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Performance Analysis of Helicopter Turboshaft Engines: The Case of Agusta A119 PT6B-37

Enes GÜNALTILI*

Necmettin Erbakan University, Faculty of Aviation and Space Sciences, Aviation and Space Engineering, Konya, Turkey

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ABSTRACT

This study presents a comprehensive energy and exergy-based performance analysis of the PT6B-37A turboshaft engine used in the Agusta A119 helicopter under varying altitude conditions. The investigation focuses on engine behavior at altitudes of 0 m, 300 m, 600 m, and 900 m, within the framework of International Standard Atmosphere (ISA) conditions. The primary objective is to assess the thermodynamic performance of the engine and to determine the impact of altitude changes on efficiency and irreversibility. A hybrid modeling approach was adopted: the engine's design point performance was simulated using GasTurb 14 software, and altitude-specific energy and exergy parameters were computed using a custom MATLAB-based analytical code. Additionally, detailed component-level analyses were conducted, focusing on the compressor, combustion chamber, turbine, and exhaust sections. According to the analysis results, the engine produced a shaft power of 712.3 kW at sea level, with an overall energy efficiency of 26.24%. As altitude increased, reductions of up to 9% were observed in shaft power and thermal efficiency, while specific fuel consumption and exergy destruction increased. The combustion chamber and exhaust were identified as the most sensitive components to atmospheric variations and the main sources of exergy losses. Chemical irreversibilities, entropy generation due to high flame temperatures, and pressure drops in the combustion process were among the key factors limiting overall efficiency. Furthermore, NOx emissions—evaluated as an environmental performance parameter—were found to decrease with increasing altitude, primarily due to lower combustion temperatures and reduced partial oxygen pressure. The findings provide valuable technical insights for engine manufacturers, operators, and researchers, offering guidance on altitude-responsive design solutions, mission planning strategies, fuel optimization, and environmental mitigation. This analysis may also contribute to the development of parameter-based design criteria for future hybrid-electric helicopter platforms.

Helikopter Turboşaft Motorlarında Performans Analizi: Agusta A119 PT6B-37 Örneği

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ÖZET

Bu çalışma, Agusta A119 helikopterinde kullanılan PT6B-37A turboşaft motorunun farklı irtifa koşullarındaki enerji ve ekserji temelli performans analizini kapsamlı bir şekilde sunmaktadır. İnceleme, Uluslararası Standart Atmosfer (ISA) koşulları altında, 0 m, 300 m, 600 m ve 900 m irtifalarda motor davranışının değerlendirilmesine odaklanmaktadır. Çalışmanın temel amacı, motorun termodinamik performansını analiz ederek irtifa değişiminin verimlilik ve tersinmezlik üzerindeki etkilerini ortaya koymaktır. Bu kapsamda hibrit bir modelleme yöntemi izlenmiştir: Motorun tasarım noktası verileri GasTurb 14 yazılımı ile simüle edilmiş, ardından MATLAB tabanlı özel bir analiz kodu aracılığıyla her irtifada enerji ve ekserji parametreleri hesaplanmıştır. Ayrıca, bileşen düzeyinde (kompresör, yanma odası, türbin, egzoz) ayrıntılı analizler gerçekleştirilmiştir. Analiz sonuçlarına göre, deniz seviyesinde motorun şaft gücü 712,3 kW, genel enerji verimliliği ise %26,24 olarak belirlenmiştir. Artan irtifa ile birlikte şaft gücü ve termal verimlilikte %9'a varan düşüşler gözlemlenirken, özgül yakıt tüketimi ve ekserji yıkımı artış göstermiştir. Özellikle yanma odası ve egzoz sisteminin atmosferik değişimlere yüksek derecede duyarlı olduğu ve ekserji kayıplarının temel kaynaklarını oluşturduğu tespit edilmiştir. Yanma odasında meydana gelen kimyasal tersinmezlikler, yüksek alev sıcaklığına bağlı entropi üretimi ve basınç kayıpları, sistemin genel verimliliğini sınırlayan ana faktörler arasında yer almıştır. Ayrıca, çevresel parametreler kapsamında değerlendirilen NOx emisyonlarının, artan irtifa ile birlikte azaldığı belirlenmiştir. Bu durum, daha düşük yanma sıcaklıkları ve kısmi oksijen basıncındaki azalmayla ilişkilidir. Elde edilen bulgular, motor üreticileri, kullanıcıları ve araştırmacılar için önemli teknik veriler sağlamakta olup; irtifaya duyarlı tasarım çözümleri, görev planlama stratejileri, yakıt optimizasyonu ve çevresel etki azaltımı açısından yol gösterici niteliktedir. Bu analiz aynı zamanda gelecekteki hibrit elektrikli helikopter platformları için referans niteliği taşıyabilecek parametre temelli tasarım kriterlerinin geliştirilmesine de katkı sağlayabilir.

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***Sorumlu Yazar:** Enes Günaltılı, *enesgunaltili@gmail.com*

INTRODUCTION

In line with the increasing operational flexibility requirement, fuel efficiency targets, and environmental sustainability concerns, the aviation industry is turning towards propulsion systems with high thermodynamic efficiency (Saravanamuttoo et al., 2017; Lefebvre & Ballal, 2010). In this context, gas turbine engines are among the indispensable components of modern aircraft with their high power-to-weight ratio, reliable operating characteristics, and compact structure. Especially in aircraft with vertical take-off and landing (VTOL) capability, such as helicopters, turboshaft engines play a critical role due to their capacity to transfer mechanical power to the rotor system (Çetin et al., 2024). Turboshaft engines basically compress atmospheric air through a compressor, then this air is mixed with fuel and converted into high-energy gases in the combustion chamber, and these gases pass through the turbine to generate mechanical energy. This cycle is thermodynamically characterized by the Brayton cycle, and the component-based performance of the engine directly determines the efficiency of the cycle. This engine type is widely used not only in civil and military air platforms but also in marine, power generation, and industrial mechanical systems. In these applications, where turboshaft engines are developed with high-performance expectations, it is imperative to quantitatively evaluate engine efficiency. Accurately evaluating the performance of turboshaft engines is of great importance for both design improvements and operational efficiency. Conventional energy analysis is a fundamental method for evaluating the overall thermal efficiency and fuel consumption of the engine, but it is limited in identifying the sources of in-engine losses in detail. Therefore, evaluations based solely on first law analysis may be insufficient to identify the true potential of the system and areas for improvement. At this point, exergy analysis, with its second law-based approach, provides a more holistic performance evaluation from a thermodynamic perspective by providing the opportunity to examine irreversibilities, irregularities, and usable energy losses in the system. Exergy analysis is an indispensable tool for optimization studies in engineering systems, as it evaluates not only the total energy input and output of a system but also how much of this energy can be converted into work. In gas turbine engines, the detection and improvement of losses, especially in key components such as the compressor, combustion chamber, and turbine, not only increases design efficiency but also contributes to the reduction of operational costs. Furthermore, the variation of engine performance at different altitudes and environmental conditions provides critical data for helicopter mission profiles. There are several energy-exergy analyses of PT6 series turboshaft engines in the literature (Bechhoefer & Hajimohammadali, 2023; Balli, 2023), mostly conducted under steady-state conditions, evaluating engine component efficiency, combustion behavior, and overall performance parameters. Recent studies have examined the effects of altitude variation on the performance of gas turbine engines, frequently mentioning the importance of investigating parameters such as shaft power, specific fuel consumption (SFC), energy, and exergy efficiency. Especially in the helicopter duty cycle, there are limited studies that analyze the behavior of turboshaft engines, such as the PT6B-37 engine at different altitudes and consider energy and exergy together. However, such analyses are of great importance for both design improvements and the development of operational strategies. In this study, we thoroughly analyze the energy and exergy of the PT6B-37 turboshaft engine used in the Agusta A119 helicopter at different heights between 0 and 900 meters, following International Standard Atmosphere (ISA) conditions. The aim is to reveal the performance variations of the engine due to altitude variation in detail, to contribute to the academic literature, and to provide decision support data for engineering design and mission planning.

