ISSN: 2821-157X | htpps://www.jasd.khadu.ir

Journal of Aerospace Defense
Volume 4 Issue 2
Summer 2025
Pages 27 – 50

Research Paper

Comparative Analysis of Carbureted and Fuel-Injected Rotax 912 Engine Performance in High-Altitude Flight Conditions Using GT-SUITE Simulations

Seyyed Ali Salari[1] ، Fathullah ommi[2]
1. PhD student in Aerospace, Faculty of Aerospace Engineering, Kish International Campus, University of Tehran
2. Faculty Member, Aerospace Department, Faculty of Mechanical Engineering, Tarbiat Modares University

Article Information

Accepted: 2025/10/15

Recceived: 2025/08/11

Keywords:

Aircraft engines, Rotax 912, Fuel injection, Altitude effects, GT-SUITE simulation, Internal combustion.

Corresponding Author: *Fathollah Ommi*

Email: *fommi@modares.ac.ir*

Abstract

The performance of naturally aspirated aircraft engines declines significantly with increasing altitude due to reduced air pressure and density, which adversely affect power, torque, in-cylinder pressure, and combustion temperature. This study aims to conduct a comparative performance analysis of the carbureted Rotax 912 ULS and the fuel-injected Rotax 912iS engines under flight altitudes up to 9,150 meters using GT-SUITE simulations. Engine models were developed based on manufacturer specifications, with the carbureted model validated against catalogue data to ensure accuracy before constructing the fuel-injected counterpart. The results show that the carbureted engine experiences up to an 80% reduction in power and a 69% reduction in in-cylinder pressure at high altitudes due to its fixed fuel–air mixture. In contrast, the electronic fuel injection (EFI) engine shows about a 55–60% reduction in power, a 65–70% reduction in torque, and nearly a 48–50% decrease in peak in-cylinder pressure at 9,150 meters, while cylinder temperature remains around 1900 K (approximately 10–15% higher than the carbureted version at the same altitude). Although EFI substantially reduces altitude-induced performance losses compared to carburetion, both configurations still exhibit marked degradation, underscoring the inherent limitations of naturally aspirated engines. These findings highlight the necessity of advanced altitude-compensation methods—such as turbocharging or optimized EFI mapping—to enhance reliability, efficiency, and safety in high-altitude aviation operations.

HOW TO CITE: *Seyyed Ali Salari، Fathullah Ummi. (2025). Comparative Analysis of Carbureted and Fuel-Injected Rotax 912 Engine Performance in High-Altitude Flight Conditions Using GT-SUITE Simulations.* Aerospace Defense, Vol 4(Issue2), Page 27–50.

ISSN: 2821-157X | htpps://www.jasd.khadu.ir

فصلنامه علمی دفاع هوافضایی
دوره۴ شماره ۲
تابستان ۱۴۰۴
صفحات ۵۰ -۲۷

مقاله پژوهشی؛ doi

تحلیل تطبیقی عملکرد موتورهای روتکس ۹۱۲ با کاربراتور و انژکتور سوخت در شرایط پروازی ارتفاع بال با استفاده از شبیه سازی GT-SUITE

سید علی سالاری[۱]، فتح اله امّی[۲]

۱. دانشجوی دکتری هوافضا، دانشکده مهندسی هوافضا پردیس بین المللی کیش دانشگاه تهران
۲. عضو هیات علمی، گروه هوافضا، دانشکده مهندسی مکانیک دانشگاه تربیت مدرس

چکیده

عملکرد موتورهای هواپیمای تنفس طبیعی به طور قابل توجهی با افزایش ارتفاع کاهش می‌یابد، به دلیل کاهش فشار و چگالی هوا، که به طور نامطلوبی بر توان، گشتاور، فشار درون سیلندر، و دمای احتراق تأثیر می‌گذارد. این مطالعه قصد دارد یک تحلیل عملکرد تطبیقی از موتورهای کاربراتوری Rotax 912 ULS و انژکتوری Rotax 912iS را در ارتفاعات پروازی تا ۹,۱۵۰ متر با استفاده از شبیه‌سازی‌های GT-SUITE انجام دهد. مدل‌های موتور بر اساس مشخصات سازنده توسعه داده شدند، با این توضیح که مدل کاربراتوری در مقابل داده‌های کاتالوگ صحت‌سنجی شد تا دقت آن قبل از ساخت نمونه انژکتوری اطمینان حاصل شود. نتایج نشان می‌دهد که موتور کاربراتوری به دلیل ترکیب ثابت سوخت و هوا تا ۸۰٪ کاهش در توان و ۶۹٪ کاهش در فشار درون سیلندر را در ارتفاعات بالا تجربه می‌کند. در مقابل، موتور تزریق سوخت الکترونیکی (EFI) حدود ۵۵—۶۰٪ کاهش در توان، ۶۵—۷۰٪ کاهش در گشتاور، و تقریباً ۴۸—۵۰ ٪ کاهش در حداکثر فشار درون سیلندر در ۹,۱۵۰ متر را نشان می‌دهد، در حالی که دمای سیلندر در حدود ۱۹۰۰ کلوین باقی می‌ماند (تقریباً ۱۰—۱۵٪ بالاتر از نسخه کاربراتوری در همان ارتفاع). اگرچه EFI به طور قابل ملاحظه‌ای از افت عملکرد ناشی از ارتفاع در مقایسه با کاربراتور می‌کاهد، هر دو پیکربندی همچنان تخریب (کاهش) عملکرد مشخصی از خود نشان می‌دهند، که بر محدودیت‌های ذاتی موتورهای تنفس طبیعی تأکید می‌کند. این یافته‌ها بر ضرورت روش‌های پیشرفته جبران ارتفاع—مانند توربوشارژینگ یا نقشه‌برداری بهینه EFI—برای افزایش قابلیت اطمینان، کارایی، و ایمنی در عملیات هوانوردی در ارتفاع بالا تأکید می‌کنند.

اطلاعات مقاله

تاریخ دریافت:
۱۴۰۴/۰۵/۲۰

تاریخ پذیرش:
۱۴۰۴/۰۷/۲۳

کلیدواژه‌ها:
موتورهای هواپیما،
روتکس ۹۱۲،
انژکتور سوخت،
اثرات ارتفاع،
شبیه سازی GT-SUITE،
احتراق داخلی

نویسنده مسئول:
فتح اله امّی

ایمیل:
fommi@modares.ac.ir

استناد: فتح اله امّی، سید علی سالاری.(۱۴۰۴). بررسی و مقایسه هسته متخلخل و ویسکوالاستیک در فرکانس‌های طبیعی سازه ساندویچی در راستای افزایش استحکام و ایمنی سازه‌های دفاعی. *دفاع هوافضایی*، دوره ۴(شماره۲)، صفحه ۵۰-۲۷.

1.Introduction

The performance of aircraft piston engines is profoundly influenced by changes in atmospheric pressure and temperature at high altitudes. As altitude increases, the reduction in air density leads to a decrease in engine power, torque, and fuel efficiency, which poses a significant challenge for aviation propulsion systems. The Rotax 912 engine, a widely used four-cylinder, four-stroke aircraft engine, is particularly affected by these altitude-induced variations due to its dependence on air-fuel mixture dynamics and combustion efficiency. The introduction of fuel injection technology in the Rotax 912iS aimed to mitigate these challenges by optimizing fuel delivery based on real-time environmental conditions. However, a comprehensive performance comparison between the carbureted and fuel-injected versions of the Rotax 912 at varying altitudes remains underexplored.

