-designed jet engine models. The choice model for the research work to be done was selected and loaded. There was no need to input Equations because it has its own solver. GasTurb does not require user-defined specific heat ratios, which are necessary for the calculations rather it uses component maps for its design point calculation. GasTurb uses a pseudo-perfect gas model in which the specific heat ratios are a function of temperature and gas composition [15].

2.2. Validation of Model

The model developed in Excel and GasTurb13 was validated by live data of functioning engines gotten from Nate Meier's jet engine (Meier, 2005b, 2005a) as shown in **Table 1**. These values were evaluated at sea-level static conditions.

2.3. Assumptions and Design Parameters

The design parameters and assumed valves used in developing the model are presented in **Table 2**.

2.4. On-Design Engine Performance

On-design performance analysis is defined at the flight conditions for which the engine is originally sized. The data used for the calculations are obtained at static sea level which means that the Mach number and altitude are zero. The performance analysis of the engine at the on-design point will be referred to as the reference point performance as it will constantly by referred to when carrying out more calculations at different atmospheric and flight conditions. These analyses will be carried out for both operative and inoperative afterburner. Sensitivity analysis is carried out on the on-design parameters to determine the effect of small changes in compressor pressure ratio and Turbine inlet temperature on thrust and specific fuel consumption. Further calculations was carried out using other component parameters with varying levels of technology between level 1 and level 3 as discussed in the book titled Elements of Gas propulsion textbook [14]. These values are presented below in **Table 3** and **Table 4**.

2.5. Off-Design Performance Analysis

A turbojet engine is said to be operating at off-design conditions when it operates

Table 1. Validation models gotten from Nate Meier's engine.

Model name	Thrust (KN)		TSFC		Airflow	Pressure Ratio
	Dry	Wet	Dry	Wet		
SNECMA, Atar09C, Mirage 111E	41.95	60.802	0.1029	0.2068	68.03	5.7
Rolls-Royce, Avon RA.7R MK 114	33.406	42.258	0.0879	0.1938	58.51	7.0
Rolls-Royce, Avon RB.146 MK 301	53.378	69.903	0.0949	0.1888	77.11	8.4
GE, J47-GE-1, F-86A	21.573	25.888	0.112068	0.11716	40.82	4.3

Table 2. Custom engine parameter.

Parameter Type	Turbojet		References
	Parameter	Values	
Ambient Parameters	Altitude	10,000 m	Klein, [16]
	Ambient Temperature	223.3 K	
	Ambient Pressure	0.2650 bar	
Parameters of the Gas Turbine	Mach number	0.8	Assumed for Design Point calculation
	Compressor Pressure Ratio	9	
	Turbine Inlet Temperature	1200	
	Intake Efficiency	0.9	
	Compressor Efficiency	0.9	
	Combustion Efficiency	0.9	
	Propelling Nozzle Efficiency	0.9	
	Mechanical Efficiency	0.9	
	Combustion Pressure loss	6%	
	Nozzle inlet Temperature (Afterburner exit)	2000 K	
Other parameters	Specific Heat at constant Pressure (Air)	1.4	Mattingly [17]
	Specific Heat at constant Pressure (Combustion Gas)	1.157	
	Specific Heat Ratio of Combustion Gases	1.333	
	Gas constant	287 J/(KgK)	
	Fuel Calorific value	42,100 KJ/Kg	Klein [16]

Table 3. On-Design parameters.

Mass flow (Kg/s)	30
Pressure ratio	9
TIT (K)	1200
Afterburner Temperature (K)	1800
Altitude (m)	0
Mach Number	0

Table 4. On-design parameters based on level of technology.

	LEVEL 1	LEVEL 2	LEVEL 3
π_c	0.8	0.84	0.88
TIT	1110	1390	1780
π_t	0.9	0.92	0.94
η_b	0.8	0.85	0.89

at atmospheric and flight conditions different from the prescribed on-design conditions. The performance projections at off design is expected to different from those at on-design conditions since the turbojet engine's geometry is designed for on-design performance. In carrying out off-design analysis, the following assumptions are made:

1) The gas is ideal and perfect;

2) The Flow at the turbine inlet and nozzle throat is choked;

3) The pressure ratio is constant;

4) Efficiencies of the various components are constant;

5) All the Power developed in the turbine is used in powering the compressor;

6) The Fuel-air ratio is constant.

The formulations for the Off-design analysis are similar to that for the on-design calculations, except for the compressor ratio, temperature values and mass flow rates. Off-design calculations were carried out for both varying Mach numbers and altitude to determine the effect of ambient temperature, pressure and flight speed on engine performance.

2.6. Optimization of Cycle

In the design of a turbojet engine, the thermodynamic variables of Turbine Inlet Temperature (TIT) and Pressure ratio, rp, are used in determining the optimum performance of the engine. Performance optimization is intended to determine under what conditions the maximum Thrust (F) and minimum SFC of the engine can be obtained. This is carried out by determining the optimum pressure ratio (rp) and the corresponding turbine inlet temperature (TIT) for which the turbojet engine performance gives maximum thrust and minimum SFC.

The optimisation studies are carried out in two modules: 1) The SFC is to be minimized without any specific thrust constraints. The study is carried out for different operating conditions and maximum TIT as indicated in Table. 2) The SFC is minimized with specific thrust constraints, in which for each TIT there is pressure ratio that gives maximum thrust. Afterwards, the analytical model developed with Microsoft Excel was used in determining the optimum running line (ORL) over a range of operating conditions.

3. Results and Discussion

The values were used in the analytical calculations of the turbojet engine parameters.

3.1. Results Validation

The validation simulations are obtained at sea level static conditions that are zero altitude and Mach number. At this level, the design point thrust is maximum. The difference in values of analytical calculations and the GasTurb simulation as shown in **Table 5** is due to the configuration of the software as described in Section 2.1.2. "Dry" result represents the performance of the engine without

Table 5. Validation results.

		Dry		Wet	
		Analytical	**GasTurb13**	**Analytical**	**GasTurb13**
Model 1	Thrust	41.94073	41.880	60.802	60.849
	SFC	0.1029	0.0899	0.2068	0.18532
Model 2	Thrust	33.406	33.427	42.258	42.373
	SFC	0.0879	0.07963	0.1938	0.1350
Model 3	Thrust	53.378	53.803	69.904	70.08
	SFC	0.0949	0.08629	0.1888	0.1888
Model 4	Thrust	21.576	21.72	25.888	26.02
	SFC	0.112068	0.0924	0.11716	0.14317

afterburner while the "wet" result represents the performance of the engine with afterburner effects.