LITERATURE SEARCH

Turboshaft engines play a critical role in aviation, particularly in helicopter applications, thanks to their high power-to-weight ratios and flexible performance profiles. In recent years, performance evaluations of these engines based on energy and exergy analysis have attracted increasing interest in both academic literature and industrial applications (Bejan, 2006; Rosen & Dincer, 2001). Turboshaft engines are defined as gas turbines that generate power to transmit force to the helicopter rotor. In a turboshaft engine, atmospheric air is compressed to high pressure by a compressor, mixed with fuel in the combustion chamber and ignited, and the resulting high-energy gas expands through the turbine blades to produce mechanical power via the Brayton cycle. Aygün et al. (2022) highlighted how important the thermodynamic performance of this engine is and conducted an energy-exergy analysis on a proposed design of a free turbine turboshaft (TSE-FT). In general, the efficiency of turboshaft engines depends on the efficiencies of components such as compressors and turbines, the heat addition in the combustion chamber, and the operating points. For example, in a study by Turan & Aydın (2016), the exergy efficiencies of turbo shaft components were calculated, with compressor and turbine efficiencies reported to be in the range of 84–89% and combustion chamber efficiency around 80%. Therefore, energy-exergy analyses and performance analyses based on the first and second laws of thermodynamics are the most fundamental methods of investigation in turbofan or turbo-shaft-type gas turbines.

Energy analysis is used as a basic tool for calculating the overall efficiency of a system, while exergy analysis identifies losses and irreversibilities in energy conversion processes, revealing potential for improvement (Çomakli et al., 2022). Advanced exergy analyses enable detailed evaluation of internal engine losses. Multiple studies in the literature have emphasized that exergy destruction in the combustion chamber is much higher than in other components. For example, Siyahi et al. (2024) noted that in exergy analysis of a helicopter turboshaft, the combustion chamber had the highest exergy destruction at 74–80%, while the turbine and compressor had destruction rates of 16–20% and 4–6%, respectively. These results indicate that combustion chambers and turbines, which are high-loss components, are typically the focus of energy-exergy analyses. Energy and exergy analysis methods are therefore routinely applied to determine engine efficiency and identify the most critical components for design improvements. Balli (2023) evaluated a helicopter turboshaft engine under different altitude and loading conditions with energy, exergy, and environmental impact analyses and showed that exergy analysis plays a critical role not only in engine performance but also in the analysis of sustainability and environmental impacts. Dinç et al. (2022) observed in their study on a turboprop engine that as flight speed and altitude increase, fuel consumption decreases while exergy efficiency increases. In other words, the engine can operate with higher exergy efficiency under high-speed and high-altitude cruise conditions. Siyahi et al. (2024) reported that altitude gain positively affects turbo-shaft performance in design studies; however, when the same TIT (turbine inlet temperature) is desired, more fuel is required due to the cold air. As a result, while altitude increase causes power loss, it is balanced by the efficiency improvement efforts in the cold environment. Jakubowski and Jakliński (2024) analyzed the design and out-of-design performance of a free power turbine turboshaft engine using a Matlab-based numerical model and conducted component-based parameter sensitivity studies. Such numerical modeling stands out as a powerful tool in determining the optimum operating points of the engine and developing design strategies. Zare et al. (2021) investigated the effects of different jet fuels (e.g., Jet A, JP-8, biofuel blends) on engine performance using a thermodynamic optimization approach and reported that fuel selection has significant effects on both energy and exergy efficiency. These findings provide important insights for future fuel diversity and sustainable fuel applications. Fuel diversity and design improvements are important topics in current studies. Engine performance calculations are also crucial for examining fuel selection and diversity. Zare et al. (2021) compared three different jet fuels (JP-4, JP-5, JP-8) in terms of exergoeconomics in a PT6-like engine. Ultimately, JP-4 fuel provided higher exergy efficiency and lower power unit cost compared to the others. This study is important in demonstrating the impact of fuel selection on performance and operating costs in the PT6 family. In alternative fuel experimental studies, Başlamışlı (2012) tested synthetic fuel blends such as GTL and

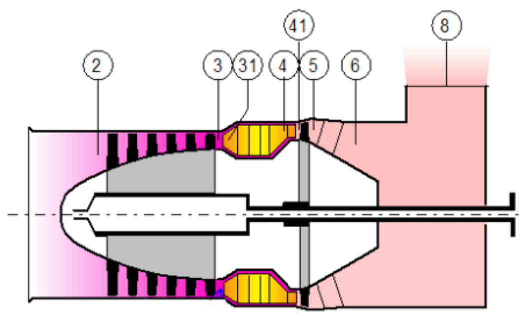
HVO in an Allison 250-C18 turboshaft engine in a METU study. In these experiments, it was observed that the use of alternative fuels caused only a 1–1.5% decrease in engine power, while CO_2 emissions increased slightly. In summary, current alternative fuels largely preserve engine performance, while limited improvements in emission composition may be observed.

In the field of design optimization, genetic algorithms and similar techniques have been used. Siyahi et al. (2024) optimized a turboshaft engine design in terms of parameters such as compressor pressure ratio and turbine inlet temperature using genetic algorithms; they found that increasing the pressure ratio and temperature improved performance, but compressor/turbine size constraints and material strength limited these gains. In such studies, more realistic results were obtained by including turbine blade cooling in exergy calculations. Research is exploring ways to improve engine efficiency within the constraints of transition strategies from low to high load operation and material engineering limitations. In summary, alternative fuel selection and optimization studies demonstrate the potential to improve both the environmental impact and mission profile performance of turbines such as the PT6B-37. Similarly, changes in engine performance under special operating conditions, such as hovering and ground effects, in helicopters must be analyzed differently from fixed-wing aircraft (Kocagil et al., 2024). Recent studies have looked at how hybrid-electric propulsion systems compare to traditional gas turbine engines to see if hybrid systems have any thermodynamic benefits when flying at low altitudes and low power levels. Additionally, researchers such as Hepbaşlı (2008) and Khaliq & Kaushik (2004) have emphasized that exergy analysis offers a more holistic optimization perspective when applied not only to internal engine evaluations but also to the entire system (e.g., helicopter power transmission systems, auxiliary power units). The literature shows that Gasturb software (Kurzke, 2024) is used effectively in turboshaft engine analyses. Gasturb stands out as a powerful simulation tool used for design point and off-design analyses, parameter studies, and optimization studies. The results obtained with this software have been observed to be consistent with the experimental and numerical studies presented in the literature. All these studies provide a valuable basis for future design and improvement studies by deepening the knowledge base on energy and exergy analyses of turboshaft engines. When all this literature is reviewed, it is clear that energy and exergy-based analyses of turboshaft engines are complementary and indispensable in terms of design improvements, sustainability goals, and operational efficiency. Pratt & Whitney Canada PT6 series turbine engines are widely used in turboprop and turboshaft applications. There are various studies in the literature related to this series. Balli (2017) performed both classical and advanced exergy analysis on a PT6-62 model turboprop engine. In the study, the exergy efficiency of the engine under actual operating conditions was calculated as 16.63% (17.13% in an unavoidable state), and the potential for improvement was found to be low. Accordingly, there is 94% unavoidable exergy loss in this engine, and the majority of the losses (approximately 86%) are caused by its own components. In conclusion, the study emphasized the need to focus on improving the compressor, combustion chamber, and power turbine. Similarly, Coban et al. (2017) observed in their experimental study on a military helicopter turboshaft that the combustion chamber had the highest exergy destruction. Aygün (2022) conducted a theoretical study, examining the engine at ten different power settings, and found exergy efficiency to vary between 13.4% and 25.6%. This result shows that the engine operates at low efficiency when transitioning to low power, with exergy efficiency increasing as power increases. Coban et al. (2017) analyzed four different torques (284–579 N·m) based on real test data. In this study, the relative exergy damage and performance parameters of the components were calculated for each load condition, thereby revealing the effect of power settings during flight on engine efficiency. Additionally, Kırmızı et al. (2024) examined turboprop engine performance under dynamic flight conditions (Mach 0–0.7, 0–7.7 km altitude) and reported that the engine's exergy efficiency varied between 15% and 25.9% depending on the flight profile. This study provides insights into how engine efficiency will change in real flight scenarios. All these studies provide useful information for performance evaluations tailored to the Agusta A119's mission profile. Ultimately, exergy analyses conducted based on the mission profile can determine the engine's actual efficiency and loss sources during different flight phases, providing valuable feedback for operational planning and activation strategies.