Aircraft piston engines, including the Rotax 912, exhibit a gradual decline in power and torque with increasing altitude. Studies indicate that power and torque decrease by approximately 11.25% and 12.5%, respectively, for every 1,000 meters of altitude gain [1]. In a detailed altitude chamber experiment, Mansouri et al. (2019) confirmed similar trends, showing up to 20% power loss at moderate altitudes and a sharp increase in BSFC. Their findings validate the adverse effects of reduced air density on combustion stability and heat transfer, emphasizing the importance of fuel-air ratio control and ignition optimization at high altitudes [2],[3].

Similarly, Shannak and Alhasan (2002) found that even modest altitude changes of around 200 meters can lead to up to 40% variation in fuel consumption and volumetric efficiency, depending on engine speed. Their study underscores the critical need to adjust the air–fuel ratio dynamically to maintain optimal performance across different altitudes. Simultaneously, fuel consumption rates increase by 14.4% at low speeds and 2.8% at high speeds per 1,000 meters, largely due to the necessity of maintaining a proper air-fuel ratio for stable combustion [4]. Thermal efficiency is also impacted, as lower ambient temperatures at higher altitudes cause a significant decrease in cylinder surface temperature, affecting overall heat management and combustion stability [5] These findings highlight the necessity of optimizing fuel mixture strategies and ignition timing to mitigate performance degradation at altitude.

The introduction of electronic fuel injection (EFI) in the Rotax 912iS represents a significant advancement in maintaining optimal performance at varying altitudes. The Engine Control Unit (ECU) continuously adjusts the fuel delivery and ignition parameters based on altitude-related changes in ambient pressure, temperature, and air density [4]. This system enhances fuel efficiency by over 20% compared to the carbureted Rotax 912ULS while also eliminating common issues such as carburetor icing and manual choke adjustments [6]. Additionally, the ECU's dual-sensor system monitors exhaust gas composition, airbox vacuum, and throttle position, ensuring that the engine operates efficiently across a wide range of environmental conditions [7] Despite these improvements, the actual performance benefits of EFI over traditional carbureted systems in high-altitude operations have not been fully quantified.

Simulation-based analyses provide valuable insights into engine behavior under different altitude conditions. Modeling approaches using 1D and 0D simulation tools such as AVL Boost and GT-Suite allow for precise predictions of power output, fuel consumption, brake mean effective pressure (BMEP), and thermal efficiency [8], [9]. Prior studies have successfully validated simulation models against experimental data, demonstrating a high degree of accuracy in predicting engine performance trends at altitude.

However, previous research primarily focused on ground-level or turbocharged engine simulations, such as those conducted on the Rotax 915iS, which includes a factory-installed turbocharger to counteract altitude-induced power loss [10]. In contrast, the naturally aspirated Rotax 912 lacks forced induction, making it significantly more susceptible to altitude-induced degradation. A detailed comparative analysis of the carbureted and fuel-injected versions of the Rotax 912 under high-altitude conditions remains necessary to determine the extent to which EFI can compensate for the loss of power and efficiency in non-turbocharged configurations. Additionally, Zhang et al. (2019) conducted a multi-objective optimization of diesel engine performance at different altitudes using Kriging surrogate models and genetic algorithms. Their findings revealed that optimal control of injection timing and compression ratio can lead to significant improvements in BSFC and power recovery, achieving up to 85% power restoration at 8000 m, highlighting the effectiveness of adaptive strategies under reduced air density conditions [11]. Similarly, Zhou et al. (2025) reviewed the state-of-the-art in two-stage turbocharging systems, emphasizing their capacity to recover up to 95% of sea-level power at 5.5 km altitude while mitigating emission deterioration. Their proposed integrated framework synthesizes system configuration, flow dynamics, and parameter optimization to enhance piston engine adaptability in both aviation and ground applications [12].

Recent investigations into small internal combustion engines at altitude have demonstrated that fuel delivery methods play a crucial role in maintaining power output and fuel economy. Experiments conducted using altitude chambers and controlled atmospheric test benches confirm that fuel injection systems provide superior adaptability to altitude changes compared to traditional carburetors [13], [14]. Furthermore, engine performance modeling under varying intake pressures and temperatures has shown that altitude effects can be partially mitigated through optimized air-fuel ratio control and intake manifold pressure regulation [15]. These findings reinforce the need for a direct comparative study between the Rotax 912ULS (carbureted) and Rotax 912iS (fuel-injected) using high-fidelity simulation techniques. In line with these efforts, Xu et al. (2025) applied a Kriging-based surrogate modeling approach combined with NSGA-III to optimize CI aviation piston engine performance at variable altitudes. Their simulation-driven study demonstrated that injection timing, compression ratio, and variable geometry turbocharger control can significantly enhance fuel economy and power recovery, achieving up to 85% power restoration at 8000 m altitude [16].

This study aims to conduct a detailed comparative analysis of the performance of the carbureted and fuel-injected Rotax 912 engines at various altitudes using GT-Suite simulations. The research will evaluate power output, fuel consumption, BMEP, and thermal efficiency while assessing the effectiveness of EFI in compensating for altitude-induced losses. Recent efforts have also focused on developing experimental setups to replicate high-altitude conditions for small engines. Schmick et al. (2011) designed a high-fidelity altitude test chamber capable of simulating flight altitudes up to 30,000 feet, with precise control over pressure, temperature, and airflow. Their system enabled detailed analysis of engine power, fuel consumption, and thermal behavior, providing a robust framework for validating numerical simulations [17].

Koh et al. (2018) performed a computational study using GSP simulation software to investigate the effects of altitude on the deteriorated performance of a high-bypass turbofan engine. Their findings showed that reduced air density at higher altitudes leads to significant decreases in air mass flow and thrust, while specific fuel consumption initially improves but worsens at very high altitudes due to increased fuel demands. This work highlights the broader impact of altitude on engine behavior and supports the importance of accurate modeling in propulsion studies [18].

Recent work by Gorgulu and Karakoç (2025) extends this line of investigation to commercial jet engines by using CFD simulations and real engine data to analyze combustion characteristics and emission behavior across varying altitudes. Their findings confirm that higher flight levels significantly reduce combustion temperature and pressure, emphasizing the importance of fuel-air ratio optimization to maintain engine efficiency and minimize emissions [19], [20]. By leveraging advanced 1D modeling and validation against empirical data, this study seeks to provide critical insights into the operational advantages and limitations of fuel injection over carburetion in non-turbocharged aircraft piston engines.

In addition, Previous investigations have been carried out in studies such as "Study of performance parameters of turbocharged aircraft engine at altitude using one-dimensional modeling" and "Performance prediction of aircraft gasoline turbocharged engine at high-altitudes." In those works, the analysis was primarily focused on turbocharged engines, where forced induction directly compensates for the loss of ambient pressure at altitude, and one-dimensional modeling approaches were employed to predict engine behavior. By contrast, in the present study, the novelty lies in the detailed examination of naturally aspirated Rotax 912 engines in both carbureted and fuel-injected configurations. A comparative and quantitative evaluation of key performance parameters—including power, torque, in-cylinder pressure, and combustion temperature—has been performed, demonstrating that although EFI provides superior adaptability under oxygen-deficient conditions compared to carburetion, naturally aspirated engines still exhibit inherent limitations at high altitudes. These results underline the necessity of advanced altitude-compensation strategies, such as turbocharging or optimized EFI mapping, thereby distinguishing the present work from earlier studies.

