International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

Vol. 44 No. 2 May 2024, pp. 446-453

Evaluating the Thermodynamic Performance of 2 Spool Gas Turboshaft Engines

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Abstract— This study examines the performance and thermodynamic behavior of a 2 spool gas turboshaft engine through simulation. The analysis reveals efficient air compression and energy extraction, with moderate losses due to irreversibilities. The combustor effectively converts fuel energy into thermal energy, demonstrating high efficiency. The overall engine performance is marked by substantial power output and acceptable fuel consumption. Detailed thermodynamic analyses, including entropy vs. temperature and enthalpy vs. entropy graphs, provide insights into energy transformations and losses. Additionally, the specific volume vs. pressure graph illustrates the effectiveness of the compression and expansion stages. These findings confirm the high efficiency and reliable performance of the 2 spool gas turboshaft engine, highlighting its potential for optimization to meet the demands of modern aviation and industrial applications.

Keywords—2 spool gas turboshaft engine; thermodynamic analysis; engine performance

I. INTRODUCTION

A gas turbine is a machine that converts energy from high-pressure and high-temperature gas into mechanical energy. Essentially, a gas turbine operates based on the Brayton cycle, where air is drawn in, compressed, mixed with fuel, and combusted in the combustion chamber to generate high-velocity hot gas. Gas turbines are widely used in various applications due to their high efficiency and ability to generate significant power from a relatively small machine. Their versatility and capability to operate in diverse environmental conditions make gas turbines a crucial technology in the modern world [1].

A turboshaft engine is a type of gas turbine engine optimized primarily to produce shaft power rather than thrust. This distinguishes it from other turbine engines, such as turbojets and turbofans, which are designed to generate significant thrust to propel aircraft forward. Turboshaft engines are commonly used in helicopters, where they power the rotor blades through a transmission system [2]. This design is highly efficient for rotary-wing aircraft due to the engine's ability to deliver substantial power in a compact and lightweight package. Turboshaft engines have a high power-to-weight ratio, making them ideal for applications where weight is a critical factor. Additionally, they are employed in various ground-based applications, such as powering pumps and generators, and in naval ships for propulsion [3].

The basic operation of a turboshaft engine involves a gas generator section, which includes a compressor, combustor, and turbine, similar to other jet engines. The key difference lies in the power turbine section, which is not mechanically connected to the gas generator. A 2 spool gas turboshaft is a type of gas turbine engine that consists of two independently rotating sets (spools) of turbines and compressors. Essentially, this engine comprises two main sets: a high-pressure compressor and turbine

(HPC and HPT) and a low-pressure compressor and turbine (LPC and LPT). These two sets are connected by different shafts, allowing them to operate at their optimal speeds independently of each other. The low-pressure compressor first draws in and increases the pressure of the incoming air before channeling it to the high-pressure compressor. The high-pressure compressor further increases the air pressure before mixing it with fuel and combusting it in the combustion chamber [4]. The resulting hot gases pass through the high-pressure turbine, which drives the high-pressure compressor, and then through the low-pressure turbine, which drives the low-pressure compressor and generates mechanical power on the output shaft [5]. This two-spool configuration offers several advantages. Firstly, its operational flexibility allows each spool to work at optimal speeds according to the workload required, thereby enhancing the overall efficiency of the engine. Secondly, the ability to separate the gas compression and expansion stages on two different shafts reduces thermal and mechanical stresses on the components, which in turn increases the reliability and lifespan of the engine [6].

Previous research on 2 spool gas turboshafts has highlighted their various advantages and widespread applications. The two-spool configuration allows for increased thermal and operational efficiency by enabling each spool to operate at different optimal speeds, thereby reducing mechanical and thermal loads on components [7]. Additionally, this two-spool design offers greater operational flexibility, particularly in helicopter applications where quick response to load changes is critical for safe and efficient flight performance [8]. It has also been noted that the two-spool turboshaft provides significant advantages in terms of reliability and maintenance compared to other gas turbine configurations, due to more even load distribution and reduced stress on critical components [9]. These studies consistently show that the 2 spool gas turboshaft is a highly efficient and reliable technology, ideal for aviation and industrial applications requiring high performance and rapid responsiveness.