MODELING AND METHOD

The performance of helicopter engines varies with flight altitude. At high altitudes, air density decreases and the mass flow rate of air entering the engine decreases, resulting in a decrease in power output. For example, a study conducted by NLR indicated that as flight altitude increases, engine power decreases, and although lower ambient temperatures slightly increase thermodynamic efficiency, this effect is offset by low air density. Therefore, an increase in altitude results in a net power loss, especially in fixed compressor designs. However, the effect of altitude on performance is somewhat more complex in exergy analyses. The general trend in the literature is that an increase in altitude reduces engine power, while exergy efficiency increases slightly due to variability in the flight profile. For these reasons, modeling engine performance and efficiency in aircraft such as the Agusta A119 according to altitude changes within the actual mission profile is of significant importance. Even though current studies don't specifically look at the PT6B-37 model, examining how other PT6 models perform and where they lose efficiency can help us make educated guesses about the PT6B-37 as well. This study aims to look closely at the PT6B-37 engine in the Agusta A119 helicopter by analyzing its performance in both ideal and real-world situations, using methods found in existing research, and to find ways to improve its parts. The analyses were conducted at design point conditions and environmental conditions under International Standard Atmosphere (ISA) conditions within the altitude range of 0-900 meters, in accordance with the objective of the study. In these analyses, we calculated how much energy the engine parts use and how efficiently they work to find areas where we can reduce losses and improve performance. Basic information about the engine is summarized in Table 1. These parameters are important for the simulation model to work realistically and accurately. In this study, the performance of the PT6B-37 model turboshaft engine was simulated using GasTurb software under different altitude conditions.

Figure 1
Agusta A119 Turboshaft Engine Model Drawing



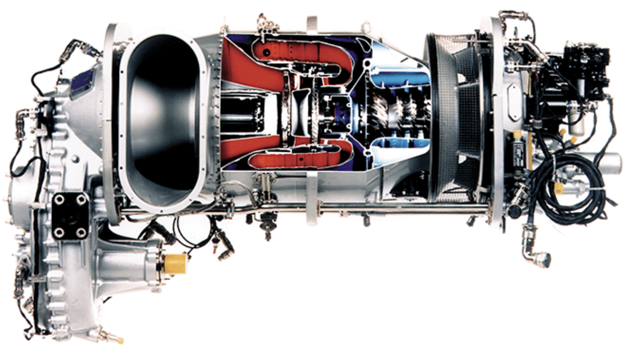
Agusta A119 Helicopter

- **Manufacturer:** Leonardo (formerly AgustaWestland)
- **Engine:** 1 × Pratt & Whitney Canada PT6B-37A turboshaft
- **Maximum Takeoff Weight:** 2.850 kg

- **Cruising Speed:** Approximately 237 km/s (128 knot)
- **Service Ceiling:** 4.572 m (15.000 ft)
- **Maximum Range:** Approximately 954 km
- **Passenger Capacity:** 8 people, including the pilot
- **Rotor Configuration:** Four-bladed, fully articulated main rotor; two-bladed tail rotor
- **Fuselage Material:** Aluminum alloy and composite materials
- **Applications:** Emergency medical services, search and rescue, firefighting, police operations, VIP transportation

The Agusta A119, which was reviewed for performance as part of the study, was designed by Leonardo as a single-engine, multi-purpose light helicopter. This model, which made its first flight in 1995, entered service in 2000. The A119 Koala is particularly notable for its low operating expenses and high performance. The helicopter is equipped with a Pratt & Whitney Canada PT6B-37A turboshaft engine with a power output of 747 kW (1,002 shp). This engine provides the helicopter with a maximum speed of 281 km/h and a flight duration of 5 hours and 20 minutes. With a maximum takeoff weight of 2,850 kg, the A119 Koala can reach a service ceiling of 4,572 meters (Leonardo, 2025). The helicopter has a range of approximately 954 km, offering high performance in the single-engine class. The cabin of the Agusta A119 is approximately 30% larger than that of other helicopters in its class. This spacious interior allows for flexible configurations for different missions. The helicopter is equipped with a four-bladed, fully articulated main rotor and a two-bladed tail rotor. The rotor blades, made of composite materials, are designed for maximum lift and minimum noise production (Ateş et al., 2023). The Agusta A119 is used for various missions, including emergency medical services, search and rescue, firefighting, police operations, and VIP transportation. Thanks to its spacious cabin volume and high performance, this helicopter can meet different operational needs.

Figure 2
Agusta A119 Turboshaft Engine Visual



Pratt & Whitney Canada PT6B-37A Engine Technical Specifications

- **Power Output:**
    - Thermodynamic Power Rating: 1.000 shp
    - Mechanical Power Rating: 900 shp
    - Shaft Output Speed: 4.373 rpm

    - Dimensions (Approximate):
        - Height: 35 inches (89 cm)
        - Width: 19,5 inches (50 cm)
        - Length: 64,5 inches (164 cm)
- **Engine Type:**
    - Free turbine turboshaft
    - Two-shaft configuration:
        - Multi-stage compressor driven by a single-stage compressor turbine.
        - An independent shaft connects the power turbine to the output shaft.
- **Key Features:**
    - Automatic fuel control system
    - Electronic power turbine valve (with manual backup feature)
    - Offset output gearbox and integrated clutch system
    - Reverse flow, radial inlet air intake (provides protection against foreign object damage)
    - Low-emission and high-stability reverse flow combustion chamber
    - Multi-stage axial and single-stage centrifugal compressor
    - Single-stage compressor turbine with cooled blades
- **Maintenance Interval:**
    - 4.500 hours (TBO - Time Between Overhaul)
- **Applications:**
    - Single-engine helicopter applications
    - Emergency medical services
    - Firefighting
    - VIP transportation
    - Corporate and public service operations