3.2. On-Design Simulation Comparison

Components maps are not used for the simulations, the difference in values between the analytical solution and that from the model as shown in **Table 6** are caused by the specific heat variations.

The T-S diagrams for the design point analysis without afterburning and with after burning are shown in **Figure 2** and **Figure 3** respectively.

Sensitivity Analysis

The effect of changes in burner exit temperature, reheat exit temperature and pressure ratio on the net thrust and specific fuel consumption are presented in **Table 7**.

3.3. Off-Design Simulation/Parametric Study

Off design parameters are calculated in GasTurb13 using component maps. The custom engine parameter was used as a base of reference for the off-design simulation.

3.3.1. Effect of Varying Altitude at a Mach Number of 0.8

As seen in **Figure 4**, increasing altitude results in reduction in the specific fuel consumption, the same trend occurs in the fuel flow and the thrust at a constant Mach number. It is noticed that the engine's maximum attainable thrust occurs at sea level. The results are similar with and without an afterburner.

The thrust also decreased as seen in **Figure 4** as the altitude increases from 0 to 10,000 m. This is due to the increased drag on the jet as it moves through the air. Definitely, there is an increase in fuel consumption as seen in **Figure 5**. The relationship between the altitude and fuel flow is presented in **Figure 6**, the higher the altitude, the less fuel is consumed.

Table 6. Results from on-design analysis.

	Dry		Wet	
	Analytical	**GasTurb13**	**Analytical**	**GasTurb13**
Thrust	22.287	19.78	33.057	28.40
SFC	0.1177	0.09016	0.1847	0.18123

Table 7. Sensitivity analysis table.

				FN	SFC	WF Total
	Unit	**Basis**	**Delta**	**%**	**%**	**%**
Burner Exit Temperature	K	1200	10	+0.43	−0.51	−0.08
Reheat Exit Temperature	K	1800	10	+0.30	+0.56	+0.87
Pressure Ratio		9	0.2	+0.26	−0.23	+0.02

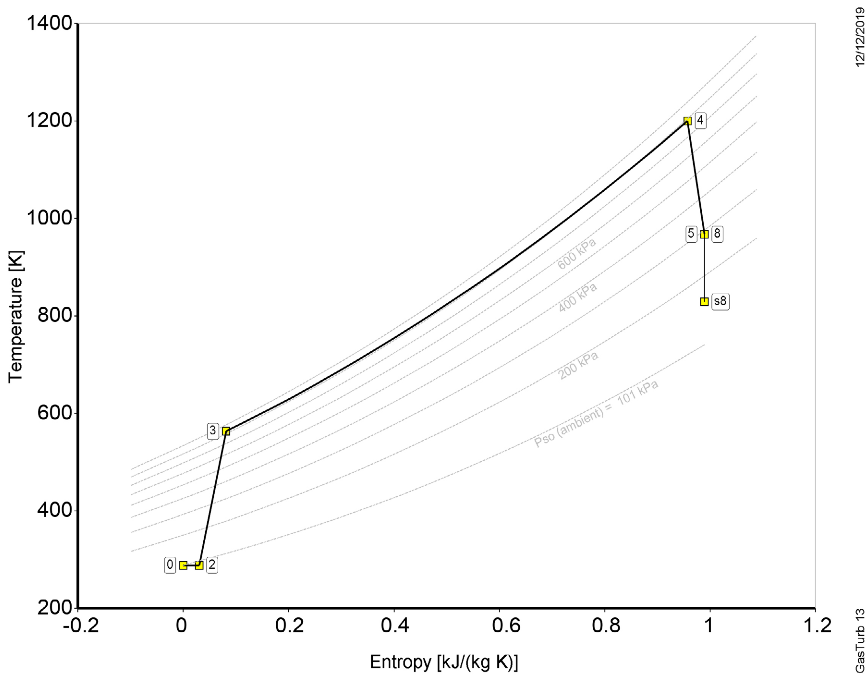

Figure 2. T-S diagram of the design point analysis without afterburner.

3.3.2. Effect of Varying Mach Number at an Altitude of 10,000 m

As seen in **Figure 7**, increasing the Mach number leads to an increase in total fuel flow in the turbojet engine this implies increased specific fuel consumption at altitude of 10,000 m as the Mach number increases. This is also the trend in the net thrust as it increases with an increase in Mach number.

The thrust also increases as seen in **Figure 8** as the Mach number increases from 0 to 2. This is due to the increased drag on the jet as it moves through the air. Definitely, there is an increase in fuel consumption as seen in **Figure 9**.

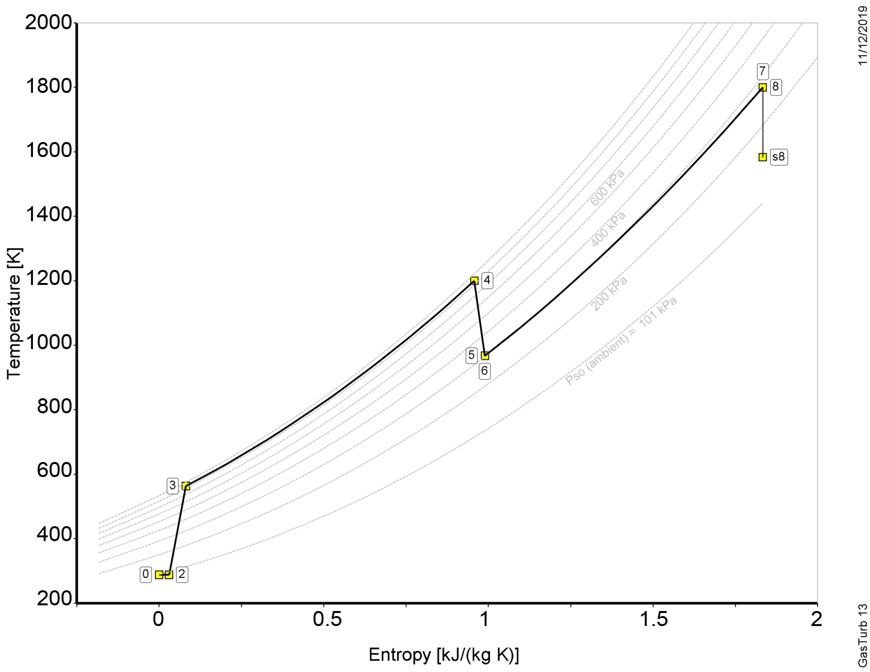

Figure 3. T-S diagram of the design point with afterburner.

