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A COMMERCIAL TURBOFAN ENGINE MODELING AND EXERGY ANALYSIS

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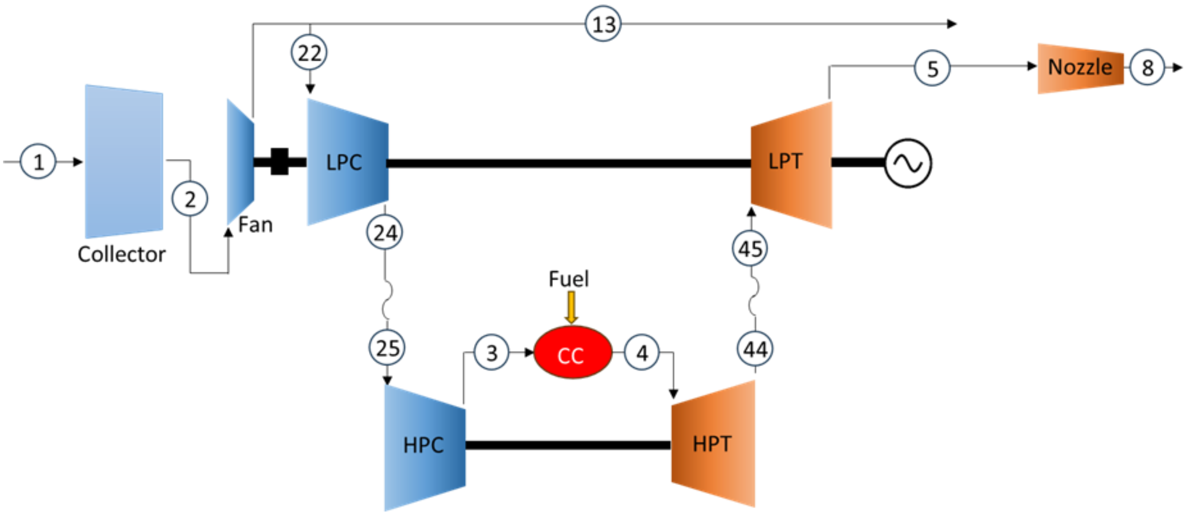
Highlights

- Thermodynamic modeling of a commerical turbofan engine.
- Performing exergy analysis to evaluate the performance criteria of engine components.
- Evaluation of how the bypass ratio affects net thrust and specific fuel consumption.

Graphical Abstract (Optional)



Thermodynamic schematic of the modelled engine

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ABSTRACT: Turbofan engines are one of the most common types of engines used in modern commercial and military aircraft due to their efficiency and performance characteristics. In this study, a thermodynamic model is generated using GasTurb 14 software for a commercial two-spool, unmixed flow, and booster turbofan engine (CFM56-5A3) used in Boeing A320-212. Besides, an exergy analysis of the modeled turbofan engine is performed. Exergy performance criteria such as exergy efficiency, exergy development potential, exergy destruction ratio, productivity lack ratio, and fuel depletion ratio are evaluated for the engine components. In addition, how bypass ratio (BPR) affects net thrust and specific fuel consumption (SFC) for the modeled turbofan engine is investigated. As a result, the net thrust and SFC values of the modeled engine and the actual engine are overlapped with 14.0% and 7.2% deviation, respectively. The maximum exergy efficiency occurs at the high-pressure turbine as 0.992. When the bypass ratio is minimum, the maximum net thrust and SFC occur as 62.24 kN and 24.08 g kN^{-1} s^{-1}, respectively. High pressure turbine has the minimum exergy development potential of 1528.5 kW.

Keywords: *Bypass ratio, Exergy analysis, Thermodynamic model, Turbofan engine*

1. INTRODUCTION

A turbofan engine is a type of aircraft engine that is commonly used in commercial airliners. It is a variation of the basic gas turbine engine, which is also known as a jet engine. Turbofan engines are designed to provide efficient propulsion by generating thrust through the combination of two main components: the core engine and the fan [1]. Exergy analysis, also known as the second law analysis, is a method used in thermodynamics to assess the quality of energy and the efficiency of energy conversion processes. While traditional thermodynamic analysis focuses on the quantities of energy and heat transfer, exergy analysis considers the quality of energy and the potential for useful work [2-4]. Exergy analysis can be employed to assess the performance of gas turbine engines, such as turbofan engines used in commercial aircraft. By analyzing the exergy flows within the engine, it is possible to identify the locations and causes of energy losses and inefficiencies. This information can help in optimizing engine design, improving fuel efficiency, and reducing emissions [5-7].

