Comparative Thermal Analysis of Turboprop and Turbofan Engines: Ideal Brayton Cycle Efficiency and Performance Implications

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Abstract— Turboprop and turbofan engines are the two main propulsion systems in modern transportation, each with different thermodynamic characteristics based on the Brayton cycle. Thermal efficiency, defined as the ratio of heat converted into useful work to total heat input, is a fundamental parameter for evaluating engine performance. This study aims to quantitatively compare the ideal thermal efficiency of turboprop and turbofan engines to understand their thermodynamic limits and performance implications for various operational missions. This research employs an analytical method based on the ideal Brayton cycle formulation, calculating thermal efficiency from compression ratio data using the adiabatic index and specific heat ratio. The TPE331-10 turboprop engine powering the CASA C-212 Aviocar and the CFM56-3 turbofan engine were selected as representative cases. The analysis shows that the CFM56-3 turbofan achieves an ideal thermal efficiency of 70.51%, significantly higher than the TPE331-10 turboprop's 48.99%. This 21.52 percentage point difference is primarily attributed to the turbofan's higher compressor pressure ratio, enabling more effective energy conversion within the cycle. However, turboprops excel at low to medium speeds due to superior propulsive efficiency from their propellers. This study concludes that although turbofans are thermodynamically superior for long-distance travel at high speeds, turboprops remain optimal for short-range operations. These findings provide valuable insights for selecting appropriate propulsion technologies and optimizing energy utilization across various transportation missions.

Keywords— Propulsion System, Thermal efficiency, Turboprops, Turbofan

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I. INTRODUCTION

Thermal efficiency is a dimensionless quantity that indicates the heat input is the energy produced from the energy source. The expected result can be heat or work, or both. The performance of components such as internal combustion engines and external combustion engines. Thermal efficiency focuses on the ratio of heat that can be converted into work with the amount of heat entering a system. This can be determined by comparing the difference between the input energy and output energy with the energy fed into a system. [1]

Understanding heat transfer is key to ensuring a system works efficiently and avoiding machine damage

due to excessive heat. Heat transfer can occur in three main ways, namely conduction (the process of heat transfer that occurs in solid materials), convection (the process of heat transfer that occurs between the surface of an object and a fluid), and radiation (the process of heat transfer that occurs through electromagnetic waves). These three methods of heat transfer have different principles and characteristics. [2]

Conduction is the transfer of heat using a solid object as a medium without the movement of particles. This occurs because particles vibrate rapidly within an object when heated, transferring energy to adjacent particles. In the context of solid objects such as metals, this process is highly effective because the particles of solid objects are tightly bound together. Convection is the transfer of heat that occurs in a liquid or gas (fluid) followed by the transfer of particles of the substance. During this process, the fluid that receives heat will become lighter, causing it to rise, while the fluid with a lower temperature will sink. Radiation is a process of heat transfer in the form of electromagnetic waves without the need for an intermediate medium, whereby heat can be transferred even in the absence of solid objects or fluids in between. [3]

The CASA C-212 Aviocar is a medium-sized passenger equipped with turboprop engines, designed and manufactured in Spain for civilian and military use. [4] The CASA C-212 is fitted with two turboprop engines for light transport, constructed of metal with high-wing components and fixed tricycle landing gear. This type is known as the AVIOCAR, which operates on short runways for both takeoff and landing. At the time, the C-212 was CASA's response to the air force's

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217

requirement for a light military transport capable of operating in areas with minimal infrastructure and unpaved runways. The AVIOCAR is powered by two Garret TPE331-10 turboprop engines, designed in 1959 and certified in 1965. The TPE331-10 was the first turboprop engine developed by Garret Air Research, which was acquired by Honeywell in 1999. [5]

Meanwhile, the powered by CFM56-3CI turbofan engines can reach a maximum speed of 910 km/h and offers better fuel efficiency and noise reduction compared to previous series. As a commercial passenger, it can carry up to 120 passengers and is the shortest in its classic series, with a design similar to its predecessor. Designed for short to medium-haul flights, this falls into the category of second-generation narrow-body jets, with a length of approximately 31 meters, and features improved avionics and a modern cockpit compared to the original series. [6]

The comparison of ideal thermal efficiency between turbofan and turboprop engines has strategic value in propulsion system research and engineering. Ideal thermal efficiency, calculated based on the Brayton cycle without considering actual losses, provides a theoretical limit for engine performance and is a very important fundamental indicator. This comparative study offers a wide range of benefits in academic, technological design, and aviation operational contexts. [21][8]