The PT6B-37A turboshaft engine developed by Pratt & Whitney Canada is a power unit designed specifically for single-engine helicopter applications, offering high reliability and performance (Pratt & Whitney Canada, 2022). This engine is used in the Agusta A119 Koala helicopter, where it provides effective service in a variety of missions. The PT6B-37A is classified in the 1,000 shaft horsepower (shp) thermodynamic class and has a mechanical power output capacity of 900 shp. The engine operates at an output shaft speed of 4,373 rpm and has dimensions of 35 inches (89 cm) in height, 19.5 inches (50 cm) in width, and 64.5 inches (164 cm) in length. The PT6B-37A's design is derived from the PT6T-3D power section and includes an offset output gearbox and an integrated clutch system. This configuration enables the two-shaft configuration of the engine, where a multi-stage compressor is driven by a single-stage compressor turbine, and an independent shaft connects the power turbine to the output shaft. Notable features of the engine include an automatic fuel control system and an electronic power turbine valve with manual backup functionality. These features provide high reliability, particularly in single-engine operations. The PT6B-37A engine is equipped with a low-emission, high-stability reverse-flow combustion chamber, a multi-stage axial and single-stage centrifugal compressor, a single-stage compressor turbine with cooled vanes, and a reverse-flow, radial-inlet air intake that provides protection against foreign object damage. This engine is part of the PT6B series, which includes over 460 engines used by 93 operators in 35 countries worldwide, and is effectively utilized in corporate, emergency medical services, firefighting, and other public service operations. The GasTurb software used in engine modeling is an advanced thermodynamic modeling and performance calculation software developed for gas turbines. This software performs design point calculations based on the user-defined engine configuration and then conducts off-design performance predictions. Thanks to GasTurb's flexible modeling capabilities, critical parameters such as the engine's compressor pressure ratio, turbine inlet/outlet temperatures, fuel flow, specific fuel consumption, and shaft power output can be calculated under different operating conditions. In particular, the engine's behavior under different speed and load conditions can be predicted using predefined compressor and turbine maps. The simulation analysis process was carried out as follows: First, the design reference point data of the PT6B-37 engine at sea level (e.g., thrust power at maximum power, compressor pressure ratio, turbine inlet temperature, etc.) were entered into the GasTurb model to ensure that the software accurately represented the engine model. At this stage, the necessary calibrations were made to match the actual performance curves of the engine. Then, environmental conditions for different altitude levels (e.g., sea level, 2000 m, 4000 m) were defined in GasTurb. For each altitude, atmospheric pressure and temperature were adjusted according to the International Standard Atmosphere (ISA) model, and the engine's equilibrium point calculations were performed under these conditions. The GasTurb software solved the engine cycle for each given altitude and ambient temperature, calculating the maximum shaft power, fuel consumption, compressor pressure ratio, and other thermodynamic quantities achievable at that altitude. For example, in the simulations, it was observed that as altitude increases, the compressor pressure ratio and achievable power output decrease due to the reduction in air density at the compressor inlet, while the fuel flow increases to maintain the same power. In this way, the performance characteristics of the PT6B-37 engine at different altitude levels were quantitatively evaluated. The results obtained reveal the engine's behavior in response to altitude changes (power loss tendency, efficiency changes, etc.) and are compared with the trends reported in the literature.

Table 1. Motor Data and Design Parameters

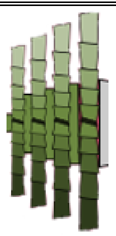
Parameter	Abb.	Quantity	Unit
Dry Air	-	-	-
Adjusted Flow Rate	$\dot{m}_{inlet}$	5.2	$kg.s^{-1}$
Pressure Ratio	P_0/P_1	0.99	-
Air Mass Flow Rate	$\dot{m}_a$	5.148	$kg.s^{-1}$
Pressure Ratio	P_3/P_2	6	-
Combustion Chamber Outlet Temperature	T_4	980	K
Fuel Chemical Formula	$C_{12}H_{23}$	-	-
Fuel Heating Value	LHV	43.124	$MJ.kg^{-1}$
Burner Pressure Ratio	P_4/P_3	0.95	-
Compressor Isentropic	$\eta_{is,AC}$	0.85	-

Efficiency			
Nominal Roller Speed	-	8000	rpm
Turbine Isentropic Efficiency	$\eta_{is,GT}$	0.93	
Altitude	-	0-900	m
Ambient Temperature	0-900 m - ISA (International Standard Atmosphere)		
Ambient Pressure	0-900 m - ISA (International Standard Atmosphere)		
0	Environment		
1	Helicopter-Engine Interface		
2	Compressor Inlet		
3	Compressor Outlet		
31	Combustion Chamber Inlet		
4	Combustion Chamber Outlet		
41	Turbine/Rotor Inlet		
5	Turbine Outlet		
6	Nozzle Throat Inlet		
8	Nozzle Throat Outlet		

FINDINGS AND DISCUSSION

The obtained data were used as basic inputs in both energy and exergy calculations. An example of the formulation used in exergy and energy analyses is given in Figure 3 for the gas turbine in general, in Figure 4 for the combustion chamber, and in Figure 5 for the compressor section.

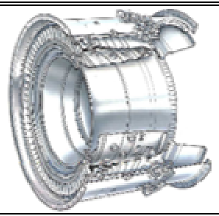
Figure 3
Station, Energy, and Exergy Equations Related to The Gas Turbine

Gas Turbine	
St41 T_{41}, P_{41} mass flow rate $\dot{m}_{41} = \dot{m}_5$ 	**St5** T_5, P_5 mass flow rate $\dot{m}_{41} = \dot{m}_5$ the total presssure at St5 $\frac{P_5}{P_{41}} = \left[1 - \frac{\left(1-\frac{T_5}{T_{41}}\right)}{\eta_{GT}}\right]^{\frac{\gamma_{cp}}{\gamma_{cp}-1}}$
The first law	$\dot{W}_{GT} = \dot{E}_{41} - \dot{E}_5 = \dot{m}_5(h_{41} - h_5)$
Exergy analysis	
Fuel exergy	$\dot{E}x_{41} - \dot{E}x_5$
Product exergy	$\dot{W}_{GT}$
Exergy destruction	$\dot{E}x_{D,GT} = \left(\dot{E}x_{41} - \dot{E}x_5\right) - \left(\dot{W}_{GT}\right)$
Exergy efficiency	$\eta_{ex,GT} = \dot{W}_{GT} / \left(\dot{E}x_{41} - \dot{E}x_5\right)$

The gas turbine diagram presented in Figure 3 comprehensively illustrates the thermodynamic relationships between the inlet (St41) and outlet (St5) stations of the turbine component of the engine, as well as the energy and exergy conversions that occur in this component. In the system assumed to operate in steady state, the mass flow rates at the inlet and outlet are constant, and the mechanical power output of the turbine is defined by the first law's energy equation. Accordingly, the power obtained from the shaft is calculated by multiplying the difference between the inlet and outlet enthalpies by the mass flow rate. In exergy analysis, the total physical and chemical exergy difference at the system's inlet and outlet is considered as fuel exergy, while the power from the turbine is called product exergy. The difference between these two quantities represents the irreversibilities occurring within the system, i.e., exergy destruction. Exergy efficiency is an important performance metric indicating how much of the net exergy entering the turbine can be converted into work, reflecting the turbine's second-law efficiency. Additionally, the total pressure ratio equation shown in the figure models pressure changes based on the temperature ratio and isentropic efficiency under the assumption of isentropic flow, providing information about the turbine's aerothermodynamic performance. These detailed analyses of each part are often used in studies to find ways to improve gas turbine performance and help in the design process by pinpointing where energy losses occur in the system.