Some of the studies conducted by researchers on modeling and exergy analysis of jet engines are summarized as follows. Akdeniz et al. [8] performed a comprehensive exergoeconomic and environmental analysis of a turbofan engine. The lowest and highest exergy efficiency of the system components were calculated for the combustion chamber (CC) and high pressure turbine (HPT) as 49.8% and 98.8%, respectively. Turan [9] carried out an exergoeconomic analysis of the commercial CFM56-7B turbofan engine used in Boeing 737. The results of the study show that the maximum exergy flow and maximum exergy cost of the turbofan engine are around 289.8 GJ/h and 5366 $/h, respectively, at HPT. Besides, the total cost of the examined engine was calculated as 394 $/h. Balli [10] studied the sustainability calculations of the high bypass ratio PW4056 turbofan engine based on exergy analysis. When the sustainability indices for the engine's maximum power mode and running power mode were compared, it was emphasized that more sustainable results are obtained in the maximum power mode. In another study, the energy and exergy analysis of a turbofan engine were performed parametrically, as well as the environmental effects of the exhaust gas were evaluated by Aygun and Turan et al. [11]. As a result, CO_2

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emission values were calculated between 1.88 kg/s and 1.5 kg/s according to different altitude cruise conditions. Koruyucu et al. [12] determined the performance parameters of a two-spool turbojet engine model using thermodynamic analysis. As a result of the study, it was stated that when the engine thrust is 516 daN, and the thrust specific fuel consumption (TSFC) rate is about 19.7 g/kN.s. In addition, the authors emphasized that due to high exergy destruction, it is necessary to focus on the CC component to improve the first law and second law efficiency ratios. Dinc et al. [13] analyzed a turboprop engine using environmental, economic and thermodynamic perspective. Exergy recovery potentials were calculated in different flight scenarios. Additionally, it was evaluated how much carbon dioxide emissions were released when maximum SFC occurred. As a result, it was evaluated how environmentally friendly the turboprop engine was and how much exergy efficiency it had in which flight stages. Şöhret et al. [14] examined a three-spool turboprop engine used in a cargo aircraft according to thermal, environmental, and ecological criteria. The engine of the cargo airplane was found to have an exergy efficiency of between 29 and 32%. Additionally, it has been observed that the ecological function is inversely correlated with engine power and energy efficiency. Ekici [15] studied thermodynamic analysis of a turboshaft engine using in agricultural spraying. Performance metrics for each turboshaft engine component were determined and presented. İt was stated that the production of entropy rises as the temperature of the turboshaft's parts rises. Coban et al. [16] performed exergy and economic analysis for a turbojet engine using jet fuel and biofuel. As a result, the exergy efficiency for HPT decreased from 99% to 98.44% when using biofuel. On the other hand, the exergy efficiency of the compressor increased from 74.52% to 75.22%. Besides, the cost rate of thrust is increased by about 16%. Ekici et al. [17] carried out a thermodynamic analysis of an experimental turbojet engine to determine exergy destruction in terms of endogenous and exogenous variables. Endogenous and exogenous exergy destruction rates were calculated as 13.55 kW and 1.59 kW, respectively. Additionally, it has been emphasized that exogenous exergy destruction occurs in the compressor component.

Considering the studies in the literature, it can be seen that exergy analysis has been performed for many turbojet engine models and their efficiency has been examined. The motivation of this study is to thermodynamically analyze the effect of bypass ratio on performance parameters and a commercial turbofan model whose exergy analysis has not been examined before in the literature. In this study, a thermodynamic model is generated for a commercial turbofan engine (CFM56-5A3) used in Boeing A320-212. In addition, an exergy analysis is performed using some exergy performance tools. Exergy performance criteria for engine components are evaluated. Also, how bypass ratio (BPR) affects net thrust and specific fuel consumption (SFC) for the modeled turbofan engine is investigated. The results obtained provide preliminary ideas for the optimization of design parameters for turbofan engine companies.

