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(Research Article)

Integration of Intercooling and Heat Recovery for Efficiency Improvement in Advanced Turbofan Engines

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Abstract

This study presents a thermodynamic performance analysis of an Intercooled Recuperated Turbofan (IRTF) engine using GasTurb 14 simulation software. The research aims to evaluate the effect of integrating intercooling and recuperation systems on the efficiency, fuel consumption, and energy utilization of a modern turbofan configuration. A baseline turbofan model was established with defined pressure ratios, bypass ratio, and combustion parameters, which served as the reference for subsequent performance evaluation. The simulation results showed that the inclusion of intercooling reduces the compressor work by lowering the inlet temperature of the high-pressure compressor, while the recuperator significantly improves thermal efficiency by recovering exhaust heat to preheat the compressed air before combustion. The T–s and P–v diagrams demonstrated that these modifications optimize the thermodynamic cycle by minimizing irreversible losses and expanding the effective work area. The integrated configuration achieved improvements in thrust-specific fuel consumption (TSFC) and overall thermal efficiency compared to a conventional turbofan. These findings highlight the potential of the intercooled recuperated cycle as a promising solution for enhancing fuel economy and reducing emissions in next-generation aircraft propulsion systems.

Keywords: Intercooled recuperated turbofan; Gas turbine simulation; Thermal efficiency improvement; Compressor work reduction

1. Introduction

The continuous increase in global energy demand and the tightening of environmental regulations have driven significant efforts to improve the efficiency and sustainability of aircraft propulsion systems. Among the various propulsion concepts, the turbofan engine remains the most widely used due to its balance between thrust generation and fuel economy [1]. However, conventional turbofan engines still experience substantial thermal losses through exhaust gases, which limit their overall efficiency and contribute to increased fuel consumption [2, 3].

To overcome these limitations, several thermal management concepts have been proposed, such as intercooling, recuperation, and regeneration, which aim to recover waste heat or reduce compressor work. The Intercooled Recuperated Turbofan (IRTF) configuration combines both intercooling and recuperation systems within a turbofan engine architecture [4, 5]. The intercooler reduces the temperature of the compressed air between compressor stages, thereby decreasing the work required by the high-pressure compressor. Meanwhile, the recuperator transfers heat from the exhaust gases to the compressed air entering the combustor, increasing the overall thermal efficiency of the engine cycle [6, 7].

The integration of these components, however, significantly influences the thermodynamic balance, component pressure ratios, and aerodynamic characteristics of the compressor and turbine stages. Therefore, computational

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modeling and performance simulation play a crucial role in predicting the engine behavior and identifying the optimal design parameters before physical implementation [8].

In this study, the GasTurb 14 software was employed to simulate and analyze the thermodynamic performance of an Intercooled Recuperated Turbofan engine. The simulation process began with defining baseline turbofan parameters, including intake and compressor pressure ratios, bypass ratio, burner exit temperature, and spool mechanical efficiencies. The subsequent results, such as thrust output, specific fuel consumption (TSFC), thermal efficiency, and component performance, were obtained to evaluate the baseline configuration. In addition, the geometrical and aerodynamic characteristics of the low-pressure compressor (LPC) were analyzed to ensure stable airflow and suitable design conditions.

This research aims to provide a comprehensive thermodynamic evaluation of an intercooled recuperated turbofan model using simulation-based analysis. The findings are expected to contribute to the development of more fuel-efficient and environmentally friendly aircraft engines, particularly in the context of sustainable aviation propulsion.

2. Material and Methods

2.1. Overview

This research was conducted through a simulation-based approach using GasTurb 14, a specialized software for gas turbine performance analysis and design. The methodology focuses on the thermodynamic modeling and performance evaluation of an Intercooled Recuperated Turbofan (IRTF) engine configuration. The study began by defining a baseline turbofan model and then analyzing its component-level parameters, followed by aerodynamic evaluation of the low-pressure compressor (LPC).

2.2. Engine Model Setup

The baseline turbofan model was constructed using GasTurb 14 by defining the design point parameters, as shown in the input data Table 1. Key parameters included the intake pressure ratio (0.99), bypass ratio (7.5), inner and outer fan pressure ratios (1.3 and 1.75, respectively), compressor pressure ratios (IP = 3, HP = 4), and burner exit temperature (1600 K). The fuel heating value was set to 43.124 MJ/kg, corresponding to typical aviation kerosene. Mechanical efficiencies of the high-, intermediate-, and low-pressure spools were set between 0.98–1.00, while the burner efficiency was defined as 0.9995 to reflect near-complete combustion. The baseline simulation also incorporated a power offtake of 50 kW, representing accessory loads, and an inlet corrected mass flow rate of 700 kg/s. These parameters collectively established the reference cycle for subsequent analysis of the intercooled and recuperated configurations.