Figure 4

Combustion Chamber-Related Station, Energy, and Exergy Equations

	Combustion Chamber	
St31 T_{31}, P_{31} mass flow rate $\dot{m}_{31} + \dot{m}_f =$ $\dot{m}_4$		**St4** T_4, P_4 mass flow rate $\dot{m}_{31} + \dot{m}_f = \dot{m}_4$ burner pressure drop $P_4 = (1 - \Delta P)P_{31}$
	The first law	$\dot{E}_{31} + \dot{E}_f - \dot{E}_4 = 0$
	Exergy analysis	
	Fuel exergy	$\dot{E}x_f$
	Product exergy	$\dot{E}x_4 - \dot{E}x_{31}$
	Exergy destruction	$\dot{E}x_{D,CC} = (\dot{E}x_f) - (\dot{E}x_4 - \dot{E}x_{31})$
	Exergy efficiency	$\eta_{ex,CC} = (\dot{E}x_4 - \dot{E}x_{31})/\dot{E}x_f$

The combustion chamber is one of the components in gas turbine engines where the highest exergy destruction occurs during the energy conversion process. Figure 4 shows the thermodynamic processes that take place at the inlet and outlet stations of this component and forms the basis for energy and exergy analysis. Compressed air and fuel mixture enter the combustion chamber, and a high-temperature combustion product is produced. According to energy analysis, the total energy of the air and fuel entering this region is equal to the energy of the combustion products exiting. However, from an exergy perspective, significant losses occur in the system due to irreversibilities. These losses are typically caused by thermodynamic imbalances in chemical reactions, temperature gradients, and pressure drops. In particular, the pressure drop in the combustion chamber has a negative effect on the overall efficiency of the engine. Therefore, exergy efficiency is an important criterion for evaluating how much of the chemical potential provided during the combustion process can be converted into usable energy. Studies in the literature show that significant increases in overall engine efficiency can be achieved by optimizing the combustion chamber. In this context, Figure 4 represents critical data from both a design and performance evaluation perspective.

Figure 5

Station, energy, and exergy equations related to compressors

Compressor		
St2 T_2, P_2 mass flow rate $\dot{m}_2$		**St3** T_3, P_3 mass flow rate $\dot{m}_3$ the total pressure at St3 $\frac{P_3}{P_2} = -\left(\frac{P_3}{P_2}\right)_{input}\left[1 - 0.075(M-1)^{1.35}\right]$ pressure ratio of AC $\Pi_{AC} = \frac{P_3}{P_2}$ the total temperature at St3 $T_3 = T_2\left[1 + \frac{1}{\eta_{AC}}\left(\Pi_{AC}^{\left[\frac{\gamma_{air}-1}{\gamma_{air}}\right]} - 1\right)\right]$
The first law		$\dot{W}_{AC} = \dot{E}_3 - \dot{E}_2 = \dot{m}_3(h_3 - h_2)$
Exergy analysis		
Fuel exergy		$\dot{W}_{AC}$
Product exergy		$\dot{E}x_3 - \dot{E}x_2$
Exergy destruction		$\dot{E}x_{D,AC} = (\dot{W}_{AC}) - (\dot{E}x_3 - \dot{E}x_2)$
Exergy efficiency		$\eta_{ex,AC} = (\dot{E}x_3 - \dot{E}x_2)/\dot{W}_{AC}$

The compressor component shown in Figure 5 forms a critical subsystem of the gas turbine engine and is responsible for compressing air at the start of the thermodynamic cycle. The pressure and temperature change between the compressor's inlet (St2) and outlet (St3) stations is one of the first important processes representing the system's energy input. According to the energy analysis, it is observed that the compressor uses mechanical energy to raise the inlet air to higher pressure and temperature levels. The mechanical power consumed in this process is considered one of the total energy inputs of the engine. According to exergy analysis, the useful conversion in the compressor stems from the increased thermodynamic potential of the air, and this increase is defined as the system's product exergy. However, due to irregularities, friction, and heat transfer during the compression process, a certain amount of exergy destruction occurs in the system. Compressor exergy efficiency indicates how much of the mechanical power provided is effective in increasing the usable energy of the air. Additionally, the pressure ratio and temperature increase equations indicated in the figure provide a modeling approach that is closer to the system's actual behavior by considering the non-isentropic nature of the compression process. In this context, the compressor component emerges not only as a preliminary unit in energy conversion processes but also as a subsystem that directly affects and has high potential for improving the overall efficiency of the system. The total pressure, total temperature, and mass flow rate values for each thermodynamic station of the engine have been determined. These values are presented in Table 2.

Table 2
Thermodynamic Station Data

Station	Mass Flow Rate (kg/s)	T (K)	P (kPa)	Station	Mass Flow Rate (kg/s)
1	5.148	288.15	101.325	1	5.148
2	5.148	288.15	100.312	2	5.148
3	5.148	512.14	601.871	3	5.148
31	5.148	512.14	601.871	31	5.148
4	5.211	980.00	571.777	4	5.211
41	5.211	980.00	571.777	41	5.211
5	5.211	657.73	104.365	5	5.211
6	5.211	657.73	104.365	6	5.211
8	5.211	657.73	104.365	8	5.211

Energy analysis was performed based on the enthalpy differences between the system's inputs and outputs, while exergy analysis was applied to determine the causes of energy losses within the system. Both physical and chemical exergy terms were taken into account in the exergy analysis. Calculations were performed by increasing the pressure and temperature of the air entering the compressor and taking into account isentropic efficiency. In the combustion chamber, the effects of combustion efficiency and pressure loss were included by evaluating the situation where the outlet temperature was increased by adding fuel.

The performance data of the engine at the 0-meter design point are given below:

- Power Taken from the Shaft: 712.3 kW
- Specific Fuel Consumption (SFC): 0.3182 kg/kWh
- Heat Rate: 13720.8 kJ/kWh
- Thermal Efficiency: 0.2624

These data were used to evaluate the energy and exergy performance of the engine and to identify areas for improvement at the component level. The following methods were followed in the energy and exergy analyses:

Energy balance: The total energy at each station was calculated to check whether energy conservation was achieved throughout the engine.

Exergy calculation: Specific exergy (specific exergy) was calculated, exergy losses were determined, and system efficiency was calculated.

Exergy efficiency (ηex): Defined as the ratio of product exergy to fuel exergy.

The results obtained using this methodology provided important clues as to which areas of the engine needed improvement. In addition, how engine performance changed at different altitudes was also analyzed. Tables 3, 4, 5, and 6 show the engine performance values at altitudes of 0, 300, 600, and 900 meters, respectively.

Table 3
Engine Performance Calculation Table Based on Altitude (0 m)

Station	Mass flow [kg.s^{-1}]	T [K]	P [kPa]
1	5.148	288.15	101.325
2	5.148	288.15	100.312
3	5.148	512.14	601.871
31	5.148	512.14	601.871
4	5.211	980.00	571.777
41	5.211	980.00	571.777
5	5.211	657.73	104.365
6	5.211	657.73	104.365
8	5.211	657.73	104.365
Shaft power delivered [kW]	712.3		
Power specific fuel consumption [kg.kW^{-1}.h^{-1}]	0.3182		
Heat rate $\frac{fuel\,flow.fuel\,heating\,value}{shaft\,power\,delivered} = \frac{\dot{m}_f LHV}{SP}$ [kJ.kW^{-1}.h^{-1}]	13720.8		
Thermal efficiency	0.2624		
Fuel flow [kg.s^{-1}]	0.06296		
NO_x severity parameters	0.11819		