Comparing ideal thermal efficiency provides a deep understanding of the theoretical performance of each engine configuration. Turbofan engines with higher pressure ratios tend to have greater ideal thermal efficiency than turboprop engines. This analysis provides a scientific basis for why turbofans excel at high-speed cruising, while turboprops are more efficient at low to medium speeds. This understanding is important in the process of selecting propulsion technology that is suitable for the characteristics of the flight mission. [22][11]

Comparative analysis helps evaluate the gap between ideal and actual performance, which reflects the magnitude of actual losses in machine operation. By knowing how much ideal efficiency can be achieved, engineers can identify which components contribute most to efficiency losses, such as compressors, combustion chambers, and turbines. This information is very useful in developing performance improvement strategies, design optimization, and machine maintenance planning. [23][15]

This comparative study provides an evaluative basis for the design and development of future propulsion technologies. Industry trends toward high efficiency, low emissions, and minimal fuel consumption are driving innovations such as intercooled recuperated turboprops, geared turbofans, and ultra-high bypass ratio turbofans. By understanding their ideal efficiencies, researchers can determine which technologies have the most potential for improving the overall performance of propulsion systems. [24][18]

The comparison of ideal efficiency also serves as a validation parameter for numerical models or thermodynamic simulations. Simulation models such as MATLAB, Thermoflex, or NPSS often use ideal efficiency as one of the initial benchmarks. By comparing turbofans and turboprops, researchers can test the accuracy of these simulation models, while also understanding the sensitivity of performance to variables such as compression ratio, turbine inlet temperature, and airflow characteristics.

This comparison is useful in determining operational and energy management policies. Turbofan engines with high ideal thermal efficiency are the right choice for medium to long haul routes, where cruising performance is a dominant factor. Conversely, turboprops are more efficient for short-haul routes because they consume less fuel at low speeds. By understanding their ideal limits, operators can determine a more cost- and energy-efficient fleet configuration.

This comparison aids in the analysis of emissions and environmental impact. Thermal efficiency is directly related to fuel consumption and CO_2 emission levels. Engines with high ideal efficiency theoretically require less energy to produce net work. Therefore, comparing turbofans and turboprops in terms of ideal efficiency helps provide an understanding of the potential for emission reductions in each type of engine and the mitigation strategies that can be implemented by the aviation industry.

This analysis also provides insight into the trade-off between thermal efficiency and propulsion efficiency. Although turbofans have higher ideal thermal efficiency, turboprops have better propulsion efficiency at low speeds due to the use of propellers. By comparing ideal efficiencies, researchers can build a comprehensive picture of the performance balance between the two types of engines, enabling a more objective assessment in the development of designs oriented towards specific mission specifications.

Comparing ideal thermal efficiency can be the basis for developing an aviation engineering curriculum. The differences in thermodynamic structure, operating characteristics, and performance limits between turbofans and turboprops provide examples when teaching the Brayton cycle, efficiency analysis, and engine design. This helps students understand basic applied thermodynamics concepts through real-world case studies. [25][20]

This comparison enables the identification of potential uses for alternative energy and environmentally friendly fuels (SAF – Sustainable Aviation Fuel). By knowing the ideal limits of engine performance, researchers can evaluate how variations in the thermophysical properties of SAF or hydrogen affect theoretical efficiency and potential for future performance improvements.

Comparing the ideal thermal efficiency of turbofan and turboprop engines is an important step that not only explains the fundamental differences between the two engines, but also provides various strategic benefits in research, design, model validation, energy analysis, and operational planning. This study enriches our understanding of theoretical performance limits and provides a solid foundation for the development of more efficient, environmentally friendly propulsion

International Journal of Marine Engineering Innovation and Research, Vol. 11(1), Mar. 2026. 216-222
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218

innovations that meet the needs of the modern aviation industry.

II. METHOD

2.1 Turboprop Engine

A turboprop engine is a hybrid engine that provides jet thrust and drives a propeller. A turboprop is basically the same as a turbojet, but in a turboprop, the turbine works through a main shaft connected to a reduction gear to rotate the propeller in front of the engine in Figure 1.

2.2 Turboprop Operating System

When the first turbojet successfully took flight, the turboprop engine was further improved. The concept of the turboprop engine itself is similar to that of a turbofan, although it has a higher bypass ratio. In addition, in a turbofan, the turbine drives a ducted fan, while in a turboprop, the turbine drives an external propeller entirely. The propeller is driven either by a gas generator turbine (Figure 2) or by another turbine classified as a free turbine or electric turbine in Figure 3.