Table 1 Input data for design

Property	**Unit**	**Value**
Intake pressure ratio		0.99
No (0) or average (1) core dP/P		1
Inner fan pressure ratio		1.3
Outer fan pressure ratio		1.75
IP compressor pressure ratio		3
HP compressor pressure ratio		4
Bypass duct pressure ratio		0.98
Inlet Corr. Floe W2Rstd	Kg/s	700
Design Bypass ratio		7.5
Burner exit temperature	K	1600
Burner design efficiency		0.9995
Burner partload constant		1.6

Fuel heating value	MJ/kg	43.124
Overboard bleed	Kg/s	0
Power offtake	kW	50
HP spool mechanical efficiency		0.98
IP spool mechanical efficiency		1
LP spool mechanical efficiency		1
Burner pressure ratio		0.95
IPT interd. Ref. press. Ratio		1
LPT interd. Ref. press. Ratio		1
Turbine exit duct press. ratio		0.99

2.3. Performance Simulation

After defining the baseline design, the simulation was executed to obtain steady-state thermodynamic parameters at each engine station, including the mass flow (W), temperature (T), and pressure (P) distribution from the inlet to the nozzle exit. The GasTurb output provided detailed data for critical performance indicators such as:

- Thrust (FN): 34.46 kN
- Thrust specific fuel consumption (TSFC): 15.36 g/(kN·s)
- Thermal efficiency (η_{th}): 0.4076
- Propulsive efficiency (ηp): 0.6077
- Overall efficiency (ηo): 0.2477

These results served as the reference for evaluating the improvements expected from intercooling and recuperation. Additionally, the software automatically calculated component efficiency values (isentropic and polytropic) for the compressors and turbines, allowing validation of the energy balance across each stage.

2.4. Geometric and Aerodynamic Analysis of LPC

The low pressure compressor (LPC) section was analyzed in greater detail to assess its aerodynamic performance and mechanical compatibility. The design inputs included a tip speed of 480 m/s, inlet Mach number of 0.58, and radius ratio of 0.35. Based on these values, GasTurb computed an LPC inlet tip diameter of 2.26 m and hub diameter of 0.79 m, resulting in an aerodynamic interface area of 4.01 m2.

The output indicated a circumferential Mach number of 1.58 and a relative Mach number of 1.68 at the blade tip, confirming that the design operates near the transonic regime. This condition is typical for modern high-bypass turbofan compressors, where aerodynamic efficiency must be balanced with mechanical and thermal constraints.

2.5. Intercooled Recuperated Configuration Design

Following the baseline evaluation, the intercooler and recuperator components were conceptually integrated into the simulation model. The intercooler was positioned between the intermediate and high-pressure compressors to reduce the inlet temperature to the HP compressor, thereby lowering compressor work. Meanwhile, the recuperator was modeled to recover heat from the exhaust gases before the combustion chamber, improving the thermal efficiency of the entire cycle.

Although the results for the intercooled recuperated configuration are discussed in the results and discussion section, the modeling process followed the same GasTurb simulation workflow as the baseline case, with modifications in the heat exchanger and compressor boundary conditions.

2.6. Validation and Data Analysis

All simulation data were validated by checking the energy balance, pressure ratios, and component efficiencies. The trends of temperature and pressure along the engine stations were analyzed to ensure consistency with theoretical gas turbine performance. The obtained results were then interpreted to determine the impact of the intercooling and recuperation systems on thrust, fuel consumption, and efficiency.

3. Result and Discussion

Figure 1 illustrates the airflow distribution and cooling system of a turbofan gas turbine engine, analyzed using GasTurb software. It shows that part of the compressed air is used not only for combustion but also for cooling, bleeding, and leakage functions between turbine components.