This article aims to provide an in-depth understanding of the 2 spool gas turboshaft, a technology that plays a vital role in various modern applications. Various data, including pressure ratio, burner exit ratio, burner design efficiency, and fuel calorific value, will be presented to determine the enthalpy and entropy values of the turbo system. It is hoped that the results presented will enhance the understanding of the performance of this type of turbine.

II. RESEACRH METHODS

To design a 2 spool gas turboshaft, several input data have been entered into the GasTurb software. The input data are presented in Table 1. This data is crucial to obtaining an overview of the expected results. Figure 1 shows a schematic image of the turbine being analyzed. In this study, the desired results include entropy, enthalpy, and the pressure vs. specific volume profile. From these three data points, a clearer picture of the effectiveness and performance of the designed gas turbine is expected to be obtained.

TABLE I. PARAMETER DESIGN

Parameter design	***Unit***	***Value***
Intake Pressure Ratio		1
Pressure Ratio		17
Burner Exit Temperature	K	1500
Burner Design Efficiency		0.95
Burner Partload Constant		1.4
Fuel Heating Value	MJ/kg	42.74371
Rel. Enthalpy of Handling Bleed		1
Overboard Bleed	kg/s	0
Rel. Overboard Bleed W_Bld/W2		0.005

Parameter design	***Unit***	***Value***
Rel. Enthalpy of Overb. Bleed		1
Rel. Enthalpy of Recirc Bleed		1
Number of HP Turbine Stages		1
HPT Rotor 1 Cooling Air / W2		0.05
Rel. Enth. PT NGV Cooling Air		0.6
Rel. Enth. PT Cooling Air		0.6
Number of PT Stages		2
Power Offtake	kW	30
HP Spool Mechanical Efficiency		0.988
Burner Pressure Ratio		0.95
LP Spool Mechanical Efficiency		0.978
Nominal PT Spool Speed [RPM]		20000

To accurately simulate and analyze the performance of the 2 spool gas turboshaft engine, we utilized the Gas Turb 14 software. This software is widely recognized for its capability to model and evaluate gas turbine engines under various operating conditions. The following key parameters were input into the software to set up our experimental model:

1. Number of High-Pressure (HP) Turbine Stages: The model includes a single high-pressure turbine stage. This stage is responsible for driving the high-pressure compressor and plays a critical role in determining the efficiency and power output of the engine.

2. HPT Rotor 1 Cooling Air / W2: The cooling air flow rate for the high-pressure turbine rotor is set to 0.05. This parameter is crucial for maintaining the structural integrity and operational efficiency of the turbine blades by preventing overheating during high-temperature operations.

3. Number of Power Turbine (PT) Stages: The engine model incorporates two power turbine stages. These stages are designed to extract energy from the high-pressure gases exiting the high-pressure turbine, converting it into mechanical power to drive the output shaft.

4. Power Offtake: A power offtake of 30 kW is specified in the model. This represents the power extracted from the engine to drive auxiliary systems or external loads, which is essential for understanding the net power output and overall efficiency of the engine.

5. HP Spool Mechanical Efficiency: The mechanical efficiency of the high-pressure spool is set at 0.988. High mechanical efficiency indicates that a minimal amount of energy is lost due to friction and other mechanical losses, thereby maximizing the energy available for useful work.

6. Burner Pressure Ratio: The pressure ratio across the burner is a critical parameter that influences the combustion process and the overall thermal efficiency of the engine. This ratio needs to be optimized to ensure complete and efficient combustion of the fuel.

7. Nominal PT Spool Speed [RPM]: The nominal speed of the power turbine spool is set to 20,000 RPM. The rotational speed of the power turbine is a key factor in determining the kinetic energy conversion efficiency and the mechanical power output of the engine.