Under this setup, the turbine operates independently from the compressor-driving turbine, enabling it to spin freely within the exhaust gas stream. In free turbine turboprop engines, an alternative configuration features a non-conventional airflow pattern where gases and air travel from the rear toward the front. This design offers significant advantages in nacelle installation, as the area behind the engine typically not required for exhaust purposes can be repurposed for components such as a wheel well or fuel tank. The compressor incorporates

either axial or centrifugal flow designs, or a combination of both. A notable example of this engine type is the PT6, produced by Pratt & Whitney in Canada.

In some configurations, a substantial gearbox is placed between the turbine and the propeller, enabling a speed reduction ratio of approximately 1:15. Turboprop engines generate thrust from two sources: the propeller and the exhaust flow. Approximately 85% of the total thrust comes from the propeller, while the remaining 15% is contributed by the jet core exhaust, which operates at lower velocities.

As stated earlier, the propeller rotates at a very low speed compared to the speed of the turbine that drives it. The speed reduction can be as much as 1:15. This speed reduction is necessary for two reasons:

1. The rotation of large-diameter propellers (ranging from 2 to 4 meters) generates substantial centrifugal forces. Since the blades are attached to the propeller hub in a fixed cantilever manner, these forces produce significant tensile stress at the blade root. Due to these stress constraints, large-diameter propellers must operate at considerably reduced rotational speeds.
2. When operating at high subsonic velocities (exceeding $M > 0.7$), the tips of the propeller blades may reach supersonic speeds. Under such conditions, airflow separation can occur and shock waves may develop. This leads to a decline in turboprop engine performance, resulting from reduced propeller efficiency and a diminished airflow rate entering the engine.
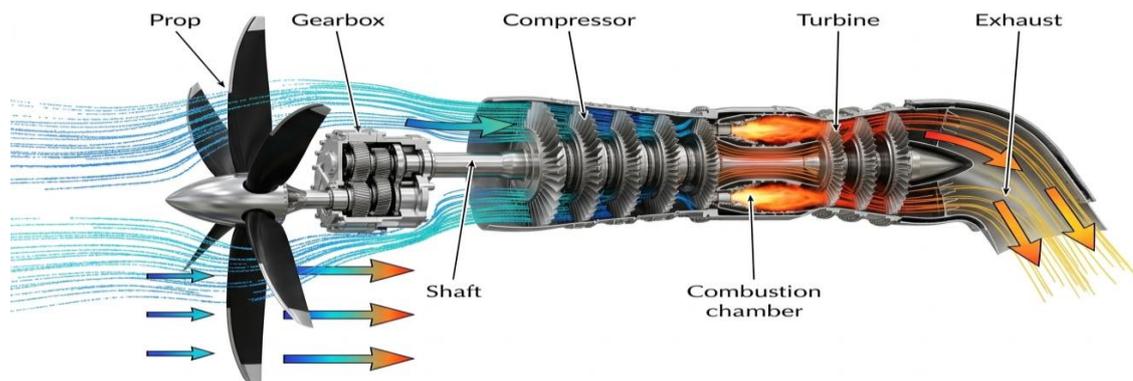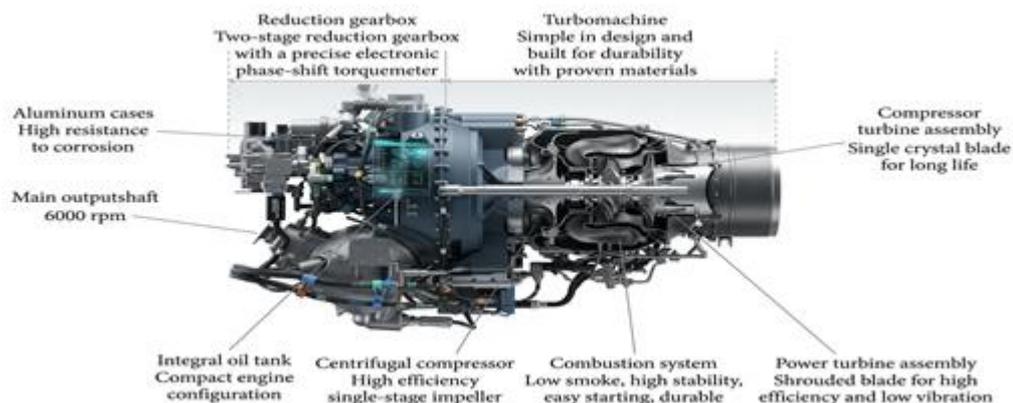