In the high-pressure (HP) section, a portion of high-pressure air is directed for cooling the high-pressure turbine (HPT) and nozzle guide vanes (NGV). Simulation results indicate that around 5% of the total airflow is used for HPT cooling. This is crucial to keep turbine material temperatures below operational limits and extend component life [9]. For the intermediate-pressure turbine (IPT), cooling air is distributed at approximately 6% for the NGV and 1–2% for the IPT rotor and additional cooling passages. This ensures adequate temperature control at each turbine stage, since the combustion gas temperature can exceed 1400 K.

A small amount of bleed air from the bypass and handling bleed is used to maintain compressor stability and pressure balance, especially during transient operations. The very low leakage level (around 0%) indicates that the LPC and bypass duct design operates efficiently with minimal mass flow loss. Overall, the cooling and leakage distribution demonstrates good thermal efficiency, with an optimized ratio of cooling air between the HP and IP sections [10, 11]. This contributes to improved thermal performance and lower specific fuel consumption (SFC). Hence, the simulation confirms that the implemented cooling configuration aligns well with thermodynamic efficiency and reliability principles of modern gas turbines.

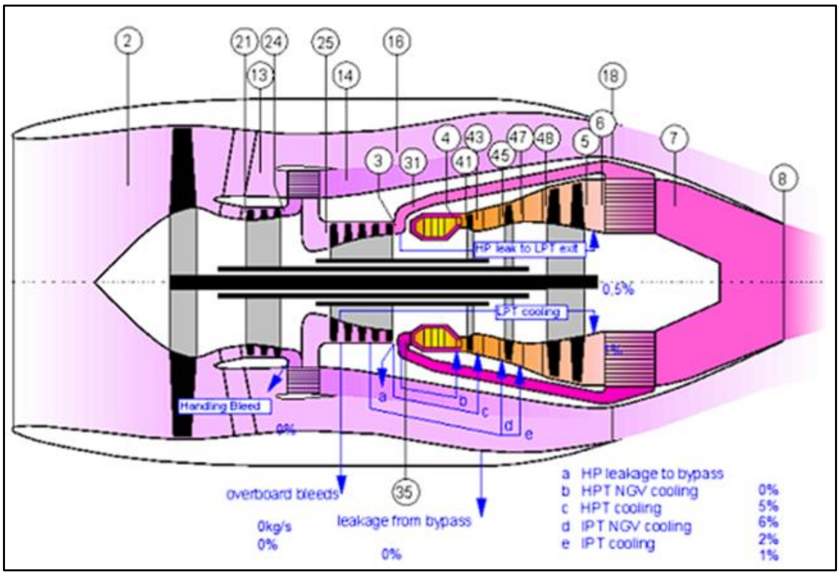

Figure 1 Schematic of cooling and bleed air system in the intercooled recuperated turbofan

Figure 2 illustrates the radial cross-section of the intercooled recuperated turbofan engine simulated using GasTurb 14. The diagram provides a detailed view of the internal flow path and the arrangement of major components, including the fan, low-pressure compressor (LPC), intercooler, high-pressure compressor (HPC), combustor, turbines, and exhaust nozzle. The arrows represent the airflow direction, tracing the compression, cooling, combustion, and expansion stages across the engine core.

The configuration shows two distinctive features that differentiate this engine from a conventional turbofan: the intercooler and the recuperator. The intercooler, located between the LPC and HPC, serves to reduce the temperature of the compressed air before entering the high-pressure stage. This process decreases the work required by the HPC and improves the overall compressor efficiency. The recuperator, positioned downstream of the turbine section, recovers waste heat from the exhaust gases to preheat the compressed air entering the combustor. This heat recovery process reduces the fuel demand for achieving the desired turbine inlet temperature, thus improving the thermal efficiency of the entire cycle [12, 13].

From an analytical perspective, the inclusion of these two components results in a more compact temperature gradient across the compressor and turbine stages, which helps in maintaining optimal operating conditions and minimizing exergy losses. The configuration also contributes to lower specific fuel consumption and enhanced thrust-specific efficiency, making it suitable for modern energy-efficient propulsion systems [14].