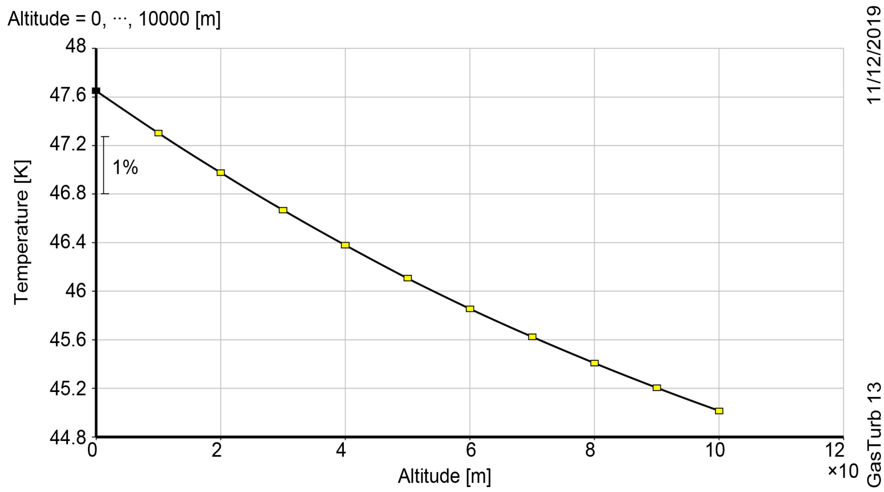

Figure 4. Specific fuel consumption against altitude at 10,000 m for Off-design performance.

3.3.3. Performance Carpet at Variable Pressure Ratio, Turbine Inlet Temperature and Afterburner Exit Temperature

This was calculated at design point and at custom engine parameters. The values obtained show the effect of pressure ratio and thrust on specific fuel consumption and Net Thrust. The carpet performance of the engine at static sea levels for the burner exit temperature conditions and reheat exit temperature conditions are presented in **Figure 10** and **Figure 11** respectively, while the carpet performance when at altitude 10,000 m and Mach number 0.8 for both burner exit and reheat exit conditions are presented in **Figure 12** and **Figure 13** respectively.

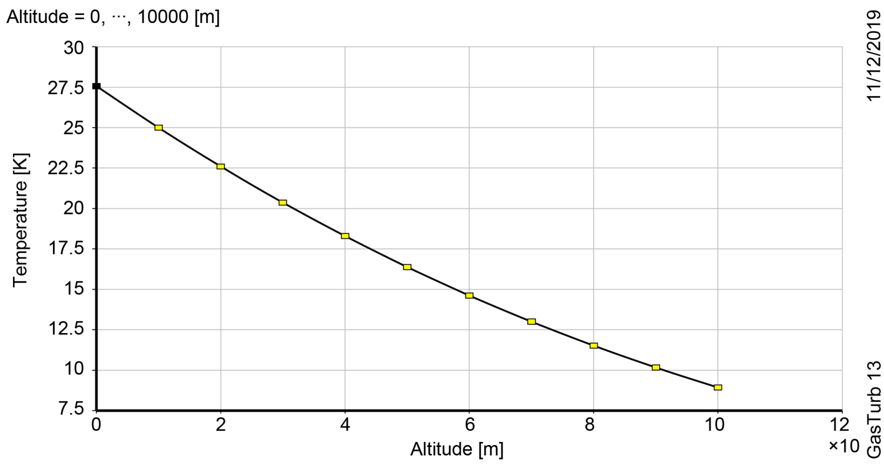

Figure 5. Thrust against altitude at 10,000 m for Off-design performance.

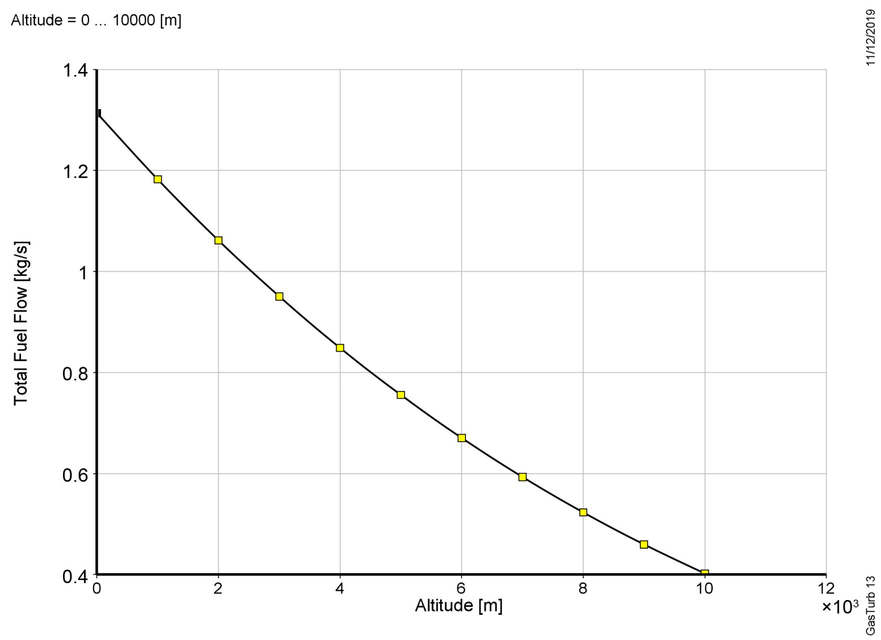

Figure 6. Fuel flow against altitude at Ma = 0.8 for off design performance.

3.4. Optimum Running Line

An optimum point line was superimposed on the compressor map as shown in Figure 14. The point at which the specific fuel consumption is lowest pressure ratio is minimum is called the cruise mode. Since there is no compressor surge, there was no need to introduce a control bleed to counter the surge. The relationship between the fuel consumption and net thrust is presented in Figure 15.