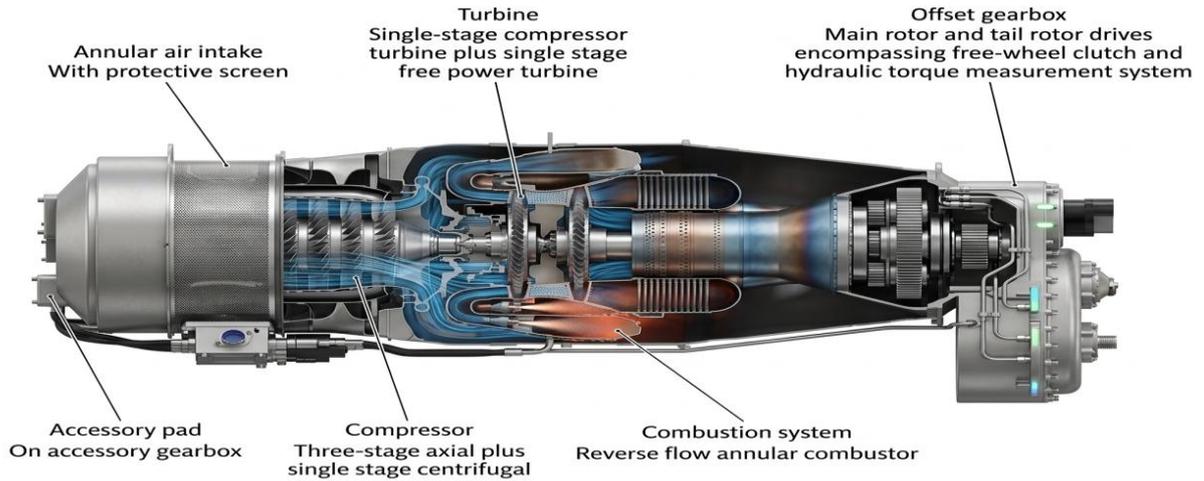**Figure 1.** Turboprop Engine

Figure 2. Engine Turboprop PT6B

International Journal of Marine Engineering Innovation and Research, Vol. 11(1), Mar. 2026. 216-222
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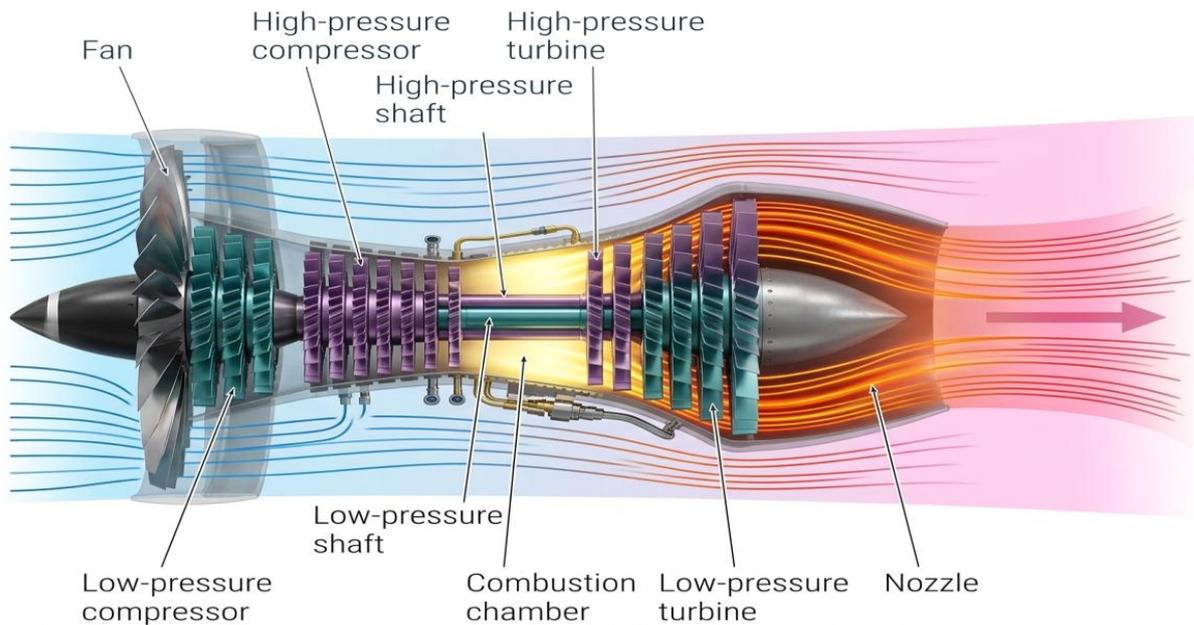
219