The present study has been motivated by the critical importance of evaluating the performance of aircraft piston engines under high-altitude flight conditions, where reduced air pressure and density lead to substantial losses in power, torque, in-cylinder pressure, and combustion temperature. These factors directly influence flight safety, fuel efficiency, and propulsion system reliability. The Rotax 912 engine, in both carbureted and fuel-injected configurations, is widely employed in light and training aircraft. However, comprehensive comparative investigations of these naturally aspirated versions at high altitudes are limited. The novelty of this work lies in utilizing high-fidelity GT-SUITE simulations to conduct a detailed comparative analysis of the carbureted (Rotax 912 ULS) and fuel-injected (Rotax 912iS) versions across altitudes up to 9,150 meters. To ensure fairness in comparison, the carbureted engine model was first validated against real-world data and subsequently adapted to develop the fuel-injected model on the same basis. The results provide a quantitative evaluation of power, torque, in-cylinder pressure, and cylinder temperature at different altitudes, demonstrating that the electronic fuel injection system offers superior adaptability in mitigating altitude-induced performance losses compared to the carbureted system. Furthermore, the findings underscore the necessity of advanced altitude-compensation technologies, such as turbocharging or optimized EFI mapping, to enhance future engine efficiency and reliability. Accordingly, this study not only addresses a gap in the literature but also provides practical insights relevant to improving safety and performance in high-altitude aviation operations.

Therefore, the main research gap lies in the absence of a comprehensive comparative analysis between the carbureted and fuel-injected versions of the Rotax 912 engine under high-altitude flight conditions. The present study addresses this gap by employing high-fidelity GT-SUITE simulations to systematically evaluate variations in power output, torque, in-cylinder pressure, and combustion temperature across both configurations. The scientific contribution of this work is to highlight the potential of Electronic Fuel Injection (EFI) technology in mitigating altitude-induced performance losses in naturally aspirated engines, while providing a direct comparison with conventional carburetion. In doing so, this research offers a valuable foundation for the future development of advanced altitude-compensation strategies, such as turbocharging or optimized EFI mapping, in light aircraft engines.

1. Methodology

In this study, the Rotax 912 engine was modeled and simulated using GT-SUITE software to perform a comparative analysis of the carbureted (Rotax 912 ULS) and fuel-injected (Rotax 912iS) configurations under various altitude conditions. GT-SUITE is a powerful tool for engine simulation, enabling the precise evaluation of internal combustion engine performance through predictive modeling techniques.

The primary objective of this study is to compare power output, torque, in-cylinder pressure, and engine temperature between the two fuel delivery systems at different altitudes. The modeling process aims to simulate and analyze how these parameters vary as atmospheric pressure decreases with increasing altitude, affecting engine combustion characteristics and efficiency.

The initial engine specifications used for the modeling are provided in Table 1:

Table 1: Input Parameters for Modeling [4]

Parameter	Value	Unit
Bore	84	mm
Stroke	61	mm
Engine Displacement	1352	cm^3
Connecting Rod Length	109	Mm
Compression Ratio	10.8:1	-
Firing Order	2-4-3-1	-
Fuel Type	Gasoline	-

Using these specifications, both carbureted and fuel-injected engine models were developed in GT-SUITE to evaluate their performance in varying altitude conditions. Figure 1 presents the schematic representation of the two engine configurations:

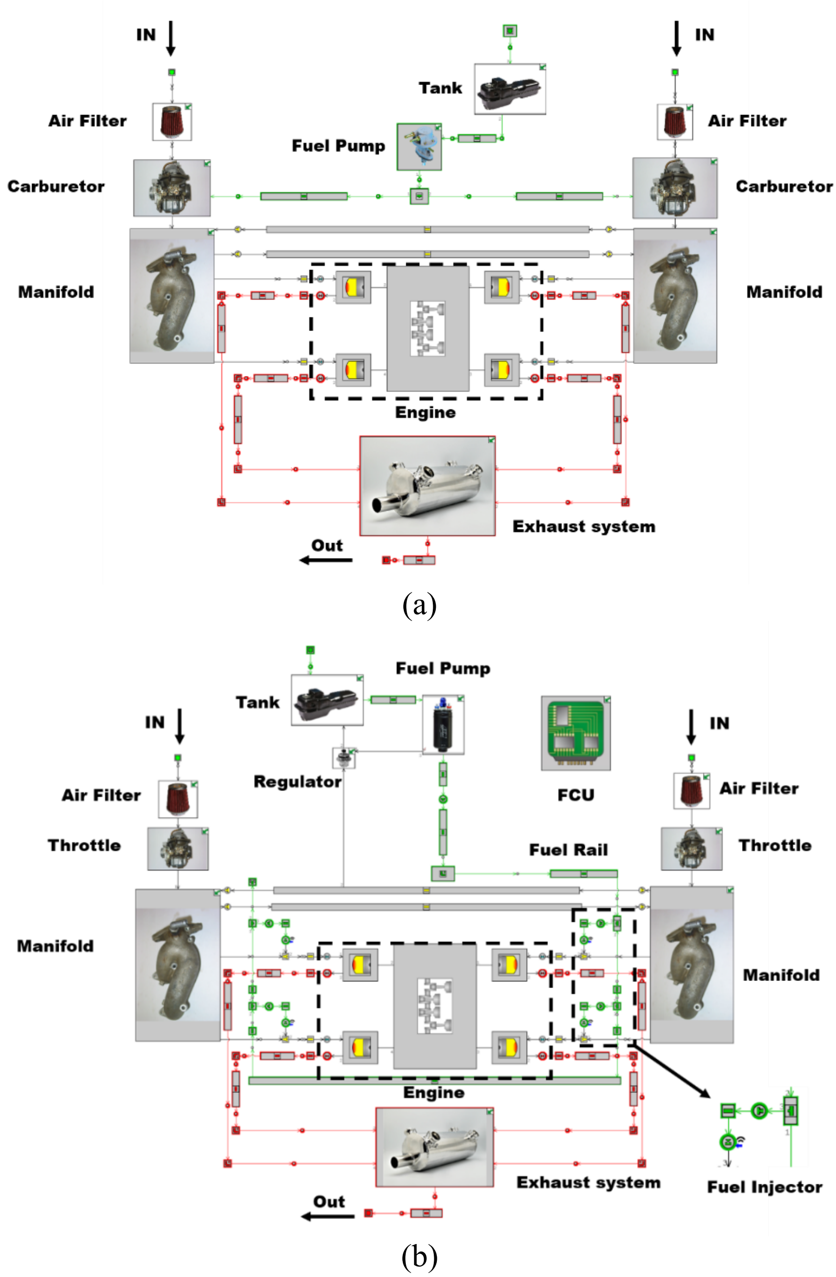


Figure 1: Schematic Representation of a) Carbureted b) Fuel-Injected Rotax 912

In this study, the Rotax 912 ULS (carbureted) engine model was first designed and developed using GT-SUITE. This initial model served as the foundation for the subsequent development of the Rotax 912iS (fuel-injected) engine model, ensuring consistency in baseline parameters while incorporating the specific characteristics of the fuel injection system. To ensure the accuracy and reliability of the simulation, the carbureted engine model was validated against empirical performance data provided by the manufacturer. The validation process confirmed that the simulated power output, torque, in-cylinder pressure, and engine temperature closely matched real-world performance values, establishing confidence in the accuracy of the developed model. Once validated, the fuel-injected engine model was designed based on the same core specifications, with modifications reflecting the differences in fuel delivery and combustion control mechanisms.

By structuring the modeling approach in this manner, a direct comparative analysis between the carbureted and fuel-injected versions of the Rotax 912 was made possible, ensuring a controlled and systematic evaluation of altitude-induced performance variations in both configurations.

