International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-7, Issue-5S3, February 2019

Thermodynamic Performance Analysis of a Micro Turbojet Engine for UAV and Drone Propulsion

Swati Chauhan, G. Jims John Wessley

Abstract—* A thermodynamic performance analysis of a single spool micro turbojet engine that can produce thrust to a maximum of 4 kN is performed using Gas Turbine Simulation Programme (GSP). There is a huge gap in the availability of micro gas turbine engines in the thrust range of 0.13 to 4.45 kN to power UAVs and drones. This analysis brings out the feasibility of thrust generation in a micro turbojet engine so as to fill the gap. The engine is analyzed for four different mass flow rates, Mach numbers ranging from 0.3 to 0.9 with the operating altitude between 5000 m to 9000 m. The nett thrust produced for a pressure range of 2.5 and is in the range of 3.9 to 4 kN at a mass flow rate of 7.6 kg/s which satisfies the expected design requirement of the engine. Also, the maximum turbine inlet temperature is less than 1000 K so that there is no need for a new material required in the combustor and turbine where the high temperaure exists. The outcomes of this analysis form a strong base for further analysis, design and fabrication of micro gas turbine engines to propel future UAVs and drones.

I. INTRODUCTION

With increasing growth and usage of Micro engines for UAV as well as drone propulsion, there is an ardent need for modeling and performance analysis of these complex machines. The performances of these engines depend on the thermodynamics of various components in the engine which makes the performance analysis of these components an essential one prior to the actual design and testing of the components. Nowadays computer models and simulation using commercial software like GasTurb, GSP, NPSS etc., have been widely used in the gas turbine industry because the manufacture and testing of compressors and turbines which form the main components of the turbojet engine is costly and time consuming. Hence, these thermodynamic analyses provide vital data that can be used to model and predict the performance of the gas turbine engine with reasonable accuracy. This paper deals with the parametric and transient analysis of a micro turbojet engine that is expected to develop a thrust in the range of 4 kN that can be used to propel UAVs and Drones. The outcomes of the analysis will play a major role in the future design of micro gas turbine engines for UAV and Drone propulsion.

II. LITERATURE BACKGROUND

During the recent years there has been an increasing interest in the areas of downscaling and development of propulsion systems suitable for UAV and drone propulsion. Some of the research findings relevant to the present study are presented below.

Janaina Ferreira da Silva et.al, work aims to give the reader an overview of the gas turbines modeling, particularly for the turbojet engine, considering the study at on-design and off design point at steady state operation and the transient behavior of the engine. The study was conducted for a turbojet engine operating at the transient regime and the results obtained were compared using two software's, in-house developed and other commercial software. They conclude that transient operation performs very quick responses. For civil aircraft, Fletcher and Walsh (2004) quoted that the gas turbine must accelerate from idle to 95% of maximum thrust at about 8 s. Military applications require quicker responses. From idle to 98% of maximum speed, it is required a time of less than 4 s. On decelerations from maximum thrust on takeoff to 75%, it requires about 4 s. It is seen that the thrust of 5kN overcomes all the values on the acceleration and deceleration performed between 60% and 100% of rotational speed. The surge margin did not represent a problem as it became positive on both tests. Soo Yong kim et.al, developed a method to simulate the gas turbine transient behavior and present analyze transient phenomena of a simple cycle gas turbine engine and is certain to shed some light to prepare the input data for control system and result compared with the existing experimental data of heavy duty gas turbine engine and showed good agreement. Investigation showed that a time step small enough to prevent an abrupt increase in TIT must be determined considering both surge margin and material confinement.