2. CFM56-5A3 TURBOFAN ENGINE MODELLING

The trial version of the GasTurb 14 software is used for modeling the considered turbofan engine. The software includes models for many types of jet engines. With a user-friendly graphical interface, simple terminology, and no obscure abbreviations, GasTurb is a robust and versatile gas turbine cycle tool for simulating the most popular types of aircraft and power generating gas turbines [18]. A two-spool, unmixed flow, and booster turbofan engine similar to the CFM56-5A3 are selected as the component configuration. The characteristics of the CFM56-5A3 used in Boeing A320-212 are given in Table 1 [19-21].

Table 1. The characteristics of CFM56-5A3

Parameter	Value
Thrust [dry]	117.88 kN
Thrust [cruise]	22.24 kN
Specific fuel consumption (SFC) [cruise]	15.18 g kN^{-1} s^{-1}
Airflow [static]	397.3 kg s^{-1}
Overall pressure ratio (OPR) [static]	27.8
Bypass ratio (BPR) [static]	6
Fan pressure ratio (FPR)	1.55
Cruise altitude	10668 m
Cruise speed	0.8 Mach
Spool number	2
Fan stages	1
Low pressure compressor (LPC) stage	3
High pressure compressor (HPC) stage	9
High pressure turbine (HPT) stage	1
Low pressure turbine (LPT) stage	4
Fan radius	0.865 m
Length	2.423 m
Width	1.829 m
Weight	2266 kg

Figure 1 shows the cycle components of the modeled turbofan engine and station numbers. The turbofan engine consists of a collector, 1 stage fan, 3 stage LPC, 9 stage HPC, 1 stage HPT, 4 stage LPT, a CC, and an exhaust nozzle.

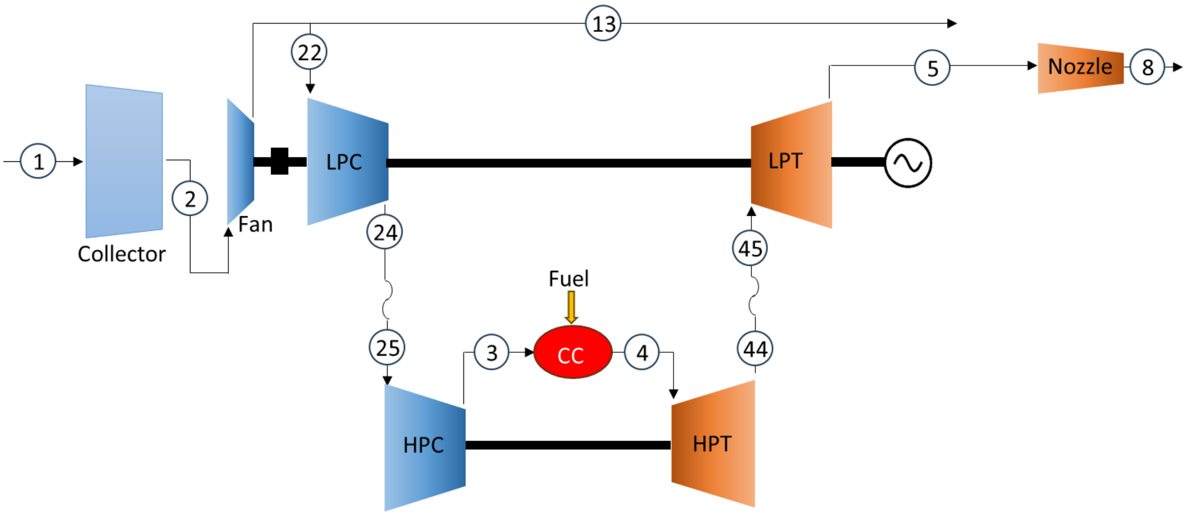

Figure 1. Thermodynamic schematic of the modeled engine

Figure 2 shows the geometric schematic and stations of the modeled turbofan engine. Output parameters are calculated by integrating many input parameters into the model within the framework of catalog information and some assumptions.