1.1. Simulation Conditions and Assumptions – Altitude levels, atmospheric conditions, fuel type, and boundary conditions used in the study.

To analyze the performance variations of the Rotax 912 engine under different altitude conditions, simulations were conducted using GT-SUITE, incorporating altitude-specific pressure and temperature changes as boundary conditions. The study focused on evaluating the power output, torque, in-cylinder pressure, and engine temperature of both carbureted (Rotax 912 ULS) and fuel-injected (Rotax 912iS) configurations across multiple altitude levels.

The baseline simulation was performed under standard sea-level conditions, with an atmospheric pressure of 101,325 Pa and a temperature of 298 K. To assess the effect of altitude, additional simulations were conducted at various flight altitudes, as summarized in Table 2.

Table 2: Altitude Levels and Corresponding Atmospheric Conditions

Level	Altitude (m)	Atmosphere Pressure (Pa)	Altitude Description
1	1	101325	Sea level
2	1000	89874	Average high terrain altitude
3	5000	54019	Maximum altitude for general aviation aircraft
4	7600	38271	Minimum operational altitude for propeller-driven aircraft
5	9150	28779	Standard operational altitude for most models

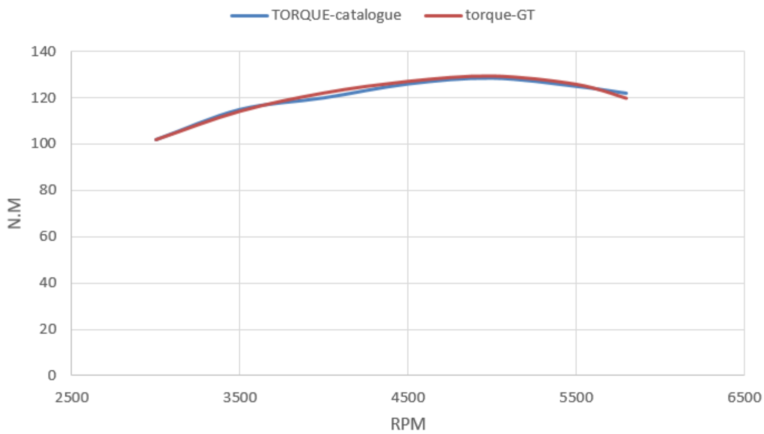
In these simulations, the atmospheric pressure at each altitude was applied as a boundary condition for the engine's air intake system. This approach allowed for an accurate representation of altitude-induced reductions in air density, which directly impact combustion characteristics and engine performance. Experimental studies using altitude chambers have confirmed that increasing altitude leads to measurable reductions in power output, torque, and in-cylinder pressure, as well as an increase in brake specific fuel consumption (BSFC). These empirical observations support the choice of boundary conditions and altitude levels applied in the present simulation setup [2].
The GT-SUITE simulation framework facilitated a detailed investigation of how altitude affects:

- Power and torque degradation due to reduced oxygen availability.
- In-cylinder pressure variations as a function of decreasing air density.
- Engine temperature changes, influenced by altitude-dependent heat transfer effects.

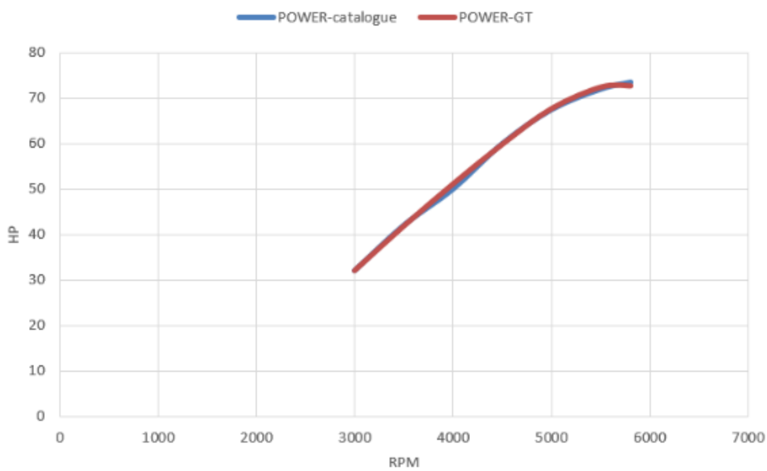
By systematically analyzing engine behavior across these altitude levels, this study provides a quantitative comparison of how carbureted and fuel-injected systems respond to altitude-induced performance losses. This allows for a direct evaluation of the effectiveness of fuel injection in maintaining engine stability compared to traditional carburetion in naturally aspirated aircraft piston engines.

1.2. Validation of the Simulation Model – Comparison with experimental/real-world data to ensure accuracy.

To ensure the accuracy and reliability of the GT-SUITE engine model, the simulation results were compared with real-world performance data provided by ROTAX for the Rotax 912iS (fuel-injected) engine. The primary focus of this validation was to assess the accuracy of simulated power output and torque values against manufacturer specifications.



a)



b)

Figure 2: Comparison of Simulated and Catalogue Data for Torque and Power (Fuel-Injected Rotax 912iS Engine)

Figure 2 illustrates the power and torque output curves obtained from the GT-SUITE simulation model of the Rotax 912 ULS (carbureted) engine, compared against the official performance data provided by ROTAX. The comparison demonstrates a high level of accuracy, with:

- A maximum deviation of approximately 2% in power output
- A maximum error of around 2% in torque values

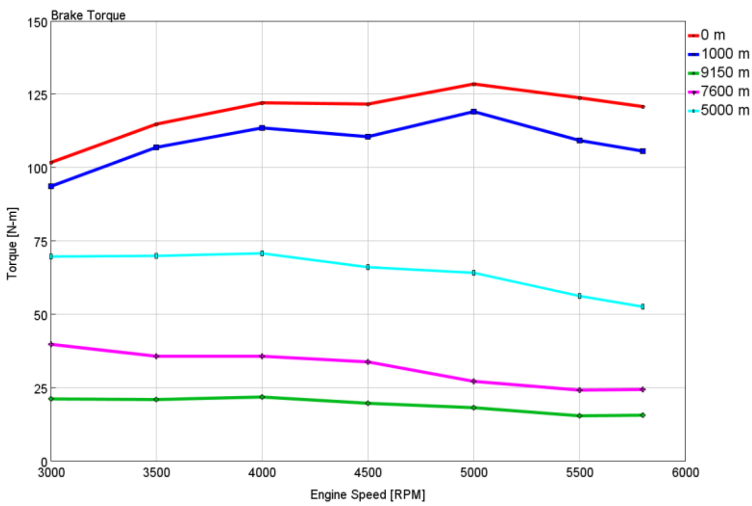
These results confirm that the developed simulation model closely replicates the real-world performance of the Rotax 912 ULS, making it a reliable tool for evaluating engine behavior under various operating conditions.

2. Results and Discussion

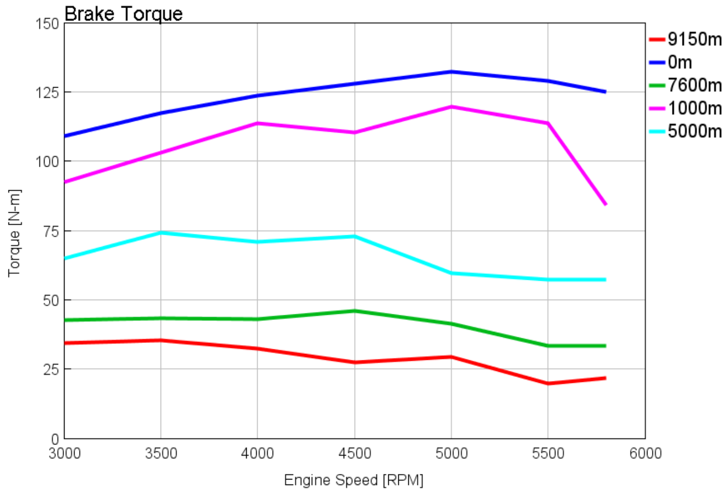
This section presents the simulation results of the Rotax 912 carbureted (912 ULS) and fuel-injected (912iS) engines under varying altitude conditions. The results focus on power output, torque, in-cylinder pressure, and engine temperature, extracted using GT-SUITE simulation software. The analysis provides insights into how altitude-induced changes in air density and pressure impact engine performance and the differences between carbureted and fuel-injected configurations.