Gobran analyzed the off-design performance of solar Centaur-40 gas turbine engine using Simulink under two conditions namely, the engine starting (from 65% to 100% speed, no load) and the engine operating during loading (constant speed of 100%). It is concluded that the maximum engine power, fuel flow rate and thermal efficiency decreases with increase in ambient temperature. Also, for a 10° increase in ambient temperature, the output power reduces by 11.16%, while the fuel flow rate and thermal efficiency decreased by 7.45 and 4% respectively. Dinesh Kumar et.al,

---

Manuscript received February 01, 2019

Swati Chauhan, Department of Aerospace Engineering, Karunya Institute of Technology and Sciences, Coimbatore, Tamilnadu, India. (e-mail: swatichauhan@karunya.edu.in)

G. Jims John Wessley, Department of Aerospace Engineering, Karunya Institute of Technology and Sciences, Coimbatore, Tamilnadu, India. (e-mail: jims_john@karunya.edu)

performed CFD aided investigation on the basic information like temperature variation, pressure variation and mass flow on the jet engine using MATLAB. This enhances the capability of manufacturing side of the

engine which has to deliver better engine efficiency and aerodynamic shape. G. Torella described the transient performance and behaviour of the gas turbines engines and concluded for the transient calculation the basic method is volume method and iterative method. Several numerical codes have been set up for different engine configuration using this method. Syed Ihtsham-ul-Haq Gilani et.al, determines design data and scaling method for performance map generation and results show that by the basic thermodynamics laws the design points data of the compressor and turbine were calculated. These performance maps can be used for the study of stimulation gas turbine as the analytical model of the gas turbine involves component maps.

Ujam, A.J., focus on performance characteristics of a turbojet with reduced inlet pressure to the compressor engine. SFC, specific thrust (FN), component pressure ratios, TE and propulsive efficiencies are the performance parameters of the engine that analysed on the model with reduced inlet pressure for the real-time test cases of desired thrust range. They found the engine works at a higher rpm to produce the same thrust. This results with an increase in the work output but decrease in the net work. Therefore, even with the increase in the compressor pressure ratio and TIT, the engine TE goes down in a small proportion. The higher exit jet velocities, the propulsive efficiency of the engine also goes down in very small proportion. The major performance parameters for commercial engines are SFC, Thermal and propulsive efficiencies whereas for the military engine, demands higher specific thrust. Specific thrust for engine increases with reduced compressor inlet pressure. This is important for the cases of shorter runways and higher climb rate. TSFC value increases and thermal and propulsive efficiency are decreased with reduced inlet pressure. SFC increase value for an engine. The range value for the engine decreases. Advantageous to employ the reduced compressor inlet pressure approach if the situation demands engine power to efficiency. If the flow control mechanism employed for certain time of flight such as landing or take off, performance decrease in these actors will not affect the engine operation.

However, the complete analysis of an entire engine is not available in the reported literature. Hence, the present study aims at performing the complete parametric analysis and transient analysis of a micro turbojet engine and determine the performance of the engine at various input parameters like mass flow rate, altitude, Mach number and pressure ratio.

III. THERMODYNAMIC RESULTS & ANALYSIS

Cycle analysis is done to basically study the thermodynamic changes of the working fluid mainly air and products of combustion as it flows through the engine. It is normally performed in two stages namely, parametric analysis and transient analysis. Parametric cycle analysis also known as design point or on-design analysis determines the engine performance at different flight conditions and design choices and limits. The Transient analysis which is also known as engine performance analysis or off-design analysis detemines the performance of a specific engine at all flight conditions and throttle settings.

In a turbojet engine, air is taken in through an opening in the front of the engine which is compressed to 3 to 12 times its original pressure in the compressor. Fuel is added to the air and burnt in the combustion chamber to raise the temperature of the fluid mixture to about 1,100 K to 1,300 K. The resulting hot air is passed through a turbine, which drives the compressor and the exhaust gasses passes through a nozzle outlet where thrust is produced because of the reactive forces of the exit stream. The main components of a turbojet engine are : a) Inlet Duct b) Compressor c) Combustion chamber d) Turbine e) Outlet Nozzle pipe.

A. Parametric Analysis

Parametric analysis of a single spool turbo jet engine is performed using NLR's Gas turbine Simulation Program (GSP-11), an off-line component-based modeling environment for gas turbines which is widely used to perform the steady state simulation of the scaled engine. GSP is a powerful tool for performance prediction and off-design analysis with respect to variables such as ambient (flight) conditions, installation losses, certain engine malfunctioning (including control system malfunctioning), component deterioration and exhaust gas emissions. The analysis is conducted for various pressure ratios of the compressor, Mach number of inlet flow as well as altitudes of operation. The Pressure ratio in the analysis ranges from 1.5 to 4, the Mach number from 0.3 to 0.9 and the altitude of operation in the range 5000 m to 9000 m. The results of the analysis are shown below. The inlet mass flow rate of air is analyzed for four different flow rates namely, 7.6 kg/s, 8.3 kg/s, 8.76 kg/s and 9.12 kg/s.