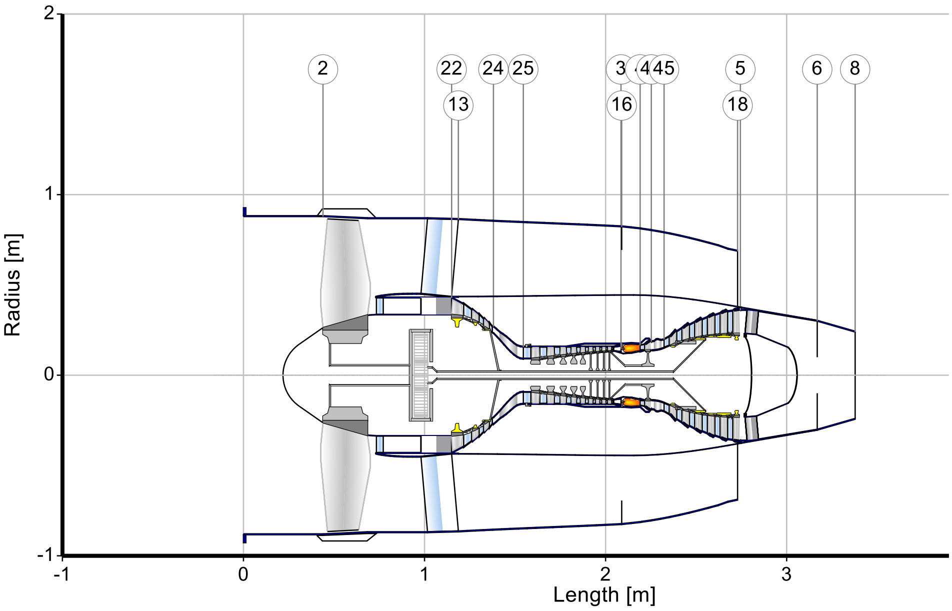

Figure 2. Modelled engine schematic

The following assumptions are taken into account when modeling the turbofan engine.

- Thermodynamic cycle is in a steady state.
- All compressions and expansions are isentropic.
- The ambient air temperature is 218.8 K at an altitude of 10668 m.
- Complete combustion in CC is provided by kerosene fuel with a lower heating value (LHV) of 42800 kJ/kg.
- Assuming no bleed air.
- The modelled engine is adiabatic.
- Engine cooling systems are not considered.

3. ENERGY, EXERGY BASED GOVERNING EQUATIONS

Exergy analysis focuses on the quality of energy and identifies the irreversibilities or losses within a system. The magnetic, electrical, nuclear, potential, and kinetic energy changes for the considered system are ignored while performing the exergy analysis. The physical exergy for all stations, as well as the chemical exergy for CC only, are included in the calculations. When ambient air and exhaust gas are considered as an ideal gas and assuming specific heat is constant, the physical exergy can be written as follows [23-26].

$$\dot{E}_{phy} = \dot{m}\left(c_p(T - T_o) - T_o\left[c_p ln\left(\frac{T}{T_o}\right) - R ln\left(\frac{P}{P_o}\right)\right]\right) \quad (1)$$

The exergy expression of jet fuel is considered as the sum of the physical and chemical exergy values as follows.

$$\dot{E}_f = \dot{E}_{phy,f} + \dot{E}_{chm,f} \quad (2)$$

Considering the fuel as an incompressible fluid, the physical exergy of the fuel is as follows [23-26].

$$\dot{E}_{phy,f} = \dot{m}_f c_{p,f}\left[T - T_o - T_o ln\left(\frac{T}{T_o}\right)\right] \quad (3)$$

The chemical exergy of the considered jet fuel ($C_{12}H_{23}$) can be expressed as an equation dependent on the LHV of fuel and a parameter defined as the exergy degree factor (σ) as follows.

$$\dot{E}_{chm,f} = \dot{m}_f \mathrm{LHV}\sigma \tag{4}$$

σ for $C_{12}H_{23}$ was calculated as 1.0616 by many researchers [8, 10].

