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Design and Analysis of Boosted Turboshaft Using GasTurb 14: A Study on Thermodynamic Performance and Cooling Systems

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Abstract—efficiency and performance are significantly influenced by thermodynamic design, including the compressor, combustion chamber, and turbine. This study aims to design and analyze a gas turbine system with a Boosted Turboshaft configuration using GasTurb 14 software. The design parameters considered include compressor pressure ratio, airflow mass, combustion efficiency, fuel calorific value, and turbine cooling system. These input parameters were processed to simulate system performance through three primary diagrams: Temperature-Entropy (T-s), Enthalpy-Entropy (h-s), and Pressure-Volume (P-v). The simulation results demonstrate that a high-pressure ratio in the compressor improves thermodynamic efficiency, while the optimal combustion temperature in the combustion chamber reaches approximately 1500 K. The expansion process in the turbine results in significant pressure and temperature drops, reflecting efficient conversion of thermal energy into mechanical energy. The cooling system was also analyzed, with 4% airflow allocated for High-Pressure Turbine (HPT) cooling and 6% for Nozzle Guide Vane (NGV) cooling, ensuring the thermal integrity of the turbine blades. Pressure leaks, such as an HP leak to LPT exit of 1%, were also accounted for to identify irreversibility within the system. This study introduces novelty in cooling system management and bleed air analysis, which are rarely highlighted in previous studies. GasTurb 14-based simulations enable detailed analysis of gas turbine designs, relevant for modern propulsion and energy generation applications. The findings are expected to contribute to the development of more efficient and reliable gas turbine technologies.

Keywords— Gas Turbine, Boosted Turboshaft, Gasturb 14, Turbine Cooling System.

I. INTRODUCTION

Gas turbines are extensively utilized across various applications, including aircraft propulsion systems, power generation, and heavy industrial sectors. Operating on the principle of converting thermal energy into mechanical energy, gas turbines consist of

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three main components: the compressor, combustion chamber, and turbine. The efficiency and performance of a gas turbine system are heavily reliant on the thermodynamic design of each component, which includes optimizing airflow, combustion, and turbine blade cooling [1]. As global energy demands continue to rise, the development of more efficient and reliable gas turbines remains a focal point of research and development [2].

However, one of the primary challenges in gas turbine design lies in managing high temperatures, which can lead to material degradation and reduced efficiency. Additionally, irreversibility in the thermodynamic cycle, such as pressure leaks and mechanical inefficiencies, hinder the enhancement of system performance [3]. To address these challenges, software-based simulations offer an effective alternative to physical testing [4]. Among the popular software tools available is GasTurb 14, which allows for detailed simulations of design parameters, such as pressure ratios, combustion efficiency, turbine cooling, and bleed air management [5]. The software provides a comprehensive graphical analysis, including T-s, h-s, and P-v diagrams, to evaluate each process within the gas turbine cycle.

This study aims to design and analyze a gas turbine system with a Boosted Turboshaft configuration using GasTurb 14. Input data, such as mass airflow, fuel calorific value, compressor pressure ratio, and combustion efficiency, are utilized to create an optimal design. Performance analysis is conducted through three primary diagrams: T-s for evaluating temperature and entropy changes, h-s for analyzing enthalpy variations, and P-v for assessing pressure and expansion efficiency. A key focus of the study is the blade cooling system, which ensures material integrity in high-pressure (HPT) and low-pressure turbines (LPT).

The novelty of this research lies in the use of highly detailed data for designing the cooling system and managing bleed air, which have rarely been addressed explicitly in previous studies. The significance of this study is in providing a practical and efficient gas turbine design framework under realistic operational conditions. The findings are expected to contribute to the development of advanced gas turbine technologies, particularly in propulsion and power generation applications.

Sources for this research include a comprehensive textbook on gas turbine theory that provides foundational concepts and insights into turbine operations, as well as a study that examines the challenges associated with the degradation of gas turbine systems over time. These references serve as key materials to understand both theoretical and practical aspects of gas turbine performance and maintenance [6,7,8]. The GasTurb 14 user manual also serves as a technical guide for simulation design. With this approach, the study aims to make a substantial contribution to the literature and the development of modern gas turbine technologies.