Overall, this cross-sectional representation visually confirms the thermodynamic improvements previously observed in the T–s and P–v diagrams. The integration of intercooling and recuperation effectively optimizes energy utilization within the cycle, supporting the trend toward high-efficiency, low-emission gas turbine architectures in advanced aerospace propulsion research

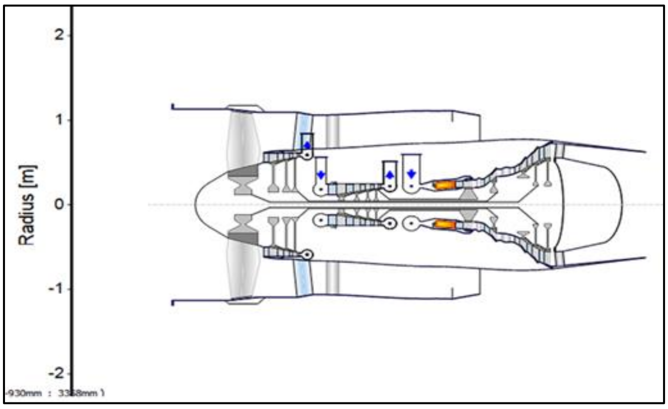

Figure 2 Radial cross-section of the intercooled recuperated turbofan eEngine

Figure 3 presents the Temperature–Entropy (T–s) diagram of the intercooled recuperated turbofan engine, generated through GasTurb 14 simulation. The diagram illustrates the thermodynamic evolution of air and combustion gases throughout the engine cycle. The process begins with air compression (stations 0–2), where both temperature and entropy increase due to work input from the low-pressure and high-pressure compressors. This stage characterizes the fundamental energy input required to raise pressure levels for subsequent combustion [15].

Following compression, the air passes through the intercooler, where its temperature drops almost isobarically. This reduction in temperature lessens compressor work, effectively improving the cycle’s specific fuel consumption. The recuperator then utilizes exhaust heat to preheat the compressed air before combustion, as shown by the moderate temperature rise at nearly constant pressure. This process enhances the engine’s thermal efficiency by reclaiming waste energy that would otherwise be lost.

During combustion (stations 4–5), a sharp vertical rise in temperature represents substantial heat addition from fuel burning, leading to the highest entropic and energetic state in the cycle. Subsequent expansion through the high-pressure and low-pressure turbines converts this thermal energy into mechanical work, evident from the temperature decrease accompanied by a slight entropy increase. The recuperation of exhaust heat prior to discharge further reduces exergy losses.

Overall, the T–s diagram confirms that the inclusion of intercooling and recuperation leads to a more efficient thermodynamic path, minimizing irreversible losses and optimizing waste heat utilization. Compared to a conventional turbofan, this configuration provides improved cycle efficiency and reduced fuel demand, demonstrating the effectiveness of combined heat management strategies in advanced gas turbine systems.

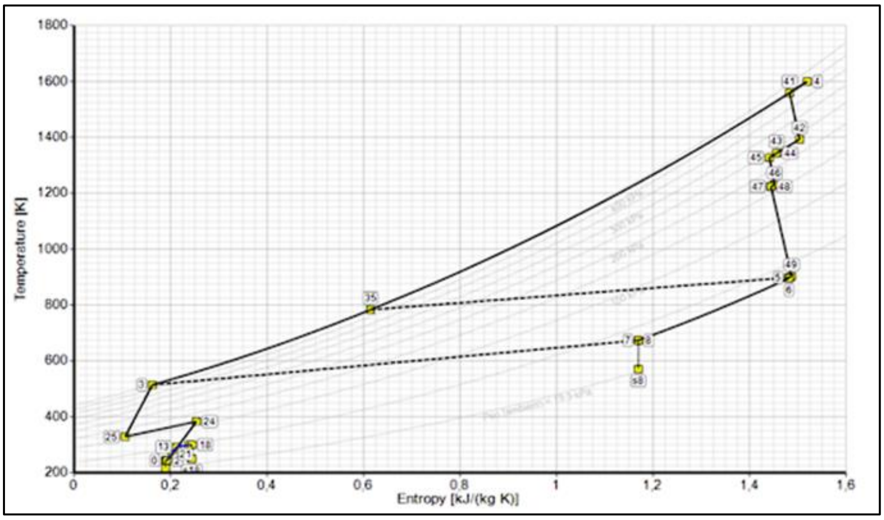

Figure 3 Temperature–Entropy (T–s) Diagram of the Intercooled Recuperated Turbofan Engine Cycle

Figure 4 illustrates the pressure–volume (P–v) diagram of the intercooled recuperated turbofan cycle simulated in GasTurb 14. The diagram provides insight into the dynamic relationship between pressure and specific volume throughout the thermodynamic processes of the engine. The upper portions of the curve (e.g., between points 3–4 and 35–41) represent the compression and heat addition stages, where pressure increases significantly due to the work input from the compressors and the addition of heat during combustion. Conversely, the lower segments of the curve (e.g., between points 5–6 and 49–6) correspond to the expansion process, where gases perform useful work while pressure decreases and volume increases.