2.1. Effect of Altitude on Engine Torque

The torque output of an internal combustion engine is directly influenced by atmospheric pressure and air density, both of which decrease as altitude increases [21]. Since the Rotax 912 engine is naturally aspirated, it relies on ambient air pressure for fuel-air mixture formation. As altitude rises, the reduced oxygen availability weakens the combustion process, leading to a progressive decline in torque output.



a)



b)

Figure 3: Comparison of Engine Torque at Different Altitudes a) carbureted b) fuel injected

Figure 3 presents a comparison of engine brake torque across different altitudes for the carbureted (Figure 3a) and fuel-injected (Figure 3b) versions of the Rotax 912 engine. Both graphs illustrate the impact of altitude-induced reductions in air density and oxygen availability on torque output, demonstrating a progressive decline in performance as altitude increases.

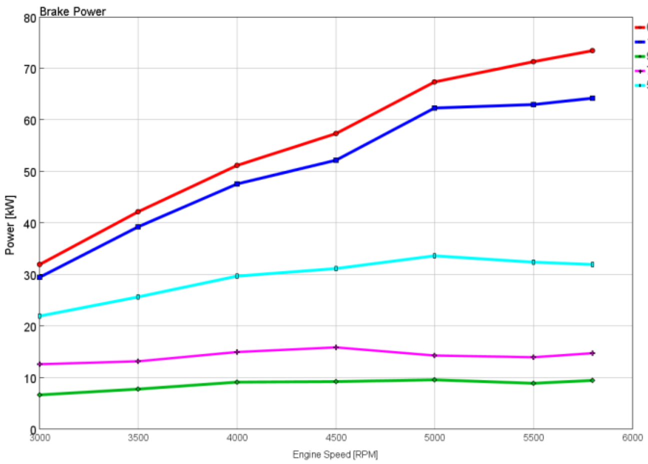
In the carbureted engine (Figure 3a), torque exhibits a steep decline with increasing altitude. At sea level (0 m), peak torque reaches approximately 125 Nm at 4500 RPM, while at 5,000 meters, torque drops to 75 Nm, representing a 40% reduction. At 9,150 meters, torque declines sharply to 20 Nm, reflecting an 84% loss from sea level. The fixed fuel-air mixture in the carbureted system limits its adaptability, making it more susceptible to altitude-induced power losses.

In contrast, the fuel-injected engine (Figure 2b) demonstrates better torque retention across all altitude levels. While torque still decreases with altitude, the EFI system dynamically adjusts fuel delivery, mitigating performance losses compared to the carbureted version. At 5,000 meters, torque remains higher than in the carbureted model, and at 9,150 meters, the reduction is less severe.

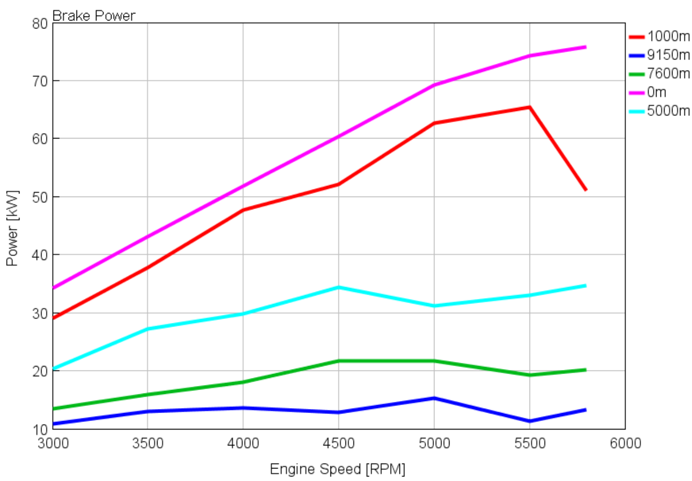
The comparison highlights the performance limitations of naturally aspirated engines at high altitudes and underscores the advantages of fuel injection in maintaining engine efficiency. These findings emphasize the need for altitude compensation technologies, such as turbocharging or optimized EFI systems, to sustain performance in aviation applications.

2.2. Effect of Altitude on Engine Power

Altitude exerts a direct influence on engine power by reducing atmospheric pressure and air density, which in turn lowers the mass flow of oxygen into the combustion chamber. Consequently, combustion efficiency diminishes, leading to a notable decline in power output at higher altitudes.



a)



b)

Figure 4: Comparison of Engine Power at Different Altitudes a) carbureted b) fuel injected

Figure 4 presents a comparison of engine brake power across different altitudes for the carbureted (Figure 4a) and fuel-injected (Figure 4b) versions of the Rotax 912 engine. Both graphs illustrate the negative impact of altitude on engine power due to reductions in air density and oxygen availability, leading to a progressive decline in performance as altitude increases.

In the carbureted engine (Figure 4a), power exhibits a steep decline with increasing altitude. At sea level (0 m), peak power reaches approximately 75 kW at 5500 RPM. At 5,000 meters, power drops to 40 kW, representing a 47% reduction. At 9,150 meters, power declines sharply to 15 kW, reflecting an 80% loss from sea level. The fixed fuel-air ratio in the carbureted system limits its adaptability, making it highly susceptible to oxygen scarcity at high altitudes.

In contrast, the fuel-injected engine (Figure 4b) demonstrates better power retention across all altitude levels. While power still decreases with altitude, the EFI system dynamically adjusts fuel delivery, mitigating performance losses compared to the carbureted version. At 5,000 meters, power remains higher than in the carbureted model, and at 9,150 meters, the reduction is less severe. The ability to optimize the air-fuel mixture in real-time allows the fuel-injected engine to perform more efficiently at high altitudes.

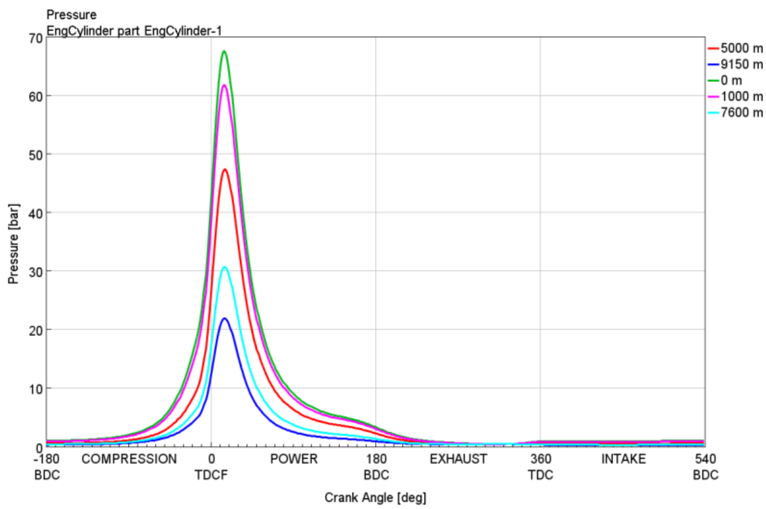
In Figure 4(b), it is noticeable that at 1000 m altitude the torque curve exhibits a sharper drop beyond approximately 5500 rpm compared to other altitude levels. A detailed review of the simulation outputs (including manifold absolute pressure, volumetric efficiency, air–fuel ratio, and injector pulse width) revealed that this behavior is caused by a temporary reduction in volumetric efficiency at high engine speeds combined with the EFI control response to intake flow variations. At 1000 m, the ambient pressure conditions lead the ECU to restrict injection duration and slightly adjust ignition timing in order to maintain the AFR within safe limits. This control action reduces the intake air mass and consequently results in a more pronounced torque decline at high rpm. Therefore, the observed difference is a real phenomenon originating from the interaction between intake dynamics and EFI logic under mid-altitude conditions rather than a plotting error.