a) Thrust produced at various Mach Number and Mass flow rates

Gross thrust is calculated using the customary equation for impulse reaction force of the flow plus the static pressure difference from throat to ambient pressure times the throat area. Net thrust is the useful thrust available excluding the drag effects like spill drag, afterbody drag etc., The gross and the nett thrust produced by the engine is shown in Fig. 1 & 2 respectively.

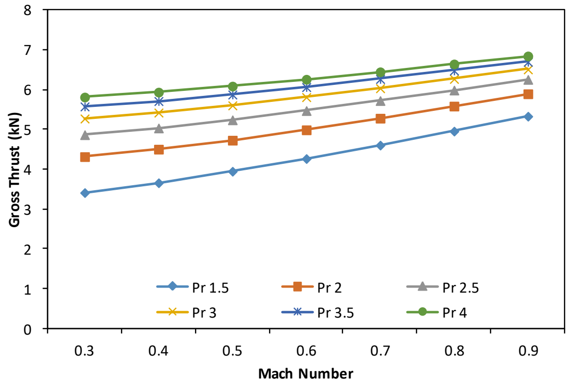

Fig. 1: Gross Thrust produced at various Mach number and Pressure Ratio

It is seen that the thrust produced increases with increase in pressure ratio as well as Mach number. The gross thrust produced ranges from 3.4 to 5.8 kN for an entry Mach number of 0.3 and it increases to 6.84 kN at a Mach number of 0.9. For a pressure ratio of 2.5, the gross thrust produced ranges from 4.8 kN to 6.25 kN as the mach number increases from 0.3 to 0.9.

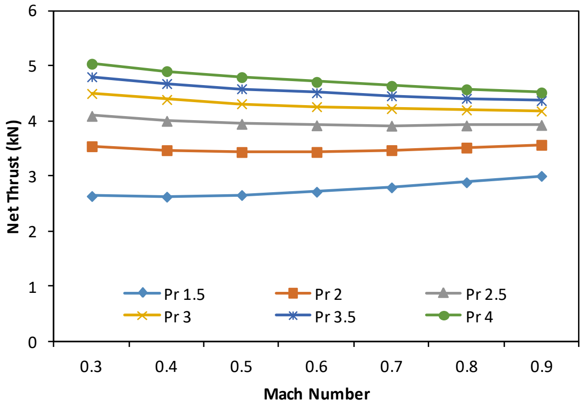

Fig. 2: Net Thrust produced at various Mach number and Pressure Ratio

Fig 2. Shows the variation of net thrust produced with respect to the change in Mach number and pressure ratios. It is seen that there is a reduction in the net thrust from the gross thrust produced. For instance, the net thrust produced for a Mach number of 0.3 varies from 2.6 to 5.03 kN for increasing pressure ratios. The net thrust available decreases with increase in Mach number and increases with increase in pressure ratio. There is a reduction of thrust to an extent of 15.9 % at Mach 0.3 which increases to 37.2 % reduction at Mach 0.9 at the pressure ratio 2.5.

b) Thrust produced at various Mach Number and Flow rates

The effect of thrust produced at various mass flow rates of inlet air was also studied. The variation of net thrust with varying Mach number and flow rate is shown in Fig. 3.

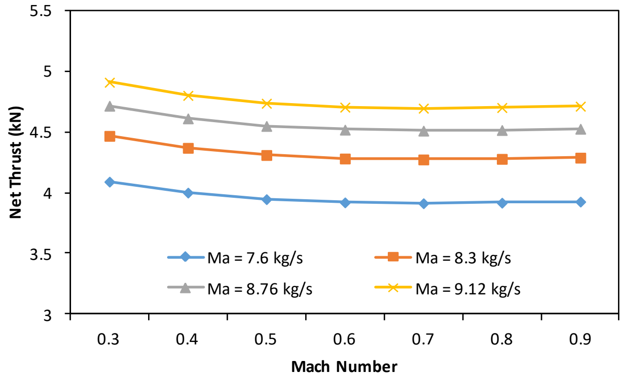

Fig. 3: Net Thrust produced at various Mach number and inlet mass flow rates

It is inferred from the above figure that the net thrust available for various Mach number remains almost constant whereas it increases with increase in pressure ratio. For a mass flow rate of 7.6 kg/s, the net thrust is 4.09 kN at a Mach number of 0.3 and it is 3.92 kN at Mach 0.9. The maximum thrust is found to be 4.7 kN at a Mach number of 0.9 and a mass flow rate of 9.12 kg/s.