3.5. Optimization Results

3.5.1. Minimizing Specific Fuel Consumption without Net Thrust Constraint

The results of the optimization simulations when there was no net thrust constraint are summarized in Table 8. The values were evaluated between pressure

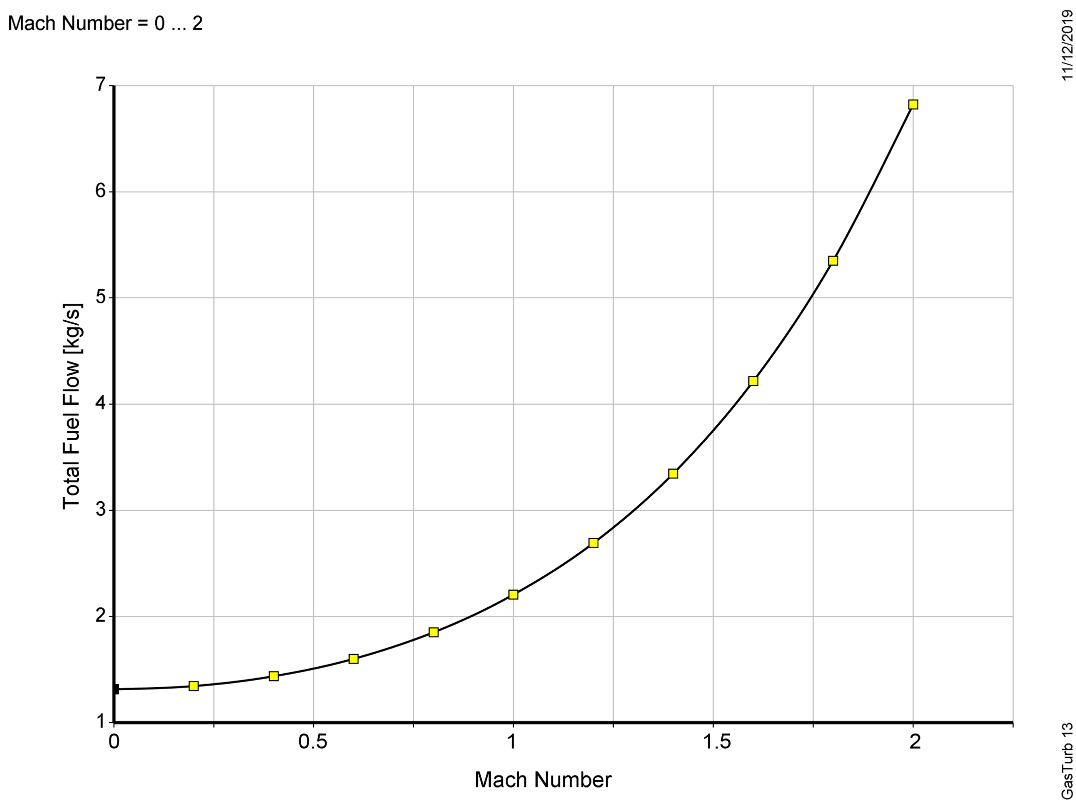

Figure 7. Fuel flow against at 10,000 m for Off-design performance.

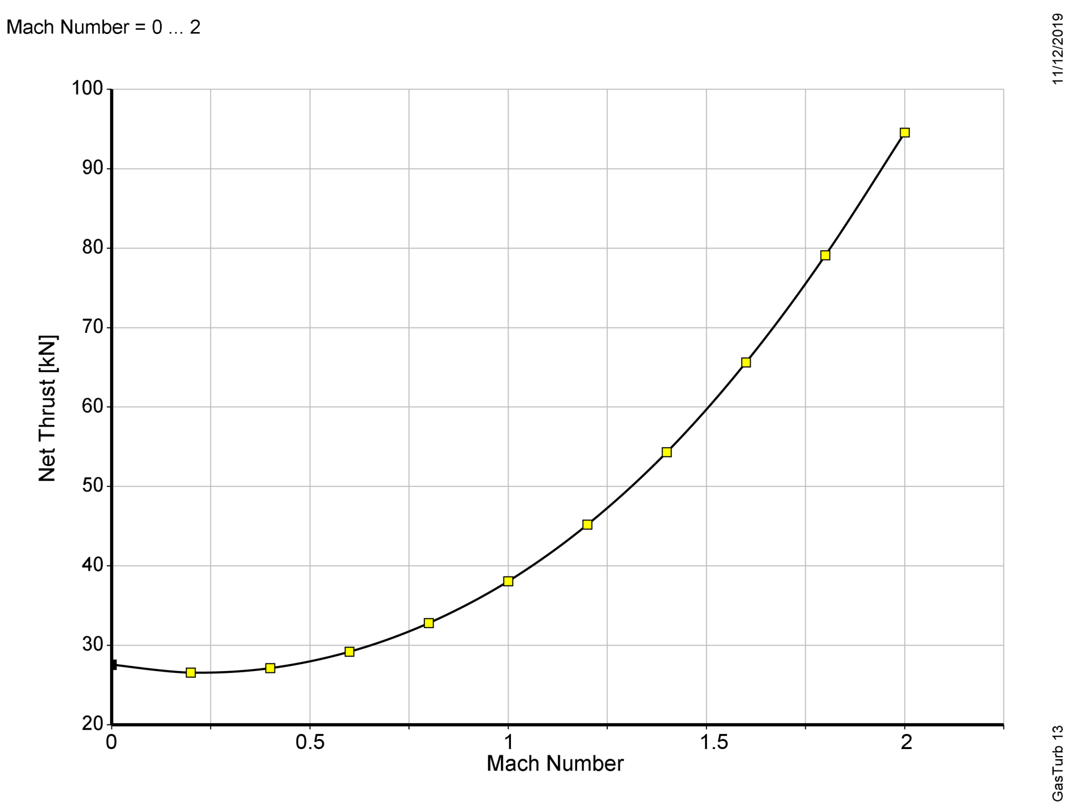

Figure 8. Net thrust against Ma at 10,000 m for Off-design performance.