8. Burner exit temperature: The burner exit temperature represents the temperature of the gases leaving the combustion chamber. A high burner exit temperature of 1500 K is crucial for maximizing the thermal energy available for conversion to mechanical energy in the turbines. This temperature influences the efficiency of the combustion process and the overall power output of the engine.

9. Burner design efficiency: The burner design efficiency of 95% indicates that the combustion process is highly efficient, with only 5% of the fuel's energy lost in the form of unburned hydrocarbons, incomplete combustion products, or heat losses.

These parameters form the basis of the experimental setup within Gas Turb 14. The software uses these inputs to simulate the thermodynamic processes within the engine, including air compression, fuel combustion, and energy extraction. By analyzing the simulation results, we can assess the performance characteristics of the 2 spool gas turboshaft engine, identify potential areas for efficiency improvements, and optimize the design for various operational scenarios.

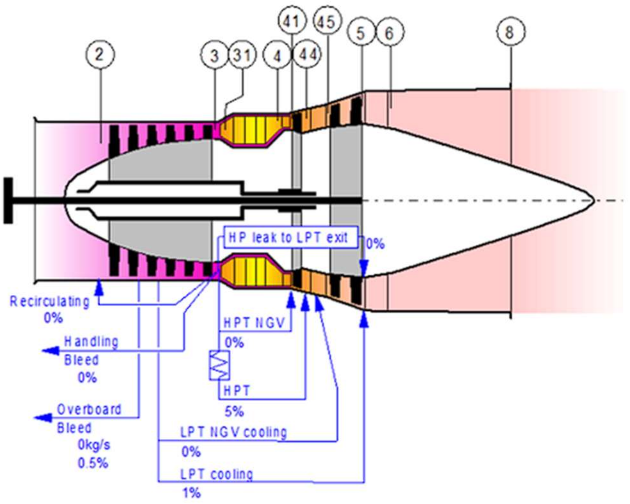

Fig. 1. Schematic diagram of 2 spool gas turboshaft engines

Additionally, the experimental setup involves conducting sensitivity analyses to evaluate how changes in key parameters affect engine performance. This includes varying the burner pressure ratio, cooling air flow rates, and power turbine speed to study their impact on efficiency, power output, and thermal management. The outcomes of these simulations will provide valuable insights into the operational behavior of the engine and guide future design enhancements.

III. RESULTS AND DISCUSSION

The simulation results from the Gas Turb 14 software provide a comprehensive overview of the efficiency metrics for the 2 spool gas turboshaft engine. These results are essential for understanding the performance characteristics and identifying areas for potential improvements. Some of the results obtained are presented as follows, such as compressor efficiency (Isentropic) of 82%. The isentropic efficiency of the compressor indicates how effectively the compressor increases the pressure of the air without adding excess entropy. An efficiency of 82% suggests that the compressor is relatively effective, though there is still room for improvement. Higher isentropic efficiency leads to lower energy losses during compression, enhancing the overall engine efficiency [10]. Another parameter obtained is burner efficiency whose value is 95%. The burner efficiency measures how well the combustion process converts the chemical energy of the fuel into thermal energy. A high burner efficiency of 95% is indicative of an effective combustion process with minimal energy loss. This high efficiency ensures that most of the fuel's energy is utilized for generating thrust, contributing significantly to the engine's overall performance [11]. Another parameter is High-Pressure (HP) Turbine Efficiency (Isentropic) whose value is 85%. The isentropic efficiency of the high-pressure turbine reflects its ability to convert thermal energy from the high-pressure gases into mechanical energy with minimal entropy increase. An efficiency of 85% demonstrates a good performance, meaning the turbine effectively extracts energy from the gases to drive the high-pressure compressor. Next is the Low-Pressure (LP) Turbine Efficiency (Isentropic) whose value is 85%. The isentropic efficiency of the low-pressure turbine is slightly higher at 89%, indicating it is very effective at converting the remaining thermal energy into mechanical energy for the output shaft. This higher efficiency is beneficial for maximizing the mechanical power output and improving overall engine performance [12]. Compressor Efficiency (Polytropic) value is 87.73%. Polytropic efficiency takes into account the variable nature of the compression process across different stages. An efficiency of 87.73% suggests that the compressor operates efficiently across its entire pressure range, contributing to overall energy efficiency by minimizing incremental losses at each stage of compression [13]. High-Pressure (HP) Turbine Efficiency (Polytropic) value is 82.54%. The polytropic efficiency of the high-pressure turbine, at 82.54%, reflects its performance across varying conditions within the turbine stages. This slightly lower value compared to isentropic efficiency indicates that there are additional small losses in real operational conditions, but the turbine still operates effectively across its entire pressure range [14]. Another value is Low-Pressure (LP) Turbine Efficiency (Polytropic) which is 87.49%. Similarly, the polytropic efficiency of the low-pressure turbine is 87.49%. This high efficiency indicates that the turbine stages are well-designed to handle varying operational conditions efficiently, ensuring consistent energy extraction and conversion to mechanical power.