The Pratt & Whitney PT6B-37A engine of the Agusta A119 helicopter shows a gradual decrease in shaft power output as it climbs above sea level. The shaft power of this engine is directly dependent on the density of the intake air; since denser air means greater mass flow and more combustible oxygen, maximum power is achieved at sea level (El-Sayed, 2008). Assuming that the engine can produce full power (e.g., ~900 shp) at 0 m altitude, it can be calculated that at around 300 m, the air density decreases by ~3% and, as a result, the available power also decreases by a few percent. A power reduction of approximately 5-6% at 600 m and 8-9% at 900 m is expected, as the air density at 900 m is only ~91% of sea level (Karakoç & Çoban, 2016). This trend is also emphasized in the literature: Engine power decreases with altitude in proportion to air density unless supercharged (Karakoç & Çoban, 2016). However, modern turboshaft engines are designed with the concept of flat rating. Although an engine such as the PT6B-37A could potentially produce a higher thermodynamic power at sea level, it is limited to a certain value by design. This allows the engine to deliver a constant maximum shaft power up to a certain critical altitude. For example, the electronic fuel control unit and power turbine valves ensure that the engine continuously produces ~900 shp during critical situations such as takeoff and cruise; the power remains nearly constant between 0–900 m as long as the engine's internal parameters (pressure and temperature limits) permit. However, once the critical altitude is exceeded—at which point the density of the ambient air begins to limit the engine's thermodynamic power capacity—shaft power begins to decline from a flat line. In summary, from 0 m to 900 m, the shaft power of the PT6B-37A decreases slightly, but this range remains largely within the engine's ability to provide steady power; if the altitude of 900 m is close to the threshold at which the engine's full power production begins to be affected, the power drop becomes more pronounced. This trend is reported to be consistent with computational models and manufacturer data (Pratt & Whitney Canada, 2022).NOx (nitrogen oxide) emissions from the PT6B-37A turboshaft engine are an important environmental parameter affected by altitude changes. NOx formation is highly sensitive to flame temperature, pressure, and oxygen concentration in the combustion chamber. At sea level, combustion chamber inlet pressure (P3) is at its highest, so flame temperatures can also rise; therefore, NOx formation tends to be maximum under these conditions. High-pressure combustion at low altitudes (e.g., 0 m) causes the fuel-air mixture to reach high temperatures, increasing thermal NOx production. Indeed, studies have shown that under typical engine operating conditions, the NOx emission index is higher at lower altitudes, and NOx formation decreases at higher altitudes with the same engine settings (Çoban et al., 2016). As altitude increases, the partial oxygen pressure in the combustion chamber decreases due to the drop in ambient pressure and the thinning of the air. This situation can slightly limit the flame temperature for the same fuel quantity and slow down NOx formation reactions. At medium altitudes such as 300 m and 600 m, a slight decrease in NOx emissions is expected compared to sea level. At 900 m, this trend may be more pronounced; however, if the PT6B-37A is forced to operate with a richer mixture to produce full power (due to reduced air intake), the flame temperature may rise again and partially affect NOx formation. Nevertheless, the net effect is generally a decrease in NOx with altitude. In high-altitude tests conducted by NASA, it was reported that NOx emissions from turbojet engines decreased significantly as altitude increased in the 16–23 km range (El-Sayed, 2008). The same study found that carbon monoxide (CO) and unburned hydrocarbon emissions increased with altitude. This finding supports the underlying mechanism of NOx reduction: At high altitudes, combustion may occur at lower temperatures and be partially incomplete (resulting in lower NOx but slightly higher CO). Therefore, when comparing altitudes of 0 m, 300 m, 600 m, and 900 m in the PT6B-37A engine, the NOx emission curve is generally expected to slope downward. The highest NOx emissions occur at sea level, while the lowest occur around 900 m (with other factors held constant). This situation is also critical in terms of NOx at low altitudes causing ozone and air quality issues at ground level. In conclusion, while altitude gain has a reducing effect on NOx emissions, the potential increase in pollutants such as CO/HC due to reduced combustion efficiency must also be considered.

Table 4

Engine Performance Calculation Table Based on Altitude (300 m)

Station	**Mass flow [kg.s^{-1}]**	**T [K]**	**P [kPa]**
1	4.984	286.20	97.773
2	4.984	286.20	96.795
3	4.984	508.80	580.769
31	4.984	508.80	580.769
4	5.046	980.00	551.731
41	5.046	980.00	551.731
5	5.046	657.76	100.706
6	5.046	657.76	100.706
8	5.046	657.76	100.706
Shaft power delivered [kW]	697.5		
Power specific fuel consumption [kg.kW^{-1}.h^{-1}]	0.3168		
Heat rate $\frac{fuel\ flow.fuel\ heating\ value}{shaft\ power\ delivered} = \frac{\dot{m}_f LHV}{SP}$ [kJ.kW^{-1}.h^{-1}]	13659.8		
Thermal efficiency	0.2635		
Fuel flow [kg.s^{-1}]	0.06137		
NO_x severity parameters	0.11453		

Altitude changes have a noticeable effect on the thermodynamic (thermal) efficiency of the engine. In general, changes in ambient temperature and pressure affect cycle efficiency in gas turbines. Compared to reference conditions at sea level, a partial improvement in the thermal efficiency of the PT6B-37A engine is observed at higher altitudes (lower pressure and temperature). This phenomenon has been reported in the literature as a typical trend for turboprop/turboshaft engines: it is clearly evident that thermal efficiency increases at higher altitudes in conjunction with a decrease in specific fuel consumption. As altitude increases, the engine's intake air temperature decreases, and the compressor's pressure ratio can operate closer to the design point despite the decrease in ambient absolute pressure. As a result, the engine's work-to-fuel ratio increases for a given power output; that is, a larger portion of the chemical energy in the fuel is converted into work. When compared, thermal efficiency at 0 m is at its lowest level because the engine operates with relatively higher specific fuel consumption even under high intake pressure conditions. At 300 m and 600 m, a slight improvement in efficiency is observed; at 900 m, the increase in efficiency becomes most pronounced. For example, a study has shown that the thermal efficiency of a turboprop engine increases from approximately 25% to 35% as altitude increases from low altitude (0 m) to high altitude (~10–14 km range) (Ekici et al., 2016). Although the 0–900 m range we analyzed is not as wide, the trend direction is the same: At 900 m altitude, the thermal efficiency of the PT6B-37A will be a few percentage points higher than at sea level. The primary reasons for this improvement are increased Carnot efficiency (due to lower ambient temperature) and the engine core operating closer to its efficiency zone with an appropriate fuel-air ratio. In short, as altitude increases, the thermal efficiency curve follows an upward trend, indicating that energy conversion is occurring more efficiently. Air flow rate (the mass flow rate of air ingested by the engine) and combustion conditions are directly affected by changes in altitude. The compressor of the PT6B-37A engine compresses air at a specific pressure ratio; for example, if the pressure ratio is simply 9:1, when the atmospheric pressure at the inlet is 0.9 bar instead of 1 bar, the outlet pressure also decreases proportionally (Pratt & Whitney, n.d.). Thus, as altitude increases, even if the compressor rotates at the same speed, the absolute pressure and density of the air it draws in are lower, resulting in a decrease in mass air flow. An engine that reaches maximum airflow at 0 m draws less air at 300 m and 600 m in parallel with the decrease in ambient density; at 900 m, the decrease in airflow is at its highest level (approximately 8–9% less air enters the engine compared to sea level). This reduced airflow may necessitate a higher fuel-to-air ratio (a “richer” mixture) to maintain the same power output. When the engine attempts to increase fuel flow to maintain power, the flame temperature may rise due to the higher fuel ratio in the mixture. However, simultaneously, the total air volume is reduced and pressure is lower, limiting the rate of combustion reactions and thermal diffusion. We can examine the changes in combustion conditions with altitude in several dimensions: First, flame temperature and combustion efficiency. At sea level, combustion occurs quickly and efficiently due to high pressure, and the flame core temperature is high. As altitude increases, the flame temperature theoretically tends to decrease for the same fuel quantity because heat loss and mixture dilution are greater in a less dense environment. This could mean lower combustion temperatures and lower NOx emissions if the engine were to continue operating at the same power. Second, combustion stability and flame structure. At lower pressure, flame velocity and stability decrease; the flame length may increase, and the risk of oscillation/instability rises. In the design of an engine like the PT6B-37A, fuel injection and air-mixture systems are optimized to maintain stable combustion up to modest altitudes like 900 m, so no significant issues are expected in this altitude range. However, at higher altitudes (e.g., several thousand meters), the lean blowout limit becomes important for engine control—as the air becomes leaner, combustion may tend to extinguish spontaneously (El-Sayed, 2008). As the airflow decreases, the air-fuel ratio in the combustion chamber also changes. At sea level, ample air intake ensures that combustion typically occurs in a lean condition, which keeps combustion temperatures under control and limits unwanted emissions. At 900 m, if the engine needs to proportionally increase fuel flow to meet power demand, the mixture may become slightly less lean (enriched). Although this has the potential to increase NOx by causing higher temperature pockets in the combustion chamber, the intensity of combustion is limited due to the overall pressure drop. As a result, while the air flow rate decreases by approximately 8–9% between 0 m and 900 m, the combustion chamber conditions change to adapt to the lower density and pressure: Flame temperature and velocity decrease slightly, NOx formation decreases, but CO and partial combustion products may increase slightly (Çoban et al., 2016). These changes are compensated for by the engine control units; for example, fuel injectors and compressor bypass valves are designed to maintain optimal mixture and stability during altitude changes. Therefore, the PT6B-37A engine maintains safe and efficient combustion conditions even as airflow decreases at altitudes of 0 m, 300 m, 600 m, and 900 m—but the combustion internal dynamics find a different equilibrium point at each altitude.