c) Specific Fuel Consumption at various Mach number and Pressure ratio

The Thrust Specific Fuel consumption of the engine at various Mach number is shown in Fig 4. It is seen that the TSFC is maximum when the pressure ratio is minimum and the TSFC is minimum when the pressure ratio is maximum for all the Mach number in this study. For a pressure ratio of 1.5 and 2, the TSFC decreases with increase in Mach number whereas it remains almost constant for a pressure ratio of 2.5. However, it is also seen that the TSFC increases when the pressure ratio increases beyond 3. For a pressure ratio of 2.5, the TSFC is beween 0.167 to 0.174 kg/Nh when the Mach number varies from 0.3 to 0.9.

d) Efficiency of the Turbojet engine

The thermal, propulsive and overall efficiency of the turbojet engine is estimated for all the assumed inlet conditions. The propulsive efficiency of two different flow rates at various Mach number is shown in Fig 5. It is seen that the propulsive efficiency increases with increase in Mach number. There is also a slight increase in propulsive efficiency as the mass of air flow increases. For a mass flow rate of 7.6 kg/s, the propulsive efficiency varies from 31.3 % to 90.1 % when the Mach number increases from 0.3 to 0.9.

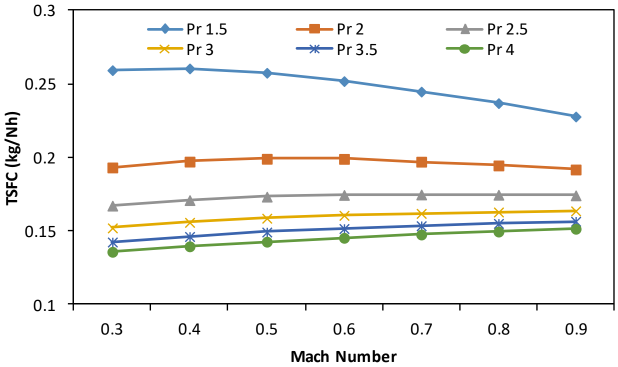

Fig. 4: TSFC at various Mach number and Pressure Ratio

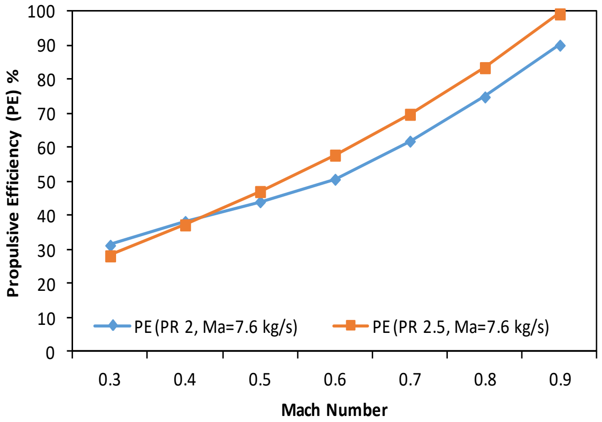

Fig. 5: Propulsive efficiency of the engine at various mass flow rates and Mach number

Fig 6. shows the variation of thermal and overall efficiency of the engine for various Mach numbers. It is found that the thermal efficiency decreases with increase in Mach number, whereas the overall efficiency increases with increase in Mach number. For a pressure ratio of 2.5, the thermal efficiency decreases from 17.8% to 14.55 % while the overall efficiency increases from 5.01% to 14.4% when the Mach number increases from 0.3 to 0.9.