Figure 3. Engine Turboprop PW200

Figure 4. CFM56-3 Engine Schematic

2.3 Compressor

For a known compressor pressure ratio π_c, the isentropic efficiency η_c, where the temperature and pressure exiting the compressor are the specific power of the compressor, is as follows:

$P_{o3} = P_{o2} . \pi_c$ ....(1)

$\Delta h_c = c_{pc}(T_{o3} - T_{o2})$ ....(2)

2.4 Turbofan Engine

Turbofan engines are similar to turboprop engines, but instead of a propeller, they use a fan. Turbofan engines typically do not use reduction gears, and the fan rotates in a duct so that it is not directly exposed to atmospheric air.

A. CFM56-3 Turbofan Engine

The CFM56-3 engine is a turbofan jet engine with a large bypass capacity and dual rotors that uses advanced axial flow technology designed for use and all its variants.

B. Main Parts of a Turbofan Engine

Basically, an engine has several main parts, namely the air intake, compressor, combustion chamber, turbine, and exhaust unit to generate thrust.

C. CFM56-3 Engine Operating System

1. Aerodynamic Engine Station

    The design of the CFM56-3 high bypass engine has a perfect airflow with two airflow sections, namely primary airflow and secondary airflow.

2. By-Pass Duct

    A bypass duct is a duct whose components are made of fabricated steel and fiberglass that connects the engine from the compressor intermediate case to the annular gas combiner.

3. Exhaust Collector

    The exhaust collector is a part located after the exhaust. This part is shaped like a nozzle that serves to accelerate airflow, thereby generating thrust.

4. Fuel System

    The low-pressure fuel pump injects fuel at various stages of the engine, while the high-pressure fuel

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220

pump passes through a fuel heater, oil cooler, fuel filter, and flow meter.

5. Oil System

The oil system in the CFM56-3 engine, which is designed as a "dry sump," occurs in the forward sump and aft sump as well as the gearbox.

6. Engine Control

Manual control of the engine is performed via two levers on the pilot's pedestal.

7. Air Flow Control

Air can operate the engine smoothly at low compression ratios. The airflow through the HPC is controlled by the IGV (Inlet Guide Vane) at the initial stage of the compressor and also by the bleed valve at the seventh stage.

8. Cooling and Sealing Air

To cool the engine internally until a consistent temperature that meets engine performance is achieved, air is taken from the LPC, bypass channel, and HPC to meet the engine's needs.

9. Anti Icing

To prevent ice from forming on the air intake during operation at low temperatures, air from the HPC level 9 duct is channeled through two anti-icing control valves via the IGV to the air intake nose fairing and circulated to heat the nose cowl.

10. Starting

To start the engine, a high-pressure air starter is used.

2.4 Research Methods

The data collection methods used in this research were field studies, literature review, discussions, and problem analysis. The research plan included exploratory research aimed at simplifying the problem for easier solution, and the Brayton cycle to analyze the thermal efficiency of a turbofan engine.

III. RESULTS AND DISCUSSION

3.1 Thermal Efficiency in Engine CFM56-3

Thermal efficiency refers to the ratio of how much heat can be converted into work compared to the total heat input into the system. To determine the performance decline of a gas turbine, input values are required. From the input parameter data, output data can be obtained through calculations. Based on these output data, we can determine the values that contribute to the performance decline of the CFM56-3 turbofan engine.

3.2 Ideal Thermal Efficiency of Turboprop Engines

For an ideal Brayton cycle (compressor and turbine with ideal isentropic processes), ideal thermal efficiency is expressed as:

For an ideal Brayton cycle (compressor and turbine with ideal isentropic processes), ideal thermal efficiency can be found by calculating the compression ratio with the adiabatic index, the specific heat capacity ratio.