The comparison highlights the performance limitations of naturally aspirated engines at high altitudes and underscores the advantages of fuel injection in maintaining engine efficiency. These findings emphasize the need for altitude compensation technologies, such as turbocharging or optimized EFI systems, to sustain engine power output in aviation applications.

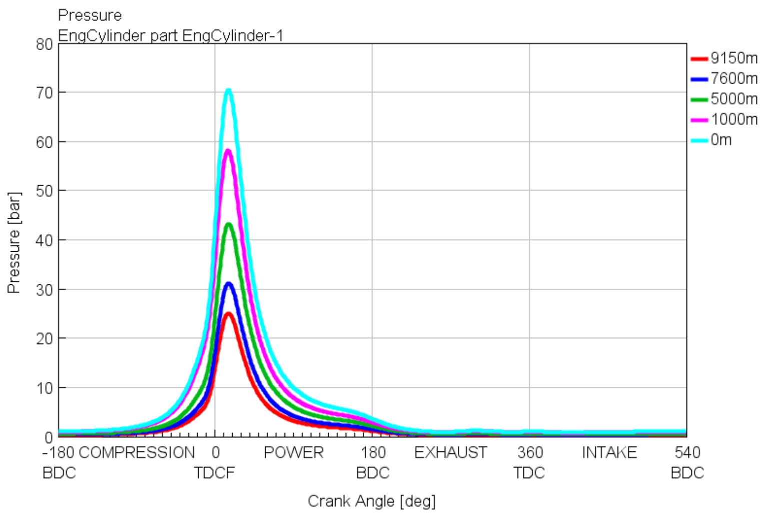
In addition to the general decreasing trend, the rate of power loss at each altitude level can be quantified. For the carbureted engine, the power reduction was approximately 47% at 5,000 m and nearly 80% at 9,150 m compared to sea level. By contrast, the fuel-injected engine retained a noticeably higher portion of its output, with power values remaining 30–35% greater than the carbureted configuration at the highest altitude. These results indicate that EFI not only slows the rate of degradation but also provides more stable power delivery across the altitude range, which is critical for maintaining operational reliability in aviation applications.

2.3. Effect of Altitude on In-Cylinder Pressure

Altitude has a direct impact on in-cylinder pressure by reducing atmospheric pressure and air density, which decreases the amount of oxygen available for combustion. As a result, combustion efficiency declines, leading to lower peak cylinder pressure and reduced engine performance at higher altitudes [22,24].



a)



b)

Figure 5: Comparison of In-Cylinder Pressure at Different Altitudes a) carbureted b) fuel injected

Figure 5 presents a comparison of in-cylinder pressure variations at different altitudes for the carbureted (Figure 4a) and fuel-injected (Figure 5b) versions of the Rotax 912 engine. The results illustrate the progressive decline in peak combustion pressure as altitude increases due to the reduction in atmospheric pressure and oxygen availability. Lower in-cylinder pressure at high altitudes results in weaker combustion, reduced power output, and overall engine performance degradation.

In the carbureted engine (Figure 5a), peak in-cylinder pressure exhibits a steep decline with increasing altitude. At sea level (0 m), peak pressure reaches approximately 65 bar, representing optimal combustion conditions. At 1,000 meters, the pressure slightly decreases, but at 5,000 meters, it drops to around 40 bar, reflecting a 38% reduction. At 9,150 meters, peak pressure falls to nearly 20 bar, indicating a 69% loss from sea level, leading to inefficient combustion and a significant reduction in engine output. The fixed air-fuel mixture in the carbureted system limits its adaptability, making it more vulnerable to altitude-induced pressure losses.

In contrast, the fuel-injected engine (Figure 5b) demonstrates higher in-cylinder pressure across all altitude levels, showing the effectiveness of dynamic fuel control. While pressure still decreases with altitude, the EFI system optimizes fuel injection timing and quantity, mitigating the decline compared to the carbureted engine. At 5,000 meters, in-cylinder pressure remains higher, and at 9,150 meters, the pressure reduction is less severe, confirming the advantages of electronic fuel injection in adapting to altitude-induced air density changes.

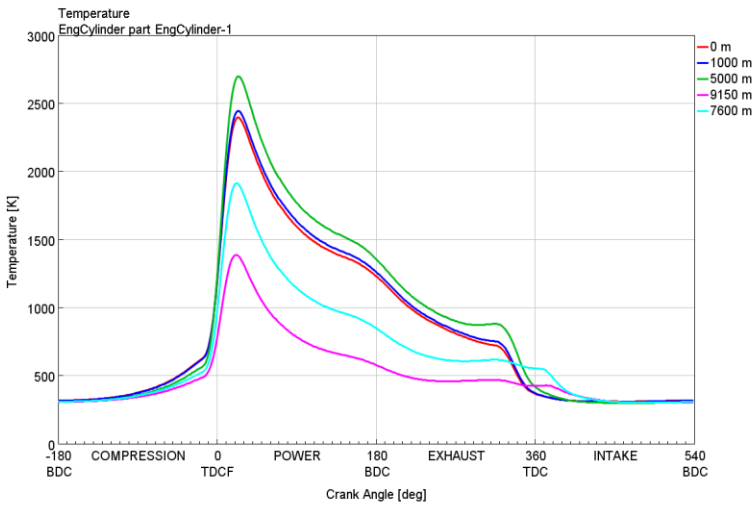
The comparison highlights the critical role of in-cylinder pressure in maintaining engine efficiency and reinforces the limitations of naturally aspirated carbureted engines at high altitudes. These findings emphasize the importance of altitude compensation technologies, such as turbocharging or advanced EFI systems, to sustain combustion efficiency and engine performance in aviation applications.

A closer examination of in-cylinder pressure variations further highlights the effect of altitude. For the carbureted engine, peak pressure declined from 65 bar at sea level to 20 bar at 9,150 m, representing a 69% reduction. The steep loss in cylinder pressure directly translates into weaker combustion and reduced indicated work. In contrast, the EFI system preserved higher peak pressures across all altitudes, with average values 15–20% greater than those of the carbureted engine. This improvement is attributed to the dynamic adjustment of the air–fuel ratio, which maintains more complete combustion under oxygen-deficient conditions. The ability to sustain higher in-cylinder pressure levels under altitude stress underscores the operational advantage of electronic fuel injection.