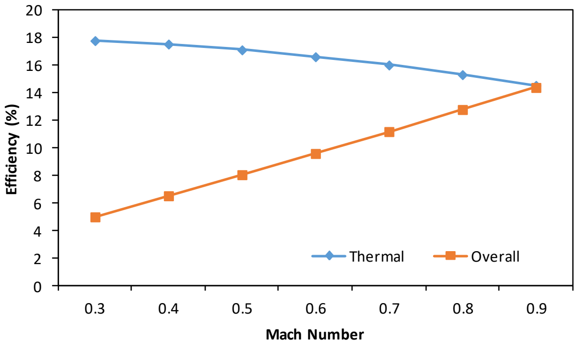

Fig. 6: Thermal and Overall effeciencies of the engine at various Mach number

B. Transient Analysis

The transient analysis is carried out to study the engine response to varying conditions with respect to time mainly to estimate the balance between the power required by the compressor and power generated by the turbine, with respect to time. This is an important analysis as this helps the control engineers to develop suitable control systems and to verify if the required power by the vehicle can be delivered within the safe limits of engine operation. The transient response plays important role to check the performance of the engine with change in throttle conditions and intake positioning with respect to time as the drone is maneuvering to attend to the mission requirements. The transient response of the engine with varying time and fuel input is estimated for various Mach number and altitudes.

a) Transient response of the engine at various Mach Number

Fig 7. Shows the transient response of the engine at various Mach number with respect to time. It is seen that the thrust increases as the fuel input increases and the system stabilizes almost within 3 seconds for all the Mach numbers of operation. The thrust increase is found to be linear with the increase in fuel flow rate.

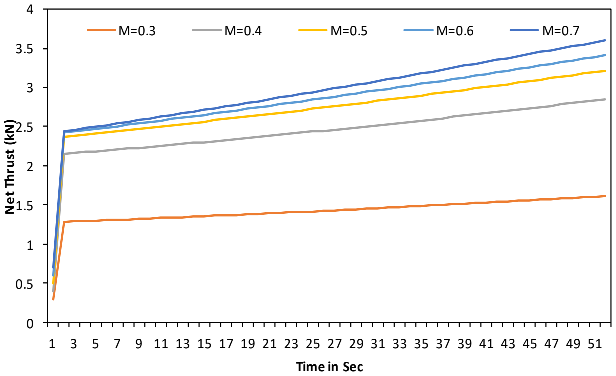

Fig. 7: Variation of thrust with respect to time and fuel flow

b) Power developed in Compressor and Turbine

Another important feature to be checked in the transient analysis is the power developed by the turbine at various conditions. Since in a single spool engine, the power developed by the turbine is used to run the compressor it is always expected that the power developed in the turbine must be higher than the power consumed by the compressor. Fig. 8 shows the power developed by the turbine and the power consumed by the compressor for a 0.3 Mach inlet condition and altitude of operation as 5000 m. It is seen that the power developed by the turbine is well ahead of the power required by the compressor thereby supplying the power required by the compressor under all conditions of operation. The power requirement of the compressor in this condition is in the range of 16.9 to 20.2 kW whereas the power produced by the turbine is in the range of 17.15 to 23.12 kW thereby making the maximum excess power availability of 12% to run the compressor.

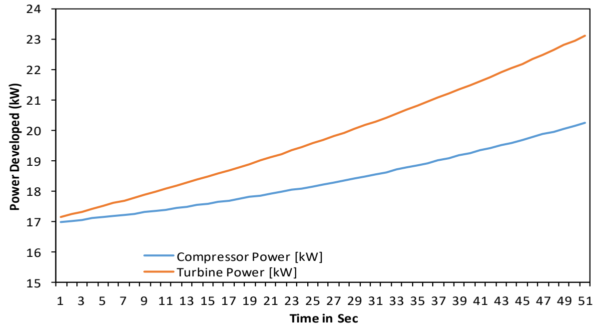

Fig. 8: Power developed in Turbine and Compressor of single spool engine

c) Temperature across engine components

The temperature and pressure variation in the working fluid as it flows through the engine is an important parameter that dictates the selection of material for the particular component. Mostly, the maximum temperature prevails in the combustion chamber and in the turbine where the combustion and the subsequent expansion take place. As there is a major setback on the availability of material that can withstand temperatures more than 1000 K, the simulation is performed to check the maximum temperature attained during the analysis for all the input conditions. A typical temperature profile across the engine components for a Mach operation of 0.3 at 5000 m altitude is given in Fig. 9.