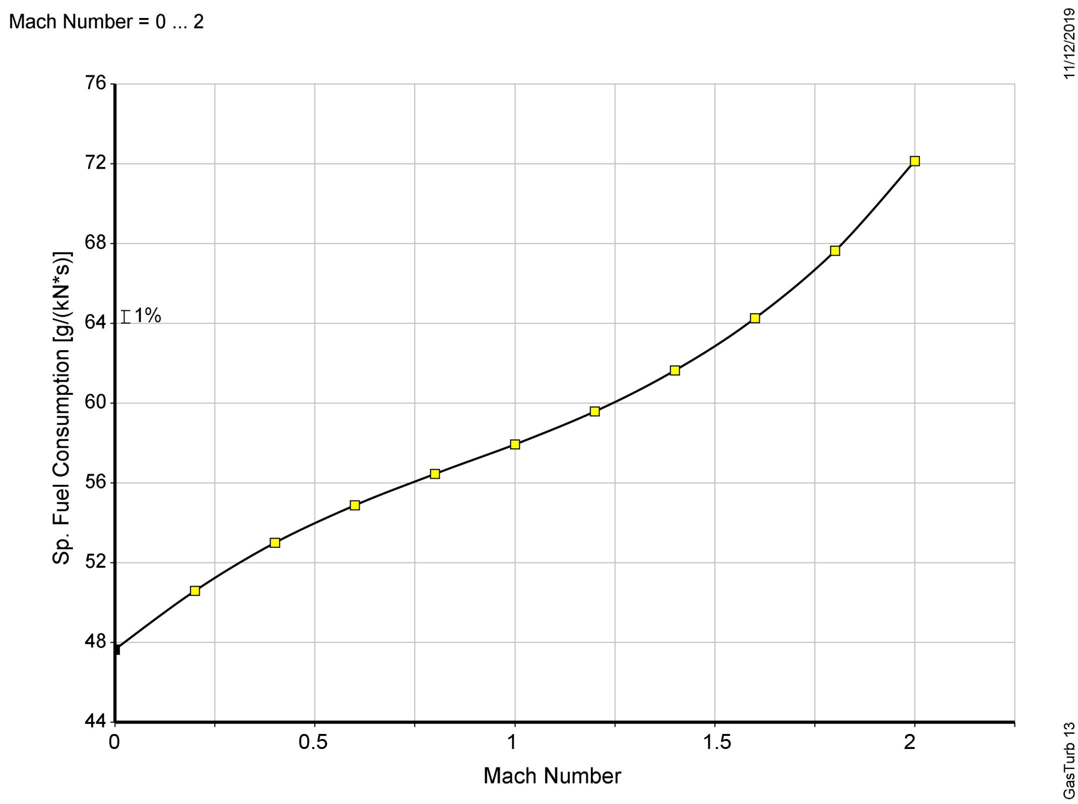

Figure 9. Specific fuel consumption against Ma at 10,000 m for Off-design performance.

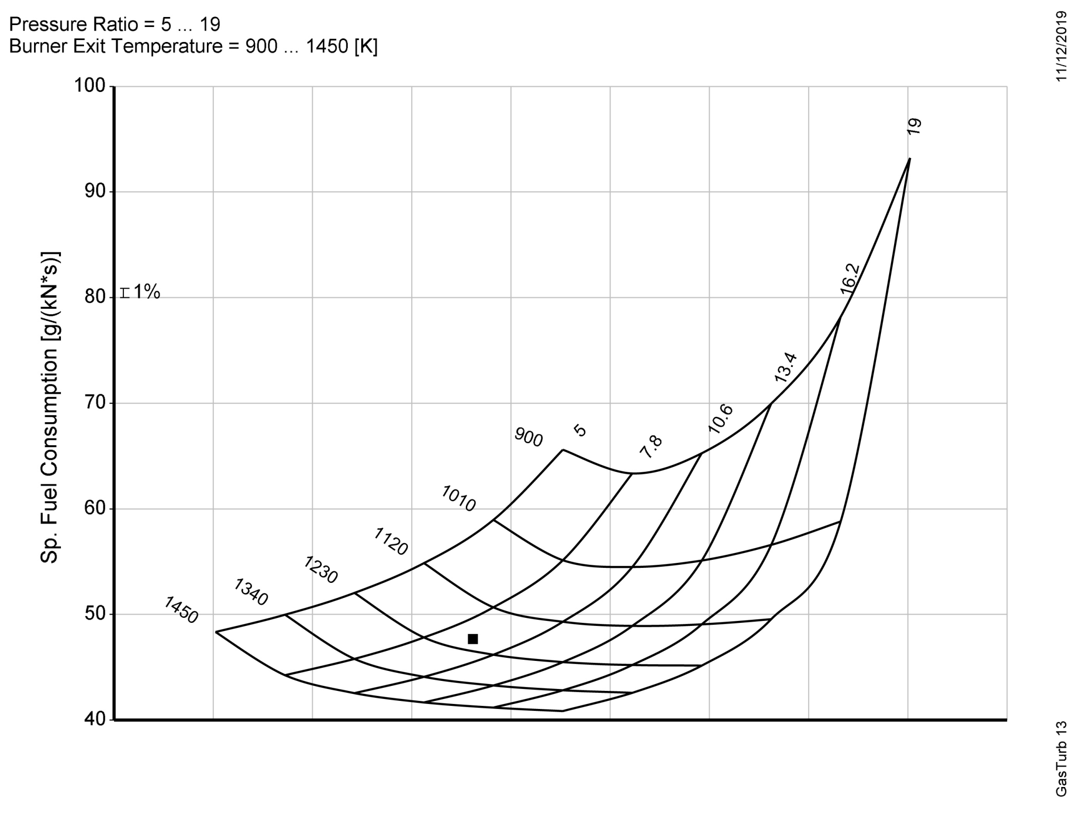

Figure 10. Performance carpet at static sea level.