II. EXPERIMENTAL DESIGN

A. *Input Data for Simulation*

TABLE I. INPUT DATA FOR DESIGN

Design	Parameters	Unit	Value
ZW2Rstd	Inlet Corr. Flow W2Rstd	kg/s	10
P2q1	Intake Pressure Ratio		1
ZP24q2	Booster Pressure Ratio		3
P25q24	Compr. Interduct Press. Ratio		0.88
ZP3q25	HP Compressor Press. Ratio		10
T4 D	Burner Exit Temperature	K	1500
e34ds	Burner Design Efficiency		0.9
e34C	Burner Partload Constant		1.7
FHV	Fuel Heating Value	MJ/kg	42.74
WBLDq2	Rel. Handling Bleed		0

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ZWBLD	Overboard Bleed	kg/s	1
ZWBLq25	Rel. Overboard Bleed W Bld/W25		0
hr bld	Rel. Enthalpy of Overb. Bleed		1
Wrecig25	Recirculating Bleed W reci/W25		0
hr reci	Rel. Enthalpy of Recirc. Bleed		1
stg HPT	Number of HP Turbine Stages		1
WCHN1q25	HPT NGV 1 Cooling Air/W25		0.06
WCHR1q25	HPT Rotor 1 Cooling Air/W25		0.04
WCHN2q25	HPT NGV 2 Cooling Air/W25		0
WCHR2q25	HPT Rotor 2 Cooling Air/W25		0
DmCl HT	HPT Cool Air Pumping Dia.	m	0
Stg LPT	Number of PT Stages		3
WCLN1q25	PT MGV 1 Cooling Air/W25		0
WCLR1q25	PT Rotor Cooling Air/W25		0.02

This study employs the GasTurb 14 software to simulate the design of a gas turbine. Table 1 shows the input data that will be used in the simulation and design process. The input data used in the simulation include key thermodynamic and design parameters, optimized for achieving the optimal performance of the turbine system. The input parameters are as follows:

- Flow and Pressure Ratios:
  - ZW2Rstd (Inlet Corr. Flow W2Rstd): Corrected air mass flow rate of 10 kg/s.
  - P2Q1 (Intake Pressure Ratio): Air intake pressure ratio.
  - ZP24Q2 (Booster Press. Ratio): Booster pressure ratio, indicating additional pressure before entering the main compressor.
  - P25Q24 (Compr. Interduct Press. Ratio): Interduct compressor pressure ratio of 0.88.
  - P23Q25 (HP Compressor Pressure Ratio): High-pressure compressor (HPC) pressure ratio of 24.

- Combustion Parameters:
  - T4 D (Burner Exit Temperature): Burner exit temperature under specified conditions in Kelvin.
  - e34ds (Burner Design Efficiency): Burner design efficiency.
  - e34C (Burner Parload Constant): Partial load constant for the burner.
  - FHV (Fuel Heating Value): Fuel heating value of 42.74376 MJ/kg.

- Bleed Air and Recirculation:
  - WBLDq2 (Rel. Handling Bleed): Percentage of bleed air for system handling.
  - ZWBLD (Overboard Bleed): Percentage of bleed air expelled.

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- Wrecirc25 (Recirculating Bleed W_recirc25): No recirculating bleed air (0%).
- br_bld and br_recirc: Relative enthalpy of bleed air and recirculating air.

B. Cooling System and Turbine Stages

- High-Pressure Turbine (HPT):
  - stg_HPT: Number of stages in the high-pressure turbine.
  - WCHN1q25 and WCHN2q25: Cooling air flow to the HPT rotor for each stage.
  - DmCL_HT: Cooling pump diameter for the high-pressure turbine.
  -
- Low-Pressure Turbine (LPT):
  - stg_LPT: Number of stages in the low-pressure turbine.
  - WCLN1q25 and WCLN2q25: Cooling air flow for the nozzle guide vane (NGV) in the LPT.
  - WCLR1q25: Cooling air flow for the LPT rotor of 0.02.

C. Simulation Process

These input data are processed by GasTurb 14 to generate performance analyses of the turbine cycle, including temperature distribution, pressure, mass flow rate, thermal efficiency, and mechanical energy output. These parameters are iteratively calibrated to ensure the design meets criteria for maximum efficiency and power output.