The mass, energy, exergy balances for control volumes with steady state flow is as follows [25, 26].
Mass balance equation:

$$\sum \dot{m}_i - \sum \dot{m}_o = 0 \tag{5}$$

Energy balance equation:

$$\sum \dot{m}_i h_i - \sum \dot{m}_o h_o + \dot{Q} - \dot{W} = 0 \tag{6}$$

Exergy balance equation:

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} + \sum_i \dot{m}\psi - \sum_o \dot{m}\psi - \dot{X}_d = 0 \tag{7}$$

Mass, energy and exergy balance for Fan:

$$\dot{m}_2 - \dot{m}_{22} - \dot{m}_{13} = 0 \tag{8}$$
$$-\dot{W}_{fan} + \dot{m}_2 h_2 - \dot{m}_{22} h_{22} - \dot{m}_{13} h_{13} = 0 \tag{9}$$
$$\dot{W}_{fan} + \dot{E}_2 - \dot{E}_{22} - \dot{E}_{13} - \dot{E}_{D,fan} = 0 \tag{10}$$

Mass, energy and exergy balance for LPC:

$$\dot{m}_{22} - \dot{m}_{24} = 0 \tag{11}$$
$$-\dot{W}_{LPC} + \dot{m}_{22} h_{22} - \dot{m}_{24} h_{24} = 0 \tag{12}$$
$$\dot{W}_{LPC} + \dot{E}_{22} - \dot{E}_{24} - \dot{E}_{D,LPC} = 0 \tag{13}$$

Mass, energy and exergy balance for HPC:

$$\dot{m}_{25} - \dot{m}_3 = 0 \tag{14}$$
$$-\dot{W}_{HPC} + \dot{m}_{25} h_{25} - \dot{m}_3 h_3 = 0 \tag{15}$$
$$\dot{W}_{HPC} + \dot{E}_{25} - \dot{E}_3 - \dot{E}_{D,HPC} = 0 \tag{16}$$

Mass, energy and exergy balance for CC:

$$\dot{m}_3 + \dot{m}_f - \dot{m}_4 = 0 \tag{17}$$
$$\dot{m}_3 h_3 + \dot{m}_f LHV \eta_f - \dot{m}_4 h_4 = 0 \tag{18}$$
$$\dot{E}_3 + \dot{E}_f - \dot{E}_4 - \dot{E}_{D,CC} = 0 \tag{19}$$

Mass, energy and exergy balance for HPT:

$$\dot{m}_4 - \dot{m}_{44} = 0 \tag{20}$$
$$\dot{W}_{HPT} + \dot{m}_4 h_4 - \dot{m}_{44} h_{44} = 0 \tag{21}$$
$$-\dot{W}_{HPT} + \dot{E}_4 - \dot{E}_{44} - \dot{E}_{D,HPT} = 0 \tag{22}$$

Mass, energy and exergy balance for LPT:

$$\dot{m}_{45} - \dot{m}_5 = 0 \quad (23)$$
$$\dot{W}_{LPT} + \dot{m}_{45}h_{45} - \dot{m}_5 h_5 = 0 \quad (24)$$
$$-\dot{W}_{LPT} + \dot{E}_{45} - \dot{E}_5 - \dot{E}_{D,LPT} = 0 \quad (25)$$

Many metric parameters have been defined in the open literature to measure the exergy performance of a system. Of these, the exergy efficiency, exergy development potential, exergy destruction ratio, productivity lack ratio, and fuel depletion ratio are selected for the modeled system [27-29].

First of all, the sum of the exergy inlet flows to any component of the system is considered as the fuel exergy ($\dot{E}_F$), and the sum of the exergy outlet flows is considered as the product exergy ($\dot{E}_P$). The exergy efficiency (ψ) is expressed as:

$$\psi = \frac{\dot{E}_P}{\dot{E}_F} \quad (26)$$

The exergy development potential (ϕ) depending on the exergy destruction rate ($\dot{E}_D$), and the exergy efficiency is expressed as follows.

$$\phi = \dot{E}_D(1 - \psi) \quad (27)$$

The exergy destruction ratio (χ) is expressed as the ratio of the exergy destruction rate at a component to the overall exergy destruction rate as follows.

$$\chi = \frac{\dot{E}_D}{\sum \dot{E}_D} \quad (28)$$

The productivity lack ratio (Ω) can be calculated using the following expression to evaluate how much of the product exergy potential is lost due to exergy destruction.

$$\Omega = \frac{\dot{E}_D}{\sum \dot{E}_P} \quad (29)$$

The fuel depletion ratio (φ) is determined using following equation. The equation is calculated as the ratio of the exergy destruction rate of a component to the overall exergy product ratio.

$$\varphi = \frac{\dot{E}_D}{\sum \dot{E}_F} \quad (30)$$

4. RESULTS AND DISCUSSION

4.1. Exergetic Performance Analysis

Thermodynamic modeling is performed for the CFM56-5A3 engine within the framework of the specified assumptions and boundary conditions. The net thrust and SFC values of the modeled engine and the actual engine are compared in Table 2. 14.0% and 7.2% errors occur for net thrust and SFC selected for validation parameters, respectively. Accordingly, the values of the parameters in the model can be used in exergy calculations with an acceptable deviation.