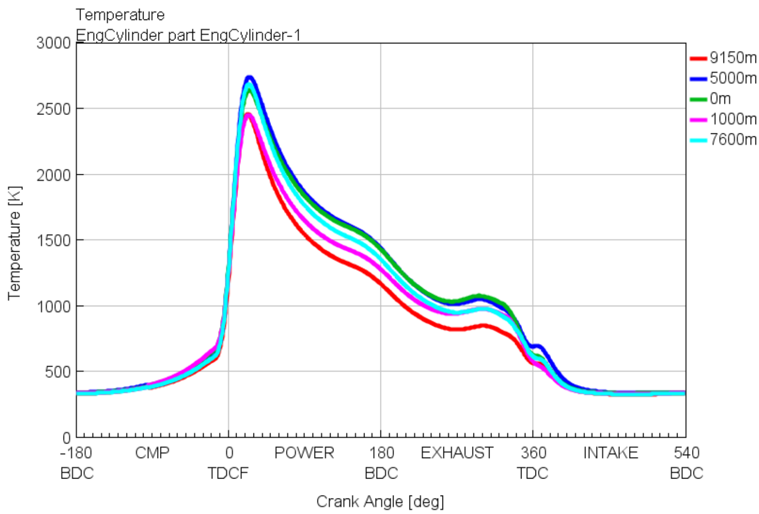
It is important to note that both subfigures (a: carbureted, b: EFI) in Figure 5 were plotted using the same axis scales to allow direct comparison. The apparent differences in curve slopes are not due to scaling inconsistencies but originate from the actual combustion characteristics of the two systems under altitude variation. Specifically, the carbureted engine shows a sharp decline in peak in-cylinder pressure, from approximately 65 bar at sea level to 20 bar at 9,150 m (a 69% reduction), reflecting poor adaptability to reduced oxygen levels. By contrast, the EFI engine sustains higher pressure levels across all altitudes, with peak values around 33–35 bar at 9,150 m, corresponding to a 48–50% reduction from sea-level conditions. This 15–20% relative improvement in retained pressure directly illustrates the superior adaptability of EFI in maintaining combustion stability under oxygen-deficient environments. The inclusion of identical scales in both subfigures ensures that the visual comparison accurately reflects the quantitative differences observed in simulation data.

2.4. Effect of Altitude on Cylinder Temperature

Cylinder temperature is a key factor in determining combustion efficiency and thermal performance of an engine. As altitude increases, the reduction in air density and oxygen availability leads to weaker combustion, resulting in a progressive decline in peak cylinder temperature. Lower temperatures at high altitudes indicate less complete combustion, which negatively impacts power output and overall engine efficiency [23].



a)



b)

Figure 6: Comparison of Cylinder 1 Temperature at Different Altitudes a) carbureted b) fuel injected

Figure 6 presents a comparison of cylinder temperature variations at different altitudes for the carbureted (Figure 6a) and fuel-injected (Figure 6b) versions of the Rotax 912 engine. The results illustrate the progressive decline in peak combustion temperature as altitude increases due to the reduction in atmospheric pressure and oxygen availability. Lower combustion temperatures at high altitudes lead to weaker combustion, reduced thermal efficiency, and lower overall engine performance.

In the carbureted engine (Figure 6a), peak cylinder temperature exhibits a steep decline with increasing altitude. At sea level (0 m), peak temperature reaches approximately 2800 K, representing optimal combustion conditions. At 1,000 meters, the temperature slightly decreases, but at 5,000 meters, it drops to around 2000 K, reflecting a 29% reduction. At 9,150 meters, peak temperature falls to approximately 1700 K, indicating a 40% loss from sea level, leading to incomplete combustion and reduced energy conversion efficiency. The fixed fuel-air mixture in the carbureted system limits its ability to compensate for changes in air density, making it more susceptible to altitude-induced thermal losses.

In contrast, the fuel-injected engine (Figure 6b) demonstrates higher cylinder temperatures across all altitude levels, showing the effectiveness of dynamic fuel control. While temperature still decreases with altitude, the EFI system optimizes fuel injection timing and mixture, reducing the rate of decline compared to the carbureted engine. At 5,000 meters, peak temperature remains higher, and at 9,150 meters, the reduction is less severe, confirming the advantages of electronic fuel injection in maintaining stable combustion efficiency at high altitudes.

The comparison highlights the critical role of cylinder temperature in maintaining combustion efficiency and reinforces the limitations of carbureted engines at high altitudes. These findings emphasize the importance of altitude compensation technologies, such as turbocharging or advanced EFI systems, to sustain thermal efficiency and engine performance in aviation applications.

For the fuel-injected Rotax 912iS engine, the simulation results show higher cylinder temperatures compared to the carbureted version under the same altitude conditions. At sea level, the peak cylinder temperature reaches approximately 2900 K, while at 5,000 meters it decreases to around 2200 K, representing a reduction of about 24%. At 9,150 meters, the peak temperature remains close to 1900 K, which is still significantly higher than that of the carbureted engine at the same altitude. These values confirm the advantage of EFI in maintaining higher combustion temperatures and more stable thermal performance under oxygen-deficient conditions.

2.5. Comparison of Carbureted and Fuel-Injected Rotax 912 Engines

The simulation results of the present study reveal that the carbureted Rotax 912 ULS engine experiences a severe performance degradation at high altitudes. At 9,150 meters, its power and torque decrease by approximately 80% and 84%, respectively, compared to sea-level conditions. In-cylinder pressure and combustion temperature also drop significantly with increasing altitude, leading to reduced thermal efficiency and unstable combustion. In contrast, the fuel-injected Rotax 912iS engine demonstrates better adaptability due to its Electronic Fuel Injection (EFI) system, which dynamically adjusts the air–fuel ratio in real time. The results show that at 9,150 meters, this engine maintains higher power and torque levels compared to the carbureted version, while also preserving higher in-cylinder pressure and combustion temperature.
These findings indicate that although both configurations are adversely affected by oxygen scarcity at high altitudes, the EFI-equipped engine is more effective in sustaining stable performance. Therefore, the direct comparison based on the data obtained in this study confirms the superiority of fuel injection over carburetion in mitigating altitude-induced performance losses.

At 9,150m altitude, the carbureted engine suffered approximately 80% and 84% reductions in power and torque, respectively, with peak in-cylinder pressure dropping by 69% and cylinder temperature decreasing by 40%. By contrast, the EFI-equipped engine retained significantly higher values, with only a 55–60% reduction in power, a 65–70% drop in torque, and about a 48–50% decline in in-cylinder pressure. Moreover, peak cylinder temperature remained around 1,900 K—10–15% higher than the carbureted version at the same altitude. These quantitative results confirm that EFI provides not only better adaptability but also measurable improvements in sustaining engine performance under oxygen-deficient conditions.

3. Conclusion

This study conducted a comparative analysis of the carbureted Rotax 912 ULS and the fuel-injected Rotax 912iS engines under flight altitudes up to 9,150 meters using GT-SUITE simulations. The results demonstrated that altitude significantly degrades engine performance by reducing power, torque, in-cylinder pressure, and combustion temperature. For the carbureted engine, power and torque decreased by 80% and 84%, respectively, while peak in-cylinder pressure declined by 69% and cylinder temperature dropped by 40% at the highest altitude. In contrast, the EFI-equipped engine showed substantially lower degradation, with a 55–60% loss in power, a 65–70% reduction in torque, and a 48–50% decline in in-cylinder pressure, while cylinder temperature remained about 10–15% higher than in the carbureted engine.

These findings clearly indicate that Electronic Fuel Injection provides not only better adaptability but also measurable performance advantages under oxygen-deficient conditions. Therefore, for naturally aspirated aircraft engines operating at moderate to high altitudes, EFI systems are strongly recommended over conventional carburetion to improve combustion stability, efficiency, and reliability. Nonetheless, both systems exhibit marked deterioration at very high altitudes, highlighting the inherent limitations of naturally aspirated designs and the necessity of integrating advanced altitude-compensation strategies—such as turbocharging or optimized EFI mapping—for future applications.