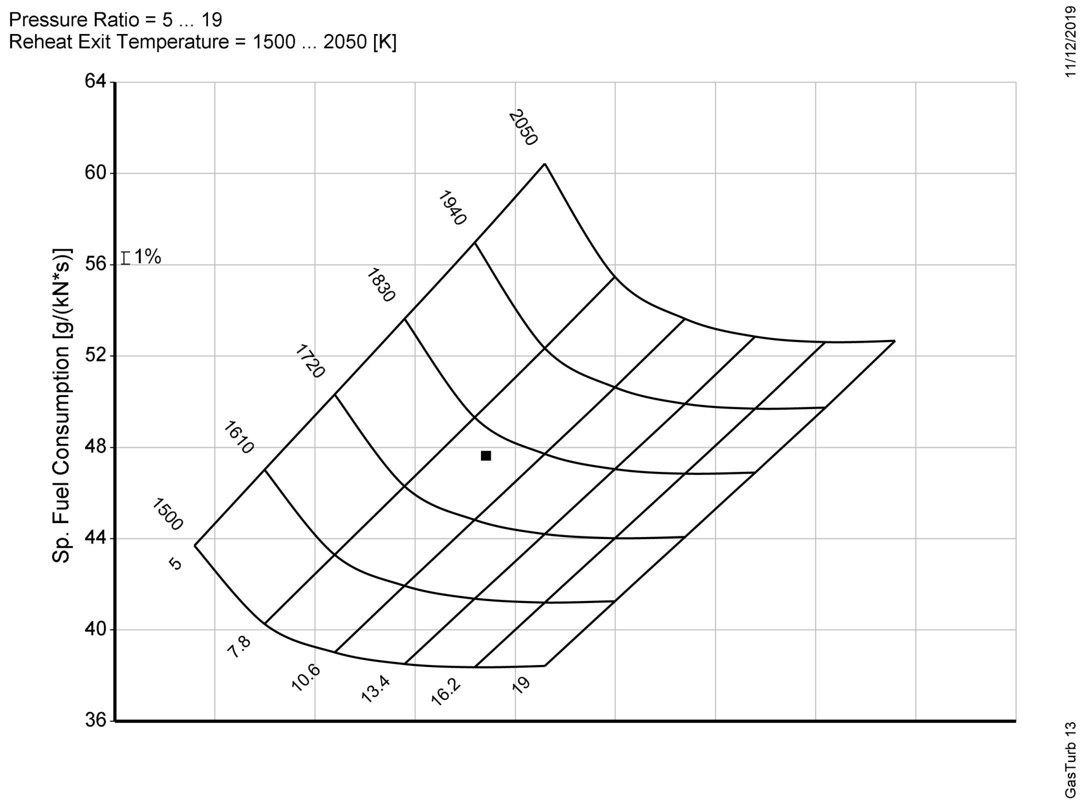

Figure 11. Performance carpet at static sea level.

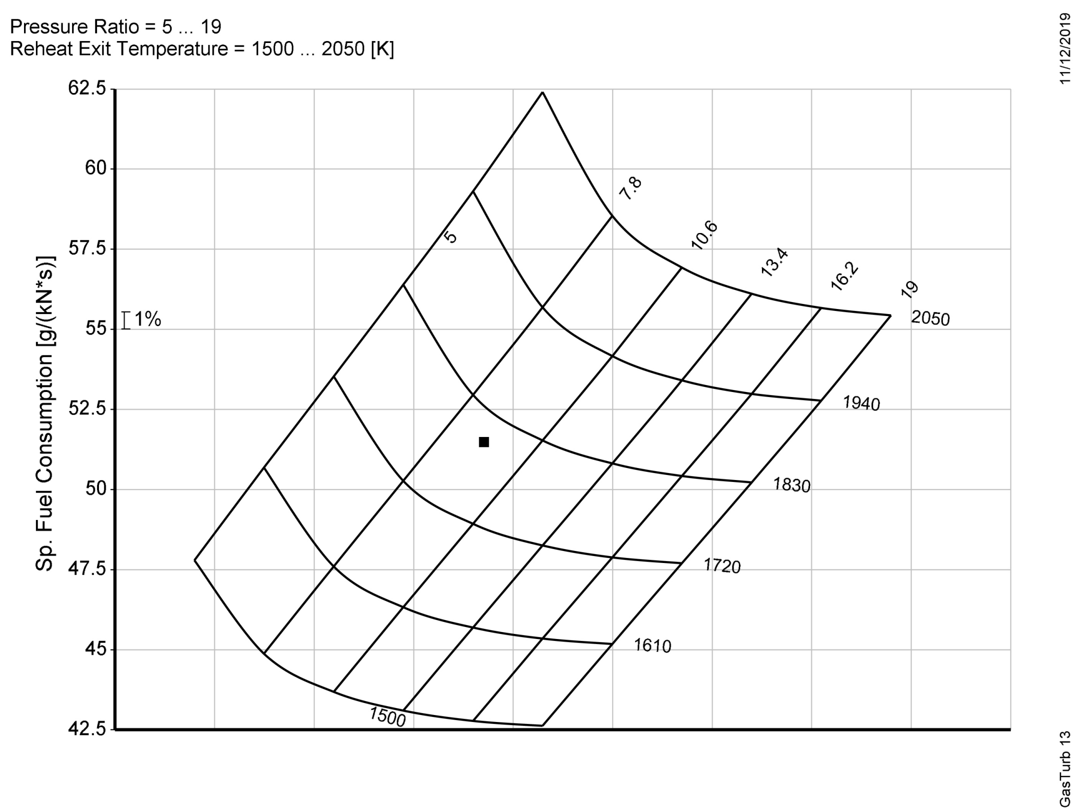

Figure 12. Performance carpet at Altitude = 10,000 m and Ma = 0.8.

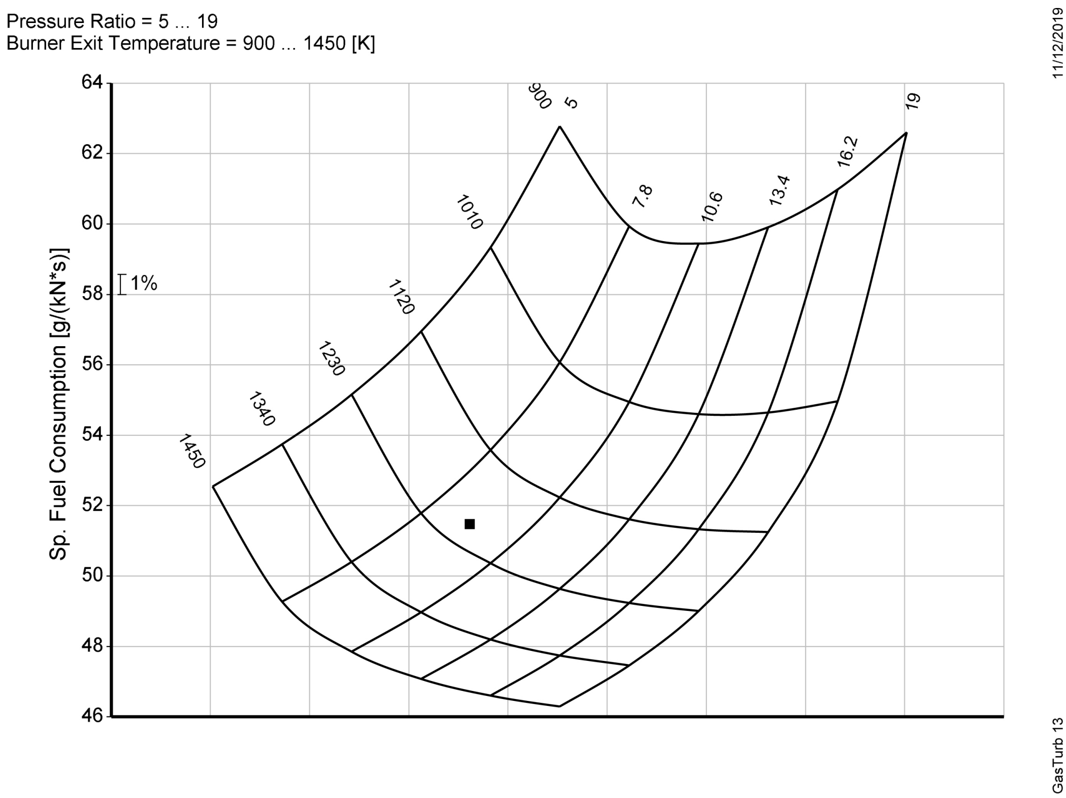

Figure 13. Performance carpet at Altitude = 10,000 m and Ma = 0.8.