Table 2. Verification of the modeled engine

Components	Net thrust (cruise), [kN]	SFC (cruise), [g kN^{-1} s^{-1}]
The modeled engine	25.86	16.35
The actual engine	22.24	15.18
Error rate (%)	14.0%	7.2%

The sum of the exergy inlet flows to any component of the system is considered as the fuel exergy ($\dot{E}_F$), the sum of the exergy outlet flows is considered as the product exergy ($\dot{E}_P$), and the exergy destruction ($\dot{E}_D$), are calculated for Fan, LPC, HPC, CC, HPT, and LPT as given in Table 3.

Table 3. The exergy rates of the components

Components	$\dot{E}_F$ (W)	$\dot{E}_P$ (W)	$\dot{E}_D$ (W)
Fan	9893705.8	9352643.0	541062.8
LPC	5957677.2	5621098.8	336578.3
HPC	13349251.3	13013100.2	336151.1
CC	32714282.6	26627567.2	6086715.4
HPT	26627567.2	26425821.9	201745.3
LPT	19949752.4	19638881.3	310871.2

Figure 3 represents the variation of the temperature and pressure values at the component stations. The temperature and pressure values at various component stations of a turbofan engine are critical for understanding its performance and efficiency. While the air inlet temperature is -38.5 °C, it reached its maximum value of 1265 °C at the CC outlet. Then it decreased to 517 °C at the LPT outlet. On the other hand, while the air inlet total pressure is 36.4 kPa, it reaches its maximum value of 1742 kPa at the CC outlet. Then it decreased to 92.2 kPa at the LPT output.

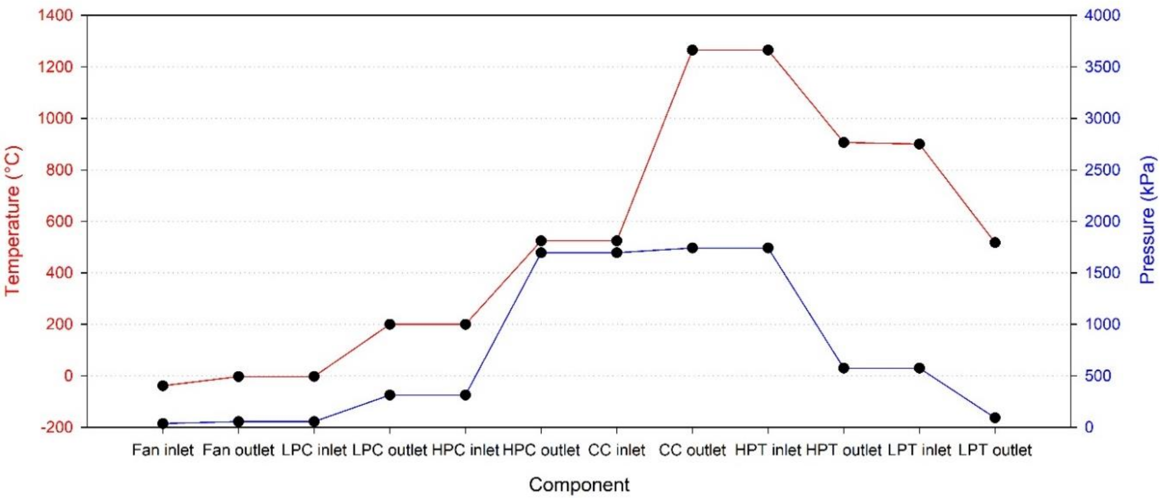

Figure 3. Temperature and pressure values of the components

Exergy efficiency, also known as second-law efficiency, is a measure of how effectively an energy conversion process or system utilizes the available energy, taking into account both the quantity and quality of the energy. The exergy efficineices of Fan, LPC, HPC, CC, HPT, and LPT components are calculated as illustrated in Figure 4. The maximum exergy efficiency occurs at HPT as 0.992. The calculated minimum exergy efficiency is 0.814 for CC.