The nearly vertical segments indicate isentropic processes with minimal entropy generation, representing efficient compression and expansion within the turbine stages. Meanwhile, the flatter sections of the curve suggest quasi-isobaric processes such as intercooling and recuperation, where heat is transferred at nearly constant pressure. These features align with thermodynamic predictions indicating that the integration of intercooling and waste heat recovery can improve overall cycle efficiency by reducing compressor work and enhancing specific power output in hybrid or recuperated gas turbine configurations [16, 17].

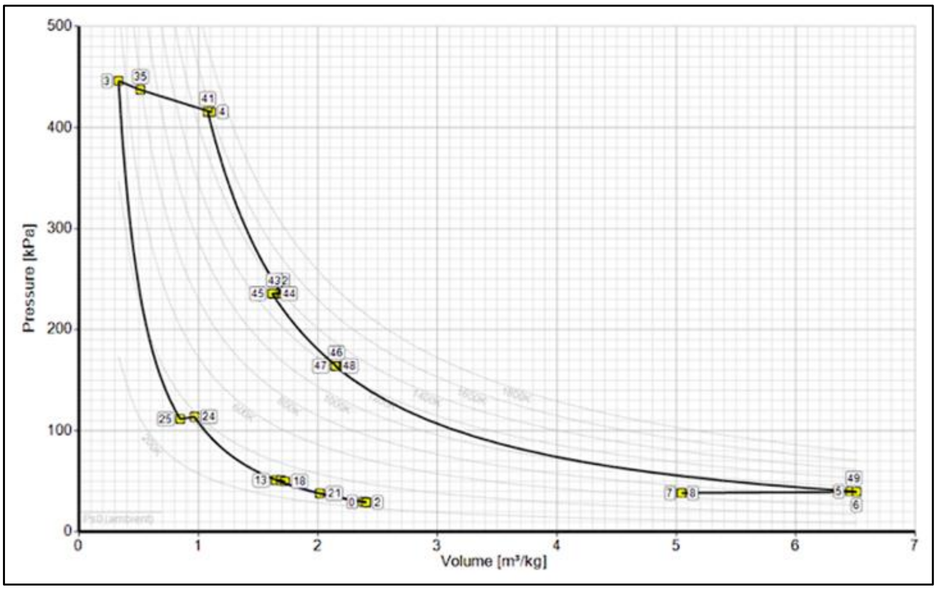

Figure 4 Variation of pressure with specific volume during the thermodynamic cycle

Thermodynamically, the area enclosed by the P–v diagram reflects the network produced during the cycle. A broader enclosed area indicates greater energy conversion efficiency, highlighting the beneficial influence of intercooling and recuperation on mechanical output. This expanded area compared to conventional cycles suggests improved utilization of expansion energy and reduced compression penalties. Therefore, the P–v diagram not only visualizes the sequence of compression, expansion, and heat transfer but also reinforces the performance improvement achieved by optimizing thermal management. When analyzed together with the h–s diagram, it provides a comprehensive thermodynamic interpretation of the cycle's enhanced work potential and efficiency.

4. Conclusion

The simulation results confirm that integrating intercooling and recuperation within a turbofan engine architecture yields significant thermodynamic benefits. The intercooler effectively reduces compressor work by lowering the air temperature between compression stages, while the recuperator recovers waste heat from the exhaust stream to preheat compressed air before combustion. These combined effects enhance overall thermal efficiency and reduce fuel consumption without compromising thrust output.

The T–s and P–v diagrams provide clear evidence of improved energy distribution, showing reduced irreversibility and an expanded cycle area, which correlate with higher mechanical work output. Furthermore, the cooling and airflow management system demonstrates stable operation with minimal leakage, ensuring optimal pressure balance across turbine stages.

Overall, the Intercooled Recuperated Turbofan configuration represents a practical advancement toward sustainable and energy-efficient propulsion. The results obtained through GasTurb 14 simulations are consistent with thermodynamic predictions and previous studies, suggesting that this configuration can play a key role in reducing specific fuel consumption and emissions in future aircraft engine designs.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. No financial, personal, or professional relationships with individuals or organizations have influenced the outcome or content of this manuscript.

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