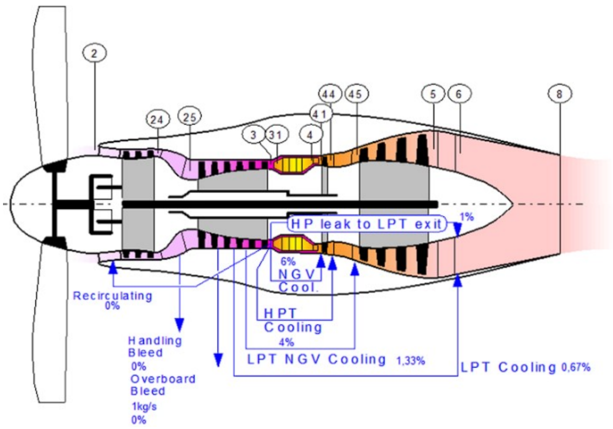

Fig. 1. Internal diagram of the designed turbine system

Figure 1 illustrates the internal diagram of the designed turbine system, encompassing main components such as the compressor, combustion chamber, high-pressure turbine (HPT), low-pressure turbine (LPT), and nozzle. This study aims to evaluate the system's performance and thermodynamic efficiency through detailed simulation.

D. Design Input Parameters and Configuration

The designed gas turbine incorporates initial parameters such as compression ratio, air mass flow rate, compressor and turbine efficiencies, and maximum combustion conditions. The system configuration includes:

- Propeller: A front component to generate mechanical thrust.

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- Low-Pressure Compressor (LPC) and High-Pressure Compressor (HPC): Compressing intake air to increase pressure and temperature before combustion.
- Combustion Chamber: Mixing air and fuel to produce high-pressure, high-temperature gases.
- High-Pressure Turbine (HPT) and Low-Pressure Turbine (LPT): Converting the energy of hot gases into mechanical power.

E. Cooling System

To protect components from high temperatures, the cooling system is implemented with the following details:

- HPT Cooling: 4% of airflow is used for cooling the HPT blades.
- NGV Cooling (Nozzle Guide Vane): 6% of airflow is directed to cool the guide vanes.
- LPT NGV Cooling: 1.33% of airflow is used for cooling the LPT nozzle.
- LPT Cooling: 0.67% of airflow is used for cooling the LPT blades.

F. Bleed Air Management

Bleed air management is also simulated, where the bleed air in this system is categorized as follows:

- Handling Bleed and Overboard Bleed: No additional bleed flow diverted from the main cycle (each 0%).
- Recirculating Air: No air recirculation (0%).

G. Leakage Analysis and Irreversibilities

The simulation includes leakage analysis, such as HP Leak to LPT Exit of 1%, which affects the overall system efficiency.

H. Performance Evaluation

The system performance is analyzed using simulation outputs from the software, including temperature distribution, pressure, and air mass flow at each stage. These results are used to evaluate the thermal and mechanical efficiency of the turbine design.

GasTurb 14 provides in-depth analysis capabilities, allowing optimization of parameters to achieve the best performance from the gas turbine system. This design demonstrates relevance for propulsion and power generation applications.

III. Results and Discussuion

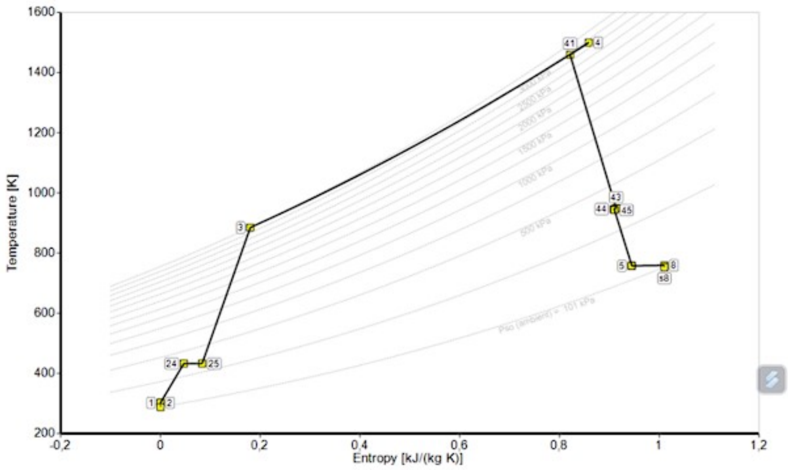

Fig. 2. Temperature-Entropy (T-s) Diagram Analysis

Figure 2 illustrates the relationship between temperature and entropy in the thermodynamic cycle of the gas turbine designed using GasTurb 14. This T-s diagram depicts the four primary processes within the cycle: compression, combustion, expansion, and exhaust.

Compression (1 → 3):

The first stage, compression, involves a significant increase in air temperature and pressure as it passes through the low-pressure compressor (LPC) and high-pressure compressor (HPC). The steep gradient in this segment reflects the high compression ratio, which directly contributes to improving the thermodynamic efficiency of the cycle. The relatively small change in entropy indicates minimal inefficiencies caused by friction and mechanical losses, suggesting that the compressor's performance is close to ideal, albeit not perfect [9].