Table 5

Engine Performance Calculation Table Based on Altitude (600 m)

Station	**Mass flow [kg.s^{-1}]**	**T [K]**	**P [kPa]**
1	4.825	284.25	94.322
2	4.825	284.25	93.378
3	4.825	505.45	560.271
31	4.825	505.45	560.271
4	4.885	980.00	532.257
41	4.885	980.00	532.257
5	4.885	657.79	97.151
6	4.885	657.79	97.151
8	4.885	657.79	97.151
Shaft power delivered [kW]	682.7		
Power specific fuel consumption [kg.kW^{-1}.h^{-1}]	0.3154		
Heat rate $\frac{fuel\ flow.fuel\ heating\ value}{shaft\ power\ delivered}=\frac{\dot{m}_f LHV}{SP}$ [kJ.kW^{-1}.h^{-1}]	13600.1		
Thermal efficiency	0.2647		
Fuel flow [kg.s^{-1}]	0.05981		
NO_x severity parameters	0.11097		

Specific fuel consumption (SFC) refers to the amount of fuel consumed per unit of power produced by the engine and is usually evaluated together with fuel flow. For the PT6B-37A engine, it has been observed that SFC decreases as altitude increases, meaning that the engine uses fuel more efficiently. The highest specific fuel consumption values are observed at sea level because, even under high pressure and temperature conditions in the combustion chamber, more fuel is consumed when the engine reaches full power in dense air. At medium altitudes such as 300 m and 600 m, the SFC decreases slightly—at these altitudes, less fuel is required to produce the same power as the engine's thermodynamic efficiency improves. At 900 m, the downward trend in specific fuel consumption becomes more pronounced. An engine that consumes 0.584 lb of fuel per horsepower-hour at sea level (approximately 0.265 kg/BHP-hour or ~0.355 kg/kWh) is expected to have a slightly lower value at 900 m. This decrease is due to improved thermal efficiency and combustion processes. From a fuel flow perspective, as altitude increases, the engine's maximum power output decreases slightly, so the mass of fuel burned per unit time during full throttle operation also decreases. In other words, while the engine requires the highest fuel flow rate (e.g., maximum fuel flow rate during takeoff) at 0 m, at 900 m, the total fuel flow is lower due to both the lower available power and the improved specific fuel consumption. This situation has a positive effect on both energy efficiency and operational range: Since less fuel is consumed per unit of power at higher altitudes, fuel economy improves as the helicopter's cruising altitude increases. As a result, when comparing fuel consumption values at altitudes of 0 m, 300 m, 600 m, and 900 m, fuel consumption decreases with altitude gain, and the engine's fuel flow requirement decreases. The heat rate is a measure of how much heat (fuel energy) is input per unit of work or power produced by the engine and is inversely proportional to thermal efficiency. For the PT6B-37A engine, a decrease in heat rate, i.e., lower fuel energy requirement, is expected as altitude increases. This is due to the increase in thermal efficiency mentioned above: As the engine becomes more efficient, less chemical energy is expended to achieve the same output. At 0 m, the heat ratio is highest, indicating that more fuel heat is required for each kW of power produced by the engine. At 900 m, the heat ratio decreases in parallel with the increase in efficiency; in other words, the engine consumes fewer joules of fuel energy per kW. This trend is a positive indicator in energy system analysis because it indicates that the system is operating in a more “efficient” thermodynamic manner. The exergy perspective, on the other hand, focuses on the maximum useful energy that can be converted from fuel. Exergy analysis evaluates engine performance by accounting for actual losses and irreversibilities. In gas turbines, the largest exergy losses typically occur in the combustion chamber—a significant portion of the fuel's exergy is lost here as waste heat and entropy production. The overall exergy efficiency of a turboshaft engine such as the PT6B-37A has been reported to be in the range of 25–30% (Ekici et al., 2016). As altitude increases, exergy efficiency also improves: at high altitudes, the ratio of converting fuel exergy into work increases due to lower specific fuel consumption and higher thermal efficiency. For example, in one study, it was noted that the exergy efficiency of a turboprop engine increased from 23% to 33% when ascending from sea level to 14 km (El-Sayed, 2008). This indicates that exergy losses resulting from combustion are relatively reduced at high altitudes, and the engine operates more efficiently due to environmental conditions. The exergy efficiency, which is lowest at 0 m, will be slightly higher at 900 m; this is because both the decrease in the heat ratio and more favorable combustion conditions allow a larger portion of the fuel exergy to be converted into mechanical work. In other words, the quality of energy increases with altitude: the system's exergetic efficiency improves, and the useful work obtained per unit of fuel increases. Understanding the performance characteristics at different altitudes is critical for both engine design optimization and helicopter mission profile planning. The designers of the PT6B-37A engine determine the optimal design point by considering the altitude and conditions where the engine will be most frequently used. For example, if a mission profile primarily requires intensive hovering and takeoff at altitudes close to sea level, the engine's low-altitude performance and cooling capacity are prioritized. In this scenario, the engine's design enables it to operate at its maximum internal parameters, maintaining steady-state power, even at sea level, thereby guaranteeing high reliability and longevity. On the other hand, if the helicopter will primarily operate at a specific altitude (e.g., 1,000–2,000 m) for extended periods, designers can optimize the engine's most efficient pressure ratio and bypass airflow for that altitude. This improves cruise fuel economy and reduces overall emissions.