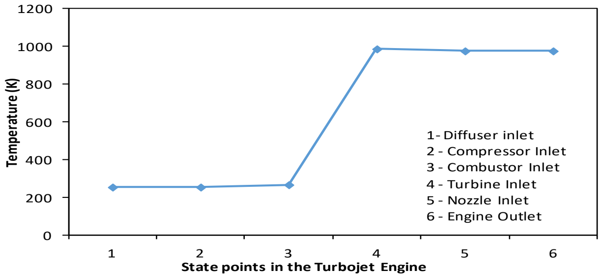

Fig. 9: Temperature Profile across the components in the engine

It is evident that the temperature at the combustor and the turbine area around 986.84 K so that there is no material constraint for the fabrication of combustor and turbine blades. It is also clear that, the temperature at the inlet is around 253.63 K while the temperature reaches 266.23 K after compression.

d) Compressor Map

The compressor map is a graph that describes a particular compressor’s performance characteristics, including efficiency, mass flow range, boost pressure capability, and turbo speed. The compressor map obtained for various inlet conditions in the study for a turbojet engine using GSP is shown below in Fig 10.

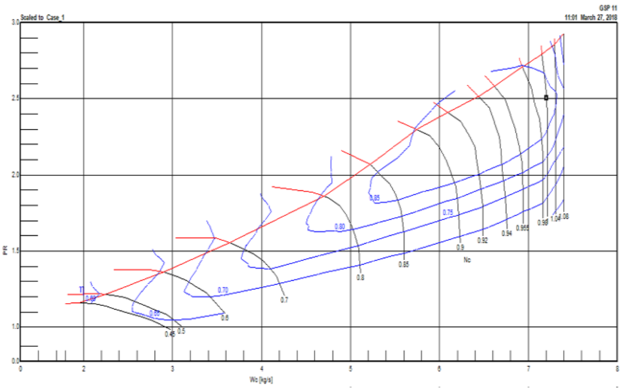

Fig. 10: Compressor Map

Fig. 10 shows the compressor performance map at a pressure ratio of 2.5. The red line on the top denotes the surge line beyond which the operation of the compressor is not possible due to flow reversal in the compressor. Also, the bottom line denotes the choke limit below which the compressor does not operate rather gets choked. The efficiency lines and the corrected mass flow rate lines for various pressure ratios are shown in the compressor map which can be efficiently used to design the compressor performance under varying conditions and time.

e) Turbine Map

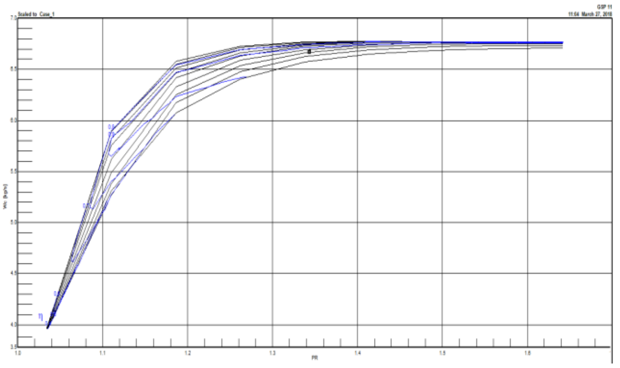

Fig. 11: Turbine Map

The turbine map obtained from the analysis is shown in Fig 11. The turbine map is orientated differently than the compressor map with the pressure/expansion ratio on the horizontal axis and the corrected flow on the vertical axis. As the burnt gases that are at a high pressure entering the turbine expands to a lower pressure in a turbine, turbines are also known as expanders. The turbine efficiency is also shown in the turbine map.

IV. CONCLUSION

The parametric and transient analysis of the single spool turbojet engine intended to produce thrust in the range of 4 kN is analysed using GSP software. The important results and conclusions are given below :

1. The thrust produced by the engine increases with increase in Mach numeber and increase in mass flow rate of inlet air.
2. The net thrust produced for a pressure range of 2.5 and Mach number ranges from 0.3 to 0.9 is in the range of 3.9 to 4 kN which satisfies

the expected design requirement of the engine.