Combustion (3 → 41):

In the combustion process, there is a dramatic increase in temperature, reaching approximately 1500 K, highlighting the optimal combustion efficiency achieved in the combustion chamber. The thermal energy added during this phase is critical for producing high-energy hot gases required for subsequent processes.

Expansion (41 → 45):

The expansion phase shows a significant temperature drop as high-energy hot gases flow through the high-pressure turbine (HPT) and low-pressure turbine (LPT). This temperature reduction corresponds to the conversion of thermal energy into mechanical energy, which powers the compressors and generates output power. The increase in entropy during this process reflects the presence of irreversibilities, such as friction on the turbine blades and imperfect heat transfer [10].

Exhaust (45 → 8):

In the final phase, exhaust gases are discharged through the nozzle, resulting in further temperature reduction and a slight increase in entropy. This step marks the conclusion of the cycle.

Overall, the T-s diagram validates the high-performance characteristics of the turbine design. High compression ratios in the compressors and optimal combustion temperatures contribute to the system's competitive thermodynamic efficiency and substantial mechanical power output. Further optimization of irreversibilities, such as reducing friction and enhancing heat transfer, could improve the overall cycle efficiency [11].

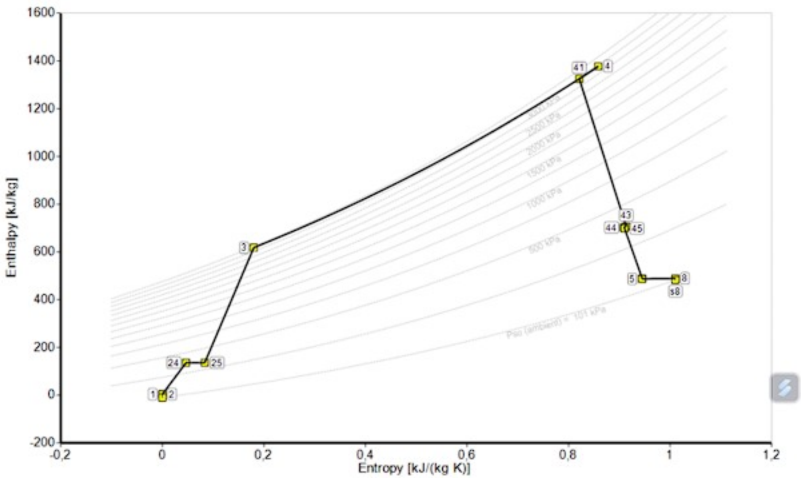

Fig. 3. Enthalpy-Entropy (h-s) Diagram Analysis

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Figure 3 illustrates the Enthalpy vs. Entropy (h-s) diagram, providing a detailed representation of the thermodynamic processes in a gas turbine cycle. This diagram offers specific insights into the changes in total energy (enthalpy) during each phase of the cycle.

Compression (1 → 3):

The compression process exhibits a significant increase in enthalpy, reflecting the energy added by the compressors to raise air pressure. This phase comprises two segments: low-pressure compression (LPC: 1 → 2 → 3), characterized by a smaller enthalpy gradient, and high-pressure compression (HPC: 3), where more energy is added. The entropy change during this process remains minimal, indicating relatively low mechanical inefficiencies. This step is critical in ensuring that the air reaches the optimal pressure and temperature conditions before entering the combustion chamber [12].

Combustion (3 → 41):

The combustion process shows a dramatic rise in enthalpy, representing the thermal energy added by fuel combustion in the combustion chamber. This energy addition is vital for driving the subsequent mechanical energy conversion during the expansion process.

Expansion (41 → 45):

During the expansion process, a significant drop in enthalpy is observed, indicating the high efficiency of the high-pressure turbine (HPT: 41 → 44) and low-pressure turbine (LPT: 44 → 45). These turbines serve to drive the compressors and generate mechanical power on the main shaft.

Nozzle and Exhaust (45 → 8):

A further enthalpy decrease in the nozzle phase (45 → 8) reflects the utilization of residual energy to generate thrust or discharge exhaust gases at a certain velocity.

This diagram underscores the critical importance of the combustion and expansion phases in optimizing the cycle's efficiency. The distribution of enthalpy in this design indicates effective energy conversion, though slight entropy increases during the expansion stages suggest the presence of irreversibilities. Further optimization could reduce energy losses at these stages to enhance overall cycle performance [13].