The results indicate that the 2 spool gas turboshaft engine demonstrates high efficiency across various components, with the burner showing the highest efficiency at 95%. The isentropic and polytropic efficiencies of both compressors and turbines are all within a good range, indicating well-optimized components. The slightly lower polytropic efficiencies suggest minor losses in real operational conditions, which is typical in practical scenarios compared to idealized isentropic processes. These efficiency metrics highlight the strengths of the 2 spool configuration, particularly in achieving high thermal and mechanical efficiency. The high efficiencies of both turbines suggest effective energy extraction and conversion processes, which are critical for the overall performance and reliability of the engine [15]. The data also points to potential areas for further optimization, particularly in improving the isentropic efficiency of the compressor and the high-pressure turbine.

The simulation results also provided additional key performance metrics for the 2 spool gas turboshaft engine, specifically the heat rate and thermal efficiency. These metrics are critical for evaluating the overall energy conversion efficiency and performance of the engine. The heat rate value is 12547.9 kJ/kWh. The heat rate is a measure of the amount of energy required to generate one kilowatt-hour (kWh) of electricity. A lower heat rate indicates a more efficient engine, as it requires less fuel to produce the same amount of electrical power. In this case, a heat rate of 12547.9 kJ/kWh suggests that the engine has a moderate level of efficiency in converting fuel energy into electrical energy. This value reflects the total energy input needed per unit of electrical output, taking into account all the inefficiencies in the system, including combustion, mechanical losses, and thermal losses [16]. One of the important parameters is thermal efficiency, the value of which is 28.69%. A thermal efficiency of 28.69% indicates that approximately 28.69% of the energy from the fuel is converted into useful mechanical work, while the remaining energy is lost as waste heat. Although this might seem low, it is typical for many gas turbine engines, which are inherently limited by the thermodynamic efficiencies defined by the Brayton cycle. Improvements in component efficiencies, such as compressors, turbines, and combustors, can help increase the overall thermal efficiency.

The heat rate indicates a moderate level of fuel efficiency, while the thermal efficiency underscores the inherent limitations of current gas turbine technology. Continuous advancements in materials, design, and operational strategies are essential for pushing these boundaries and achieving higher efficiencies, which are crucial for reducing operational costs and environmental impact in both aviation and industrial applications.