When planning flight profiles, pilots and operations planners must take into account changes in engine performance depending on altitude. For example, a helicopter carrying a heavy load requires maximum power during takeoff at sea level; however, once the load is lightened or as soon as possible, it can achieve fuel savings by climbing to a higher cruise altitude. Even between 0–900 m, climbing a few hundred meters can extend range and improve mission efficiency by reducing the engine's specific fuel consumption. Although helicopters typically do not operate at very high altitudes due to local weather conditions and mission requirements (generally operating below 5,000 m due to limited high-altitude performance), selecting the optimal flight level within the available altitude range is still important. For example, in search-and-rescue missions, flying at 500–1000 m altitude when terrain permits may be more efficient than flying at 100 m altitude, as the engine consumes less fuel and is subjected to less stress at this altitude (Karakoç & Çoban, 2016). From an environmental impact perspective, altitude-dependent changes in engine performance offer important insights. Emissions from fuel burned at low altitudes (NOx, CO, HC, and particulates) directly affect air quality at ground level and have adverse effects on human health. Therefore, prolonged hovering near the ground or flying at low altitudes during helicopter operations contributes more to local air pollution. In mission planning, if possible, having the helicopter ascend above a certain altitude during non-critical phases can help disperse emissions more widely into the atmosphere and reduce concentrations at ground level. For example, a helicopter's rapid climb after takeoff disperses noise and emissions away from the airport area. Additionally, due to the NOx trend mentioned above, conducting a significant portion of emissions at slightly higher altitudes can reduce the ozone and smog effects on the ground. However, on the other hand, NOx emitted at high altitudes can contribute to ozone formation and climate change in the upper troposphere—studies on aircraft emissions show that NOx has different environmental impacts at different altitudes (El-Sayed, 2008). Therefore, environmental optimization must consider not only local air quality but also global climate impacts. In the context of design optimization, manufacturers use various technologies to improve the engine in terms of both performance and emissions. Advanced combustion chamber designs (e.g., radial-quench RQL combustor technology) aim to control NOx formation while minimizing efficiency losses. Additionally, exergy analyses reveal where the engine experiences losses, enabling the design of more efficient compressor/turbine aerodynamics or heat recovery systems (e.g., regenerators) based on this data. Despite weight and volume constraints in helicopter engines like the PT6B-37A, continuous improvements aim to achieve cleaner and more powerful engines both at sea level and at altitude. In conclusion, the performance data of the PT6B-37A engine at altitudes of 0 m, 300 m, 600 m, and 900 m provide valuable insights from both an engineering and operational perspective. When the decrease in shaft power, improvement in thermal efficiency, reduction in specific fuel consumption and heat ratio, and decrease in NOx emissions are evaluated together, the helicopter's operational efficiency at different altitudes becomes clear. This information provides technical insights that contribute to the literature on engine design and development, as well as guiding fuel efficiency and environmental impact optimization in helicopter mission planning.

Table 6
Engine Performance Calculation Table Based on Altitude (900 m)

Station	**Mass flow [kg.s^{-1}]**	**T [K]**	**P [kPa]**
1	4.670	282.30	90.970
2	4.670	282.30	90.060
3	4.670	502.10	540.362
31	4.670	502.10	540.362
4	4.728	980.00	513.344
41	4.728	980.00	513.344
5	4.728	657.82	93.699
6	4.728	657.82	93.699
8	4.728	657.82	93.699
Shaft power delivered [kW]	668.0		
Power specific fuel consumption [kg.kW^{-1}.h^{-1}]	0.3140		
Heat rate $\frac{fuel\ flow.fuel\ heating\ value}{shaft\ power\ delivered} = \frac{\dot{m}_f LHV}{SP}$	13541.6		

[kJ.kW^{-1}.h^{-1}]	
Thermal efficiency	0.2658
Fuel flow [kg.s^{-1}]	0.05827
NO_x severity parameters	0.10750

Performance analyses at different altitudes are important in revealing how the PT6B-37 turboshaft engine behaves not only at the design point but also under changing atmospheric conditions. The calculations show that the engine's shaft power, specific fuel consumption (SFC), thermal efficiency, and exergy efficiency change a lot at altitudes of 0 m, 300 m, 600 m, and 900 m. Upon examining the results, it is observed that the decrease in atmospheric pressure due to altitude increases causes a reduction in air density at the compressor inlet, leading to decreases of approximately 9% in shaft power and thermal efficiency. Additionally, negative changes in SFC and exergy efficiency were observed. This aligns with the phenomenon of high-altitude performance loss mentioned in the literature. The literature says that problems in the combustion chamber and pressure drops in the turbine section are more noticeable at high altitudes, which leads to greater overall exergy loss. This study supports such findings, demonstrating that the altitude effect is a significant parameter influencing engine performance. In particular, shaft power loss and increased SFC values should be carefully considered in terms of operational expenses and fuel efficiency.

The findings also provide a critical perspective for design engineers. Modeling the contribution of altitude compensation technologies (e.g., variable geometry compressors, intercooled compression, or auxiliary air supply systems) to performance in a Gasturb environment is recommended for future studies. Additionally, conducting such analyses under different load profiles (e.g., hovering, climbing, and cruising) could provide important insights for achieving optimal performance across the entire operational envelope of the engine. This study provides an applied example of the improvement strategies proposed in the literature by thoroughly evaluating energy and exergy losses at high altitudes, thereby creating a valuable reference for both academic and industrial studies.

CONCLUSION

Within the scope of this study, energy and exergy-based performance analyses were conducted on the PT6B-37A turboshaft engine used in the Agusta A119 helicopter at altitudes of 0 m, 300 m, 600 m, and 900 m, and original findings contributing to the literature were obtained. The calculations showed that the overall energy efficiency of the engine was 26.24%, while the shaft output power was 712.3 kW at sea level. With increasing altitude, approximately 9% decreases in shaft power and thermal efficiency were observed, while significant increases in specific fuel consumption and exergy losses were detected. These trends highlight the sensitivity of gas turbine engines to atmospheric conditions and demonstrate that altitude effects directly impact not only performance outputs but also environmental emissions and fuel economy. Thermodynamic analyses revealed that isentropic efficiency losses in the compressor and turbine units limit system performance, while the largest exergy losses occur in the combustion chamber and exhaust outlet. Chemical imbalances observed in the combustion chamber, inhomogeneity in flame temperature distribution, and high entropy production are among the key factors reducing the system's overall exergy efficiency. In contrast, a significant portion of the mechanical power obtained from the turbine outlet was successfully preserved and transferred to the shaft outlet. Additionally, the observed trends of reduced fuel consumption and improved thermal efficiency at medium altitudes of 900 m indicate that careful selection of flight altitude in mission profile planning is critically important for both operational efficiency and environmental sustainability. When evaluating NOx emission trends, a decrease in NOx production was observed due to the decrease in combustion chamber temperatures and partial oxygen pressure with increasing altitude. While this represents a positive development in terms of environmental performance, the possibility of unburned emission components such as CO and HC increasing with altitude should also be considered. The findings of this study provide multi-dimensional outputs not only in terms of engine performance and efficiency but also in terms of mission profile planning, environmental impact management, and design decisions.

Future studies plan to evaluate the effects of alternative fuel types (e.g., sustainable aviation fuels and nano-aluminum-blended jet fuels) on performance. Additionally, the contributions of geometric and material-based design improvements in engine components to exergy and energy efficiency will be analyzed using numerical methods. Furthermore, the integration potential of new-generation systems that provide altitude compensation, such as variable-geometry compressor systems, auxiliary air supply solutions, and multi-stage combustion technologies, will also be investigated. These analyses will form a critical foundation for both improving engine efficiency and achieving sustainable aviation goals.

Ethics Committee Approval

No human or animal subjects requiring ethics committee approval were used in this study. The research was conducted on publicly available data sets, literature reviews or theoretical analyses. In accordance with ethical rules, academic honesty and scientific ethical rules were fully complied with at every stage of the research process. Therefore, ethics committee approval was not required.

Author Contributions

Research Design (CRediT 1) Author 1 (100%)

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