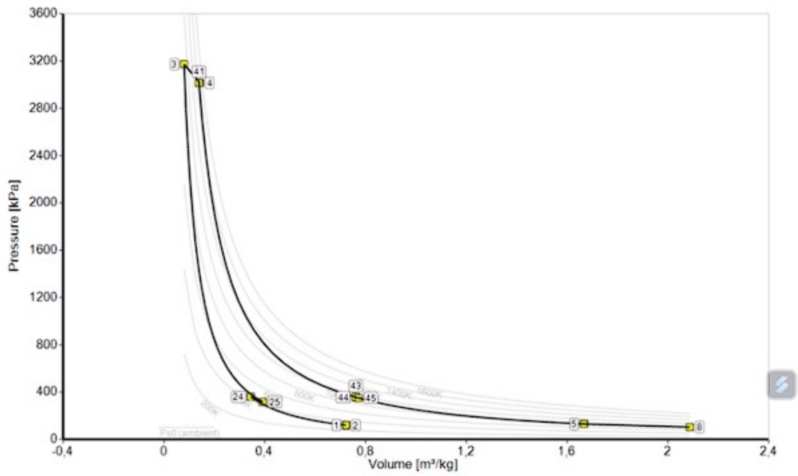

Fig. 4. Pressure-Volume (P-v) Diagram Analysis

Figure 4 represents the Pressure-Volume (P-v) diagram, illustrating the relationship between pressure and specific volume at each stage of the gas turbine cycle. This diagram provides crucial insights into the thermodynamic performance of the turbine system, particularly concerning pressure efficiency and gas expansion.

Compression Stage (1 → 3):

The compression stage exhibits a significant pressure increase from approximately 100 kPa to over 3000 kPa. Specific air volume decreases during this stage as air is compressed through the low-pressure compressor (LPC: 1 → 2) and high-pressure compressor (HPC: 2 → 3). This pressure rise highlights the compressor's capability to enhance air density, which is critical for improving combustion efficiency in subsequent stages. The steep pressure gradient indicates optimal compressor performance, though minor irreversibilities may occur due to friction and mechanical inefficiencies [14].

Combustion Stage (3 → 41):

In the combustion stage, there is an increase in the specific volume of air as fuel combustion in the combustion chamber produces high-pressure, high-temperature gas.

Expansion Stage (41 → 45):

During the expansion phase, a significant pressure drop occurs as the hot gases pass through the high-pressure turbine (HPT: 41 → 44) and the low-pressure turbine (LPT: 44 → 45). This pressure drop signifies the conversion of thermal energy into mechanical energy.

Exhaust Stage (45 → 8):

In the final stage, the exhaust gases are released at a pressure close to atmospheric pressure, indicating efficient energy release from the cycle.

Overall, the P-v diagram highlights the critical roles of compression and expansion in determining cycle efficiency. Optimizing the system's maximum and minimum pressures could further enhance thermodynamic efficiency, particularly by minimizing irreversibilities in critical stages. This diagram also provides valuable insights for identifying potential improvements in the gas turbine cycle design.

IV. Conclusion

This study successfully designed and analyzed a gas turbine system with a Boosted Turboshaft configuration using GasTurb 14 software. Based on the simulations conducted, several key findings were obtained.

Firstly, the high-pressure ratio in the compressor significantly contributed to the enhancement of the system's thermodynamic efficiency. The optimal combustion temperature in the combustion chamber reached approximately 1500 K, generating substantial thermal energy for the turbine expansion process.

Secondly, the cooling system analysis demonstrated that allocating 4% of the airflow for the High-Pressure Turbine (HPT) and 6% for the Nozzle Guide Vane (NGV) effectively maintained the thermal integrity of the turbine blades.

The expansion process in the High-Pressure Turbine (HPT) and Low-Pressure Turbine (LPT) showed significant reductions in pressure and temperature, reflecting the efficient conversion of thermal energy into mechanical energy. System irreversibility analysis revealed a pressure leakage of 1% at the HP Leak to LPT Exit, providing valuable insights for future design optimizations.

The T-s, h-s, and P-v diagrams provided a clear representation of the thermodynamic dynamics at each stage of the cycle, supporting a comprehensive evaluation of system performance.

Overall, this study contributes to the development of more efficient and practical gas turbine designs for modern applications, such as aircraft propulsion and power generation. The novelty of this research lies in its detailed analysis of the cooling system and bleed air, aspects rarely emphasized in previous studies. The findings of this research are expected to serve as a guide for further advancements in gas turbine technology, particularly through simulation-based approaches.

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