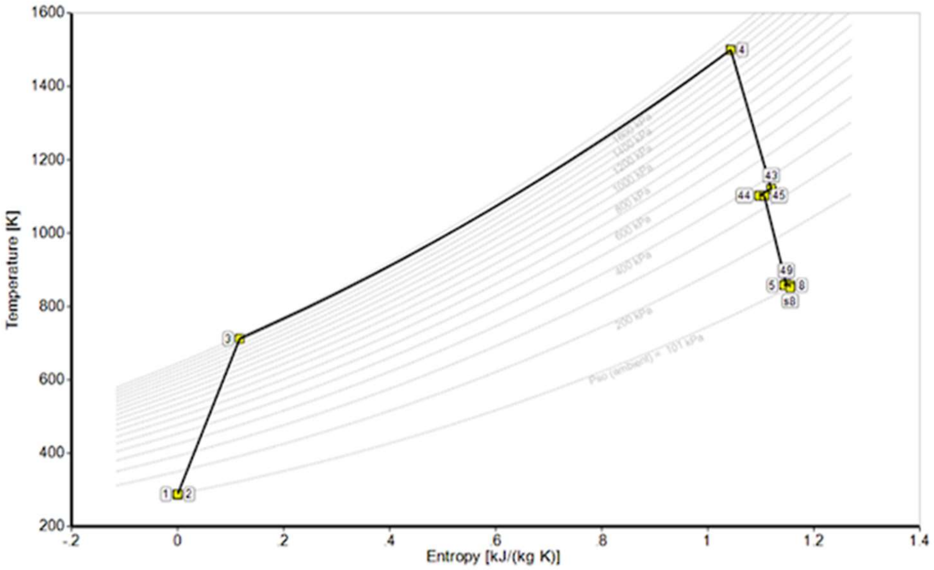

Fig. 2. Temperature versus entropy

Figure 2 shows the results of temperature versus entropy. In the compressor outlet, after the air is compressed, its temperature rises to 710 K due to the work done on it by the compressor. The entropy increases to 0.7 kJ/kg.K, indicating that some irreversibilities (e.g., friction, heat losses) have occurred during compression, causing an increase in entropy. In the combustor, fuel is burned, significantly increasing the temperature of the gases to 1500 K. The entropy also increases to 1.05 kJ/kg.K. The increase in entropy is due to the combustion process, which is highly irreversible, contributing to a substantial rise in entropy. The high-pressure turbine extracts energy from the hot gases to drive the high-pressure compressor. As the gases expand and do work on the turbine blades, their temperature drops to 1100 K. The entropy increases slightly to 1.16 kJ/kg.K due to the irreversible processes within the turbine, such as friction and heat transfer.

The low-pressure turbine further extracts energy from the gases to drive the low-pressure compressor or output shaft. The temperature drops further to 800 K, and the entropy increases to 1.18 kJ/kg.K. This additional increase in entropy reflects further irreversibilities within the low-pressure turbine.