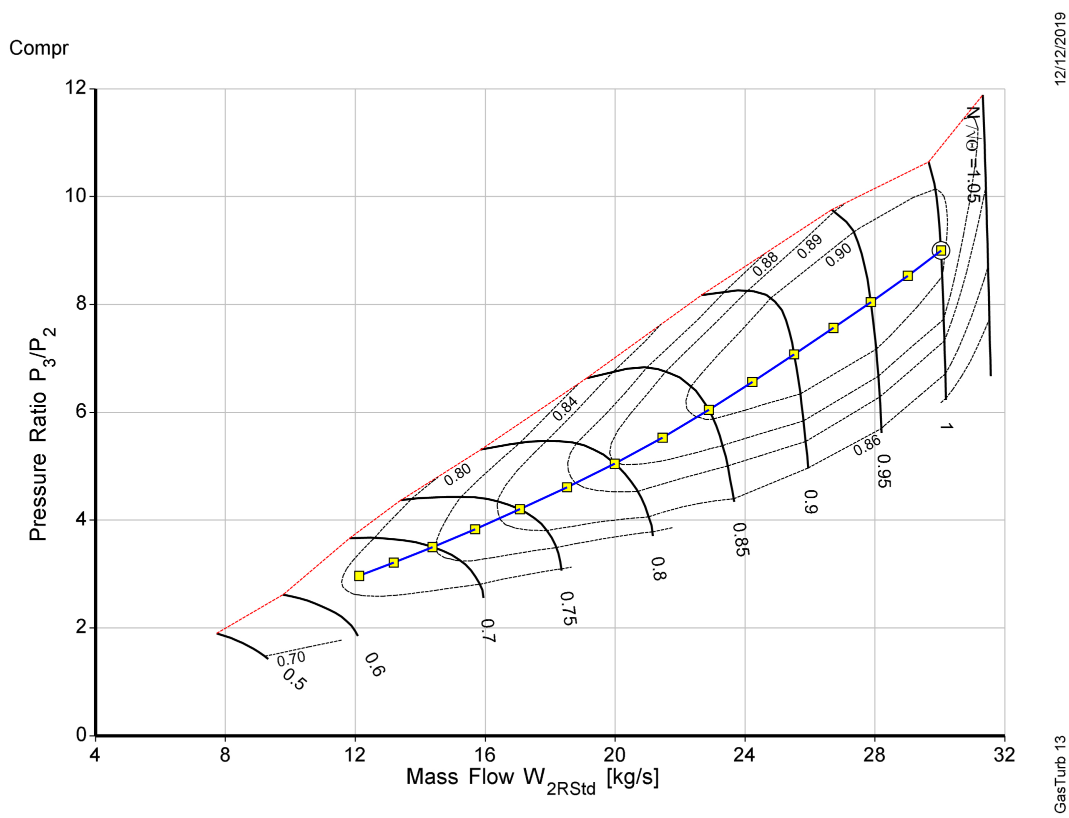

Figure 14. Operating line superimposed upon the compressor map.

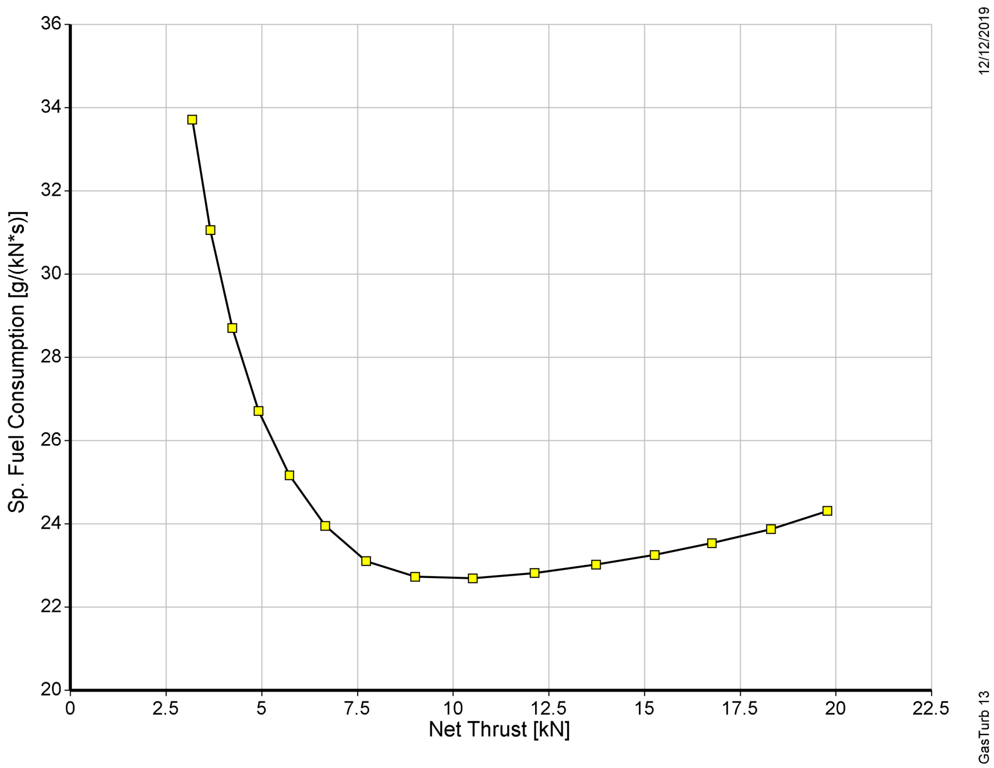

Figure 15. Engine operating line.