References

[1] H. Ding, R. Liu, Z. Zhang, C. Yang, Y. Jiao, and L. Hu, “Study on the influence of high-altitude on performance of an opposed-piston gasoline engine,” *Proc. 2020 Asia-Pacific Conf. Image Process. Electron. Comput. IPEC 2020*, no. October 2021, pp. 164–171, 2020, doi: 10.1109/IPEC49694.2020.9115160.

[2] H. Mansouri and F. Ommi, “Performance prediction of aircraft gasoline turbocharged engine at high-altitudes,” *Appl. Therm. Eng.*, vol. 156, pp. 587–596, Jun. 2019, doi: 10.1016/J.APPLTHERMALENG.2019.04.116.

[3] M. H. Shojaeefard, S. E. Hosseini, and J. Zare, “CFD simulation and Pareto-based multi-objective shape optimization of the centrifugal pump inducer applying GMDH neural network, modified NSGA-II, and TOPSIS,” *Struct. Multidiscip. Optim.*, vol. 60, no. 4, pp. 1509–1525, Oct. 2019, doi: 10.1007/S00158-019-02280-0/METRICS.

[4] B. A. Shannak and M. Alhasan, “Effect of atmospheric altitude on engine performance,” *Forsch. im Ingenieurwesen/Engineering Res.*, vol. 67, no. 4, pp. 157–160, Sep. 2002, doi: 10.1007/S10010-002-0087-Y/METRICS.

[5] S. Davari, F. Ommi, Z. Saboohi, and S. E. Hosseini, “Conceptual Design of a Conventional Aero Gas Turbine Combustor for Soot and Gaseous Emissions Reduction,” *J. Engine Res.*, 2025.

[6] M. Dopona, N. Foxhall, and C. Dutzler, “912iS Fuel Injected Aircraft Engine,” *SAE Tech. Pap.*, vol. 4, Oct. 2012, doi: 10.4271/2012-32-0049.

[7] S. Davari, F. Ommi, and Z. saboohi, “Experimental study of the effects of adding methylated homopolymer to gasoline on the engine performance and pollutant emissions,” *J. Solid Fluid Mech.*, vol. 11, no. 5, pp. 199–210, 2021, doi: https://doi.org/10.22044/jsfm.2021.9753.3200.

[8] M. Otkur, “Altitude Performance and Fuel Consumption Modelling of Aircraft Piston Engine Rotax 912 S/ULS,” *J. Adv. Res. Appl. Sci. Eng. Technol.*, vol. 23, no. 1, pp. 18–25, 2021, doi: 10.37934/araset.23.1.1825.

[9] Ł. Grabowski, K. Siadkowska, and K. Skiba, “Simulation Research of Aircraft Piston Engine Rotax 912,” *MATEC Web Conf.*, vol. 252, p. 05007, 2019, doi: 10.1051/MATECCONF/201925205007.

[10] R. C. Nugroho *et al.*, “Performance Simulation of Rotax 915iS PUNA MALE Engine Using AVL Boost,” *AIP Conf. Proc.*, vol. 2941, no. 1, Dec. 2023, doi: 10.1063/5.0184501/2929197.

[11] H. Zhang, L. Shi, K. Deng, S. Liu, and Z. Yang, “Experiment investigation on the performance and regulation rule of two-stage turbocharged diesel engine for various altitudes operation,” *Energy*, vol. 192, p. 116653, Feb. 2020, doi: 10.1016/J.ENERGY.2019.116653.

[12] Y. Zhou *et al.*, “Piston engine energy utilization for variable-altitude applications: A review of two-stage turbocharging technologies,” *Renew. Sustain. Energy Rev.*, vol. 223, p. 116036, Nov. 2025, doi: 10.1016/J.RSER.2025.116036.

[13] T. D. Husaboe, M. D. Polanka, J. A. Rittenhouse, P. J. Litke, and J. L. Hoke, “Dependence of Small Internal Combustion Engine’s Performance on Altitude,” *https://doi.org/10.2514/1.B35133*, vol. 30, no. 5, pp. 1328–1333, Sep. 2014, doi:

10.2514/1.B35133.

[14] T. D. Husaboe, J. A. Rittenhouse, M. D. Polanka, P. J. Litke, and J. L. Hoke, "Small internal combustion engine dependence on inlet pressure and temperature at altitude," *49th AIAA/ASME/SAE/ASEE Jt. Propuls. Conf.*, vol. 1 PartF, 2013, doi: 10.2514/6.2013-3649;PAGEGROUP:STRING:PUBLICATION.

[15] S. Davari, F. Ommi, Z. Saboohi, and S. E. Hosseini, "Hybrid Multi-Objective Optimization of Gas Turbine Combustor to Reduce Non-Volatile Particulate Matter and Gaseous Emissions," 2025, doi: SSRN 5191746.

[16] Y. Xu *et al.*, "Multi-objective optimization of variable altitude high-dimensional compression-ignition aviation piston engine based on Kriging model and NSGA-III," *Energy*, vol. 320, p. 135306, Apr. 2025, doi: 10.1016/J.ENERGY.2025.135306.

[17] S. Davari and S. E. Hosseini, "A review on the oxygenated fuels on engine performance parameters and emissions of spark ignition engines," *OSF*, 2025, doi: https://doi.org/10.31219/osf.io/r2e7f_v1.

[18] W. C. Koh, N. M. Mazlan, P. Rajendran, and M. A. Ismail, "A Computational Study to Investigate the Effect of Altitude on Deteriorated Engine Performance," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 370, no. 1, p. 012001, May 2018, doi: 10.1088/1757-899X/370/1/012001.

[19] Y. F. Gorgulu, B. Sahin, S. Ekici, and T. H. Karakoc, "Altitude-Dependent Analysis of Combustion Performance and Emissions in a Commercial Aircraft Engine Leveraging Real Engine Data," *Int. J. Aeronaut. Sp. Sci.*, pp. 1–17, Jun. 2025, doi: 10.1007/S42405-025-00982-Y/TABLES/3.

[20] S. E. Hosseini and F. Salehi, "Analyzing overlap ratio effect on performance of a modified Savonius wind turbine," *Phys. Fluids*, vol. 35, no. 12, Dec. 2023, doi: 10.1063/5.0180735/2929698.

[21] D. Jamshidi, D. P. Borazjani, S. E. Hosseini, and S. Davari, "Impact of Exhaust Manifold Design on Internal Combustion Engine Performance Combustion Engine Performance," pp. 0–9, 2025, doi: 10.20944/preprints202502.1065.v1.

[22] S. Davari, F. Ommi, Z. Saboohi, and M. Safar, "Experimental study of the effect of a non-oxygenated additive on spark-ignition engine performance and pollutant emissions," *Int. J. Eng. Trans. A Basics*, vol. 34, no. 4, pp. 1035–1045, 2021, doi: 10.5829/ije.2021.34.04a.30.

[23]Amirzdeh, M., Hosseini Moradi, S. A., ghobadi, N. Real Time Detection of Multi-Rotor Unmanned Aerial Vehicle Using YOLOv5 Optimized Algorithm. Journal of Advanced Defense Science & Technology, 2023; 14(1): 11-22.

[24] S. Davari, F. Ommi, and Z. Saboohi, "Investigating the Effects of Adding Butene , Homopolymer to Gasoline on Engine Performance Parameters and Pollutant Emissions : Empirical Study and Process Optimization," J. Inst. Eng. Ser. C, 2021, doi: 10.1007/s40032-021-00780-x.