Numerical result

$rp^{(\gamma-1)/\gamma} = 10.4^{(1.4-1)/1.4} = 10.4^{0.4/1.4}$

$= 10.4^{0.2857} \approx 0.5100845324$

Calculate the ideal efficiency

$\eta_{ideal} = 1 - 0.5100845324 = 0.4899154676$

Convert to percentage

$\eta_{ideal} \times 100\% = 48.99154676\% \approx 48.99\%$

Therefore, for the TPE331-10, we obtain:

Ideal thermal efficiency (Brayton) = 48.99%

3.3 Comparison of the ideal thermal efficiency of a turbofan (CFM56-3) with a turboprop (TPE331-10)

1. Theoretical difference: The ideal efficiency of a turbofan is 70.5%, which is 21.52 percentage points higher than the ideal efficiency of a TPE331 turboprop at 48.99%. This means that, within the thermodynamic limits of the Brayton cycle, a turbofan (with higher PR and design conditions) can convert a greater portion of the fuel's heat energy into net work than a turboprop.

2. The ideal efficiency value is only a theoretical limit: it does not take into account actual losses (isentropic inefficiencies, mechanical losses, bypass flow in turbofans, gearbox and propeller losses in turboprops, etc.).

3. This ideal comparison is very useful for understanding thermodynamic limits, but it does not directly determine the actual operational efficiency for a given mission. The turbofan study actually reports an actual efficiency (44.0%) that is well below its ideal efficiency due to real component losses.

TABLE 1.
COMPARISON OF THE IDEAL THERMAL EFFICIENCY OF TURBOFAN AND TURBOPROP ENGINES

Engine	Type	Ideal Thermal Efficiency (Bryton)
CFM56-3	Turbofan	70,51%
TPE331-10	Turboprop	48,99%

IV. CONCLUSION

Based on the results of calculations and comparative analysis of the ideal thermal efficiency of the TPE331-10 turboprop engine and the ideal thermal efficiency of the CFM56-3 turbofan engine, it can be concluded that there is a very significant fundamental difference in the thermodynamic performance limits of the two types of engines. The ideal efficiency values obtained through the Brayton cycle formulation show that the TPE331-10 turboprop engine has an ideal thermal efficiency of approximately forty eight point nine percent, while the CFM56-3 turbofan engine has an ideal efficiency of approximately seventy point five one percent, as reported in previous studies. This difference in ideal efficiency reflects the basic characteristics of the two engines, both in terms of cycle architecture, compression ratio, and design operating conditions.

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221

The higher ideal thermal efficiency value of turbofans indicates that the cycle design used in turbofan engines is more effective in converting fuel heat energy into net mechanical energy when compared to turboprops. This is mainly influenced by the compression ratio value, which is generally higher in turbofans, allowing the Brayton cycle to operate more efficiently at a wider range of pressures and temperatures. These conditions enable turbofans to produce high thermal efficiency during high-speed cruising operations and at high altitudes, where this type of engine is designed to operate optimally.

Conversely, the lower ideal efficiency of turboprops compared to turbofans cannot be viewed as a design flaw, but rather as a consequence of the engine's orientation towards providing shaft power rather than jet thrust. Turboprop engines prioritize the conversion of energy from the thermodynamic cycle into mechanical power to drive the propeller, which ultimately provides very high propulsion efficiency at low to medium speeds. Thus, the lower ideal thermal efficiency value must be understood as part of a systemic trade-off between cycle thermal efficiency and total propulsion efficiency.

This analysis also explains that the ideal efficiency value does not directly describe the performance of the engine under actual operating conditions, but rather serves as a theoretical limit that allows for an assessment of the effectiveness of each engine's components and design quality. When compared to actual efficiency, as in the case of the CFM56-3, which has an actual efficiency of around forty-four percent, there is a significant difference between ideal and operational conditions. This difference arises due to real losses such as compressor and turbine inefficiency, mechanical transmission losses, incomplete combustion phenomena, and deviations in actual temperature and pressure from theoretical values. Similar phenomena are also expected to occur in turboprop engines, although the analysis of their actual efficiency requires further experimental data.

Thus, comparing the ideal thermal efficiency of turbofan and turboprop engines provides a deeper understanding of the fundamental thermodynamic characteristics of both types of engines, as well as clarifying the technical reasons behind the use of turbofans in high-speed flight and turboprops in short- and medium-range flight. This comparison is not only relevant in the context of performance analysis, but also provides a strong basis for planning further research, developing engine technology, and evaluating the potential for performance improvements through component engineering or the development of new, more efficient fuels. This study confirms that a comprehensive understanding of ideal thermal efficiency is an important first step in the development of more efficient, reliable, and sustainable modern engines.

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222

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