Table 8. Optimisation results at different operating conditions.

Operating Conditions					Optimum conditions	
Altitude (m)	Mach Number	TIT (K)	Reheat Temperature (K)		Thrust (KN)	SFC Kg/N hr
0 m	0	1450	1800	16.8504	7.10	0.1751
10,000 m	0.8	1450	1800	19.6336	11.58	0.0991

Table 9. Optimisation results at different operating conditions.

Operating Conditions					Optimum conditions	
Altitude (m)	Mach Number	TIT (K)	Reheat Temperature (K)		Pressure Ratio	SFC Kg/N hr
0 m	0	1450	1800	16.8504	7.8	0.1538
10,000 m	0.8	1450	1800	19.6336	16.78	0.0887

ratio of 5 and 20 and with a maximum turbine inlet temperature constraint of 1450 K.

3.5.2. Minimizing Specific Fuel Consumption with a Constraint on Net Thrust

The effect of constraining the thrust is shown in Table 9. A constraint of thrust at 15 KN was introduced and the optimal pressure ratio at which there is minimal fuel consumption was calculated. The pressure ratio at a maximum Thrust of 15 KN was determined to be 16.78.

4. Conclusion

This study has shown that the altitude and Mach numbers are limiting factors when the specific fuel consumption is minimised without constraining the minimum thrust thereby resulting in a two-dimensional optimisation problem. Results from this work show that TSFC reduces as the Altitude and Mach number increases at optimised turbine inlet temperature and compressor pressure ratio. Practical considerations, however, limit the potential improvements. The significant trends observed in this study are: 1) At increased Altitude and Mach number the TIT increases; 2) Pressure ratio decreases at increasing Altitude; 3) Significant reduction in Thrust at increasing; 4) Presence of an afterburner improved the thrust but also increases the Specific fuel consumption. The sensitivity study of the on-design cycle showed that there is little or no effect on the TSFC due to small deviations from optimum design values. It further showed that the TSFC of the optimised cycle is quite sensitive to variations in TIT and pressure ratio. However, the overall pressure ratio remains the limiting factor in all the cases studied

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

References

[1] Farokhi, S. (2012) Aircraft Propulsion. 2nd Edition, John Wiley and Sons, Kansas.

[2] Gobran, M.H. (2013) Off-Design Performance of Solar Centaur-40 Gasturbine Engine Using Simulink. *Ain Shams Engineering Journal*, **4**, 285-298. https://doi.org/10.1016/j.asej.2012.08.007

[3] Lazzarettoand, T. (2001) Analytical and Neural Network Models for Gas Turbine Design and Off-Design Simulation. *International Journal of Applied Thermodynamics*, **4**, 173-182.

[4] Shpiro, S.R. and Caddy, M.J. (1974) NECOMP: The Navy Engine Performance Program. Paper No. 74-GT-83, American Society of Mechanical Engineers, New York. https://doi.org/10.1115/74-GT-83

[5] Wittenberg, H. (1978) Prediction of Off-Design Performance of Turbojet and Turbofan Engines. *AGARD Conference Proceedings*, **242**, 4.1-4.31.

[6] Sellers, J.J. and Daniels, C.J. (1975) DYNGEN—A Program for Calculating Steady State and Transient Performance of Turbojet and Turbofan Engines. NASA TN D-7901, National Aeronautics and Space Administration (NASA), Washington DC.

[7] Yang, Y.H. (1991) A New Method of Predicting the Performance of Gas Turbine Engines. *Journal of Engineering for Gas Turbines and Power*, **113**, 106-111. https://doi.org/10.1115/1.2906516

[8] Zhu, P. and Saravanamutto, H.I.H. (1992) Simulation of an Advanced Twin Spool Industrial Gas Turbine. *Journal of Engineering for Gas Turbines and Power*, **114**,

180-186. https://doi.org/10.1115/1.2906568

[9] Najjar, Y. and Balawneh, I. (2015) Optimization of Gas Turbines for Sustainable Turbojet Propulsion. *Propulsion and Power Research*, **4**, 114-121. https://doi.org/10.1016/j.jppr.2015.05.004

[10] Bakalis, D.P. and Stamatis, A.G. (2012) Data Analysis and Performance Model Calibration of a Small Turbojet Engine. *Proceedings of the Institution of Mechanical Engineers*, *Part G*: *Journal of Aerospace Engineering*, **226**, 1523-1533. https://doi.org/10.1177/0954410011425126

[11] Wood, A. and Pilidis, P. (1997) A Variable Cycle Jet Engine for ASTOVL Aircraft. *Aircraft Engineering and Aerospace Technology*, **69**, 534-539. https://doi.org/10.1108/00022669710186002

[12] Najjar, Y.S.H. and Al-Sharif, S.F. (2006) Thermodynamic Optimization of the Turbofan Cycle. *Aircraft Engineering and Aerospace Technology*, **78**, 467-480. https://doi.org/10.1108/00022660610707139

[13] He, X., Wang, H., Tao, F. and Ge, G. (2021) Performance Analysis of Constant-Pressure Pumped Hydro Combined with Compressed Air Energy Storage System Considering Off-Design Model of Compressor. *Energy and Power Engineering*, **13**, 11-18. https://doi.org/10.4236/epe.2021.134B002

[14] Suzuki, H., Kawasaki, K., Endo, M. and Sakakibara, Y. (2020) Structure and Screech Tone of Radially Underexpanded Jet Emitted by Facing Cylinders. *Open Journal of Fluid Dynamics*, **10**, 52-62. https://doi.org/10.4236/ojfd.2020.101004

[15] Sung, R. (2013) A Comparative Study of the Gas Turbine Simulation Program (GSP) 11 and GasTurb 11 on Their Respective Simulations for a Single-Spool Turbojet. Master's Thesis, University of Tennessee, Knoxville.

[16] Klein, D. and Abeykoon, C. (2015) Modelling of a Turbojet Gas Turbine Engine. 2015 *Internet Technologies and Applications*, Wrexham, 8-11 September 2015, 200-206. https://doi.org/10.1109/ITechA.2015.7317395

[17] Mattingly, J.D. (2010) Elements of Gas Turbine Propulsion. 1st Edition, TATA McGraw-Hill, New Dehli.

Nomenclature

P: Pressure

T: Temperature

Ma: Mach Number

η: Isentropic Efficiency

F: Fuel to air ratio

Cp: Specific heat capacity

W: Power

TIT: Turbine inlet temperature