3. A mass flow rate of inlet air in the range of 7.6 kg/s is seen to produce a net thrust of 3.92 to 4.1 kN at various Mach conditions.
4. The TSFC is maximum when the pressure ratio is minimum and the TSFC is minimum when the pressure ratio is maximum for all the Mach number in this study.
5. The thermal efficiency decreases with increase in Mach number, whereas the overall efficiency increases with increase in Mach number.
6. The power produced by the Turbine is 12% over and above the power required to run the compressor.
7. The maximum temperature in the cycle in the combustion chamber is 986.84 K which is within the tolerable limit of 1100 K.

Thus the feasibility of a practical micro turbojet engine that can produce power in the range of 4 kN that can power small UAVs and drones is established. The detailed design and fabrication of the components will certainly lead to the evolution of a new efficient propulsion system in the near future.

ACKNOWLEDGEMENT

The authors wish to thank the support and permission granted by NLR - Netherlands Aerospace Centre by granting the license to use the Gas Turbine Simulation Program GSP 11 for carrying the analysis

REFERENCES

1. Janina Ferreira da Silva, Cleverson Bringhenti and Jesuino Takachi Tomita, “Turbojet Transient Performance Simulation”, 22nd International congress of Mechanical Engineering, pp. 9748-9759, 2013.
2. Soo Yong Kim and B. Soudarev, “Transient Analysis of a Simple Cycle Gas Turbine Engine”, KSAS International Journal, Vol, No. 2, pp. 22-29, 2000.
3. M. H. Gobran, “Off-design performance of solar Centaur-40 gas turbine engine using Simulink,” Ain Shams Engineering Journal 4, pp. 285-298, 2013.
4. Dinesh Kumar and R.K. Gupta, “Parametric and performance analysis of Turbojet engine through MATLAB,” International Journal for Technological Research in Engineering 3(10), pp.2653-2657, 2016.
5. G. Torella, “Transient Performance and Behaviour of Gas Turbine engines”, The Gas turbine and Aeroengine Congress and Exposition, Brussels, Belgium, pp. 1-8, June 11-14, 1990.
6. Syed Ihtsham-ul-Haq Gilani, Aklilu Tesfamichael Baheta, and Mohad. Amin A.Majid, “Thermodynamics Approach to Determine a Gas Turbine Components Design Data and Scaling Method for Performance Map Generation”, 1st International Conference on Plant Equipment and Reliability (ICPER), Selangor, Malaysia, March 27-28, 2008.
7. A. J. Ujam, “Parametric analysis of a Turbojet engine with reduced inlet pressure to compressor”, IOSR Journal of Engineering 3(8), 29-37, 2015.
8. Saeed Farokhi, “Aircraft Propulsion”, Second Edition, John Wiley & Sons, Ltd., May 2014, ISBN: 978-1-118-80677-7.
9. Irwin E. Treager, “Aircraft Gas Turbine Engine Technology”, Third Edition, Tata McGraw-Hill Publishing Company Limited, New Delhi, 2009, ISBN-13:978-0-07-463111-9.
10. HIH Saravanamuttoo, H.Cohen, GFC Rogers, “Gas Turbine Theory”, Fifth Edition, Pearson, 2014, ISBN 978-81-7758-902-3.
11. Jack D. Mattingly, “Elements of Gas Turbine Propulsion”, Indian Edition, Tata McGraw-Hill Publishing Company Limited, New Delhi, 2014, ISBN-13:978-0-07-060628-9.
12. Philip G Hill, Carl Peterson, “Mechanics and Thermodynamics of Propulsion”, Second Edition, Addison Wesley Longman, Inc., 1999, ISBN:0-201-52483-X.
13. A.S. Rangwala, “Theory and Practice in Gas Turbines”, New Age International (P) Limited, 2010, ISBN:978-81-224-2809.
14. Gitin M. Maitra, L. V. Prasad, “Handbook of Mechanical Design”, Second Edition, Tata McGraw-Hill, 1985, ISBN: 0074517589.