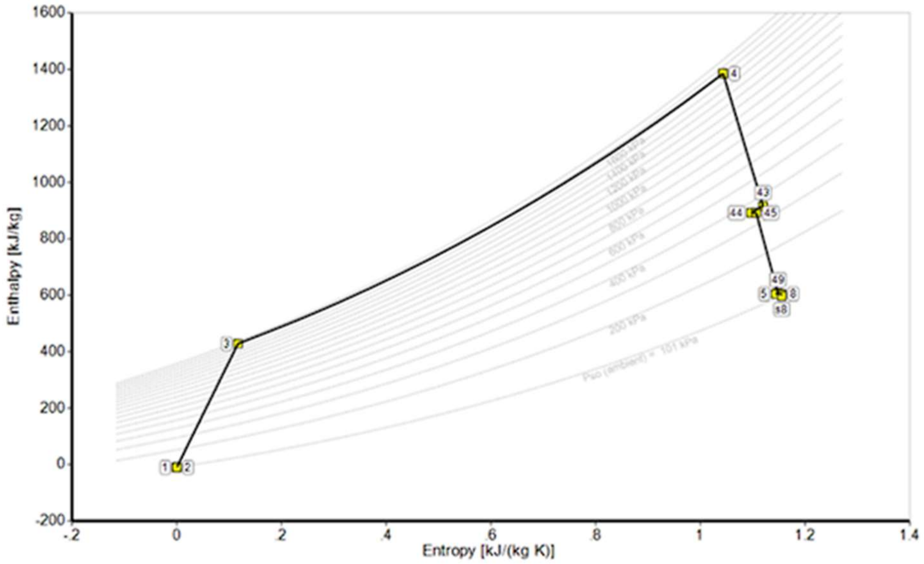

Fig. 3. Entropy versus enthalpy

Figure 3 shows the results of entropy versus enthalpy. After compression, the air pressure and temperature increase, resulting in higher enthalpy (400 kJ/kg) and a slight increase in entropy (0.17 kJ/kg.K). This reflects the work done by the compressor on the air, increasing its energy content and causing some irreversibilities, which is shown by the increase in entropy. In the combustor, fuel is burned, significantly increasing the temperature and energy content of the air. This results in a substantial increase in enthalpy (1400 kJ/kg) and a marked rise in entropy (1.05 kJ/kg.K) due to the highly irreversible combustion process.

The high-pressure turbine extracts energy from the hot gases to drive the high-pressure compressor. As the gases expand and do work on the turbine blades, their enthalpy decreases to 625 kJ/kg. The entropy increases to 1.16 kJ/kg.K due to the irreversibilities associated with the expansion process in the turbine.

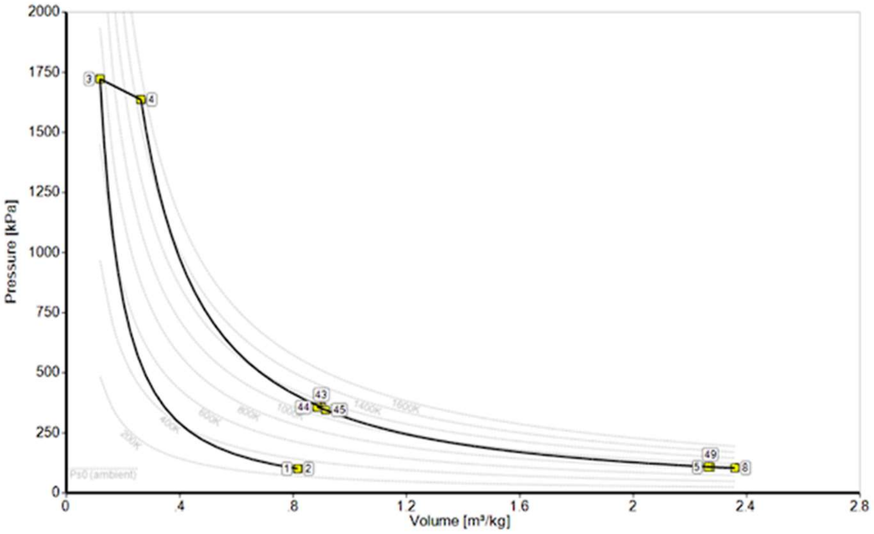

Fig. 4. Specific volume versus pressure

Figure 4 shows the results of specific volume versus pressure. In the combustor, there is a slight drop in pressure to 1600 kPa due to pressure losses in the combustion chamber. The specific volume increases slightly due to the heat addition which increases the temperature, thus increasing the specific volume despite the pressure being relatively high. The specific volume in the high-pressure turbine increased significantly from the combustor outlet. The high-pressure turbine extracts extracts energy from the hot gases, causing the pressure to drop to 375 kPa. The decrease in pressure and the relatively high temperature result in a substantial increase in specific volume [17].

IV. CONCLUSION

This study analyzed the performance of a 2 spool gas turboshaft engine using simulations. Results highlighted effective air compression and energy extraction, with efficiencies indicating moderate losses due to irreversibilities. The combustor showed high efficiency in converting fuel energy into thermal energy, while the overall engine demonstrated substantial power output with acceptable fuel consumption. Thermodynamic analysis, including entropy vs. temperature and enthalpy vs. entropy graphs, provided insights into energy transformations and losses. The specific volume vs. pressure graph illustrated the effectiveness of compression and expansion stages. The study confirms the engine's high efficiency and reliable performance across various applications, with potential for further optimization to meet modern demands in aviation and industry.

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