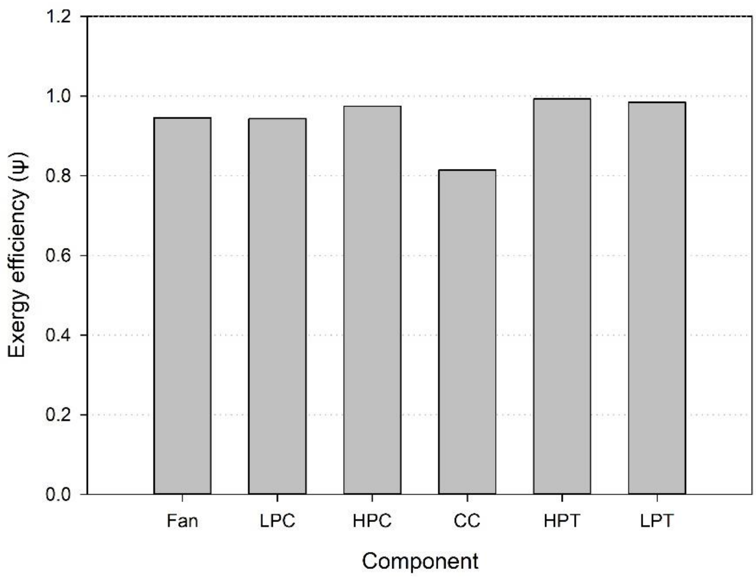

Figure 4. Exergy efficiencies of the components

The exergy development potentials of a turbofan engine represent the opportunities for improving the engine's efficiency by reducing exergy losses and enhancing the useful work output. Analyzing these potentials is a critical aspect of the ongoing efforts to make jet engines more energy-efficient and environmentally friendly. Figure 5 shows the calculated exergy development potentials of Fan, LPC, HPC, CC, HPT, and LPT. CC with a ϕ of 1132 kW appears to have much more exergy development than other components. HPT has the minimum exergy development potential of 1528.5 kW.

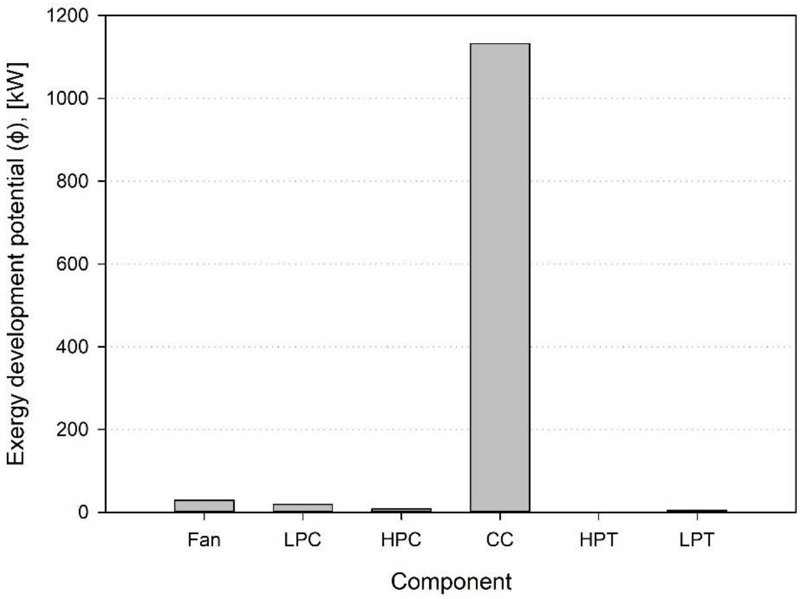

Figure 5. Exergy development potentials of the components

The exergy destruction ratio of a turbofan engine is a measure of how efficiently the engine converts the available energy into useful work while minimizing exergy losses or destruction. Exergy destruction, also known as exergy loss, refers to the wasted energy in a system that cannot be converted into useful work and is typically associated with irreversibilities within the system. Figure 6 depicts the exergy destruction ratios of Fan, LPC, HPC, CC, HPT, and LPT. CC has an exergy destruction value of 0.779. The exergy destruction rates of other components vary between 0.026 and 0.069. These values show that there is much more exergy destruction in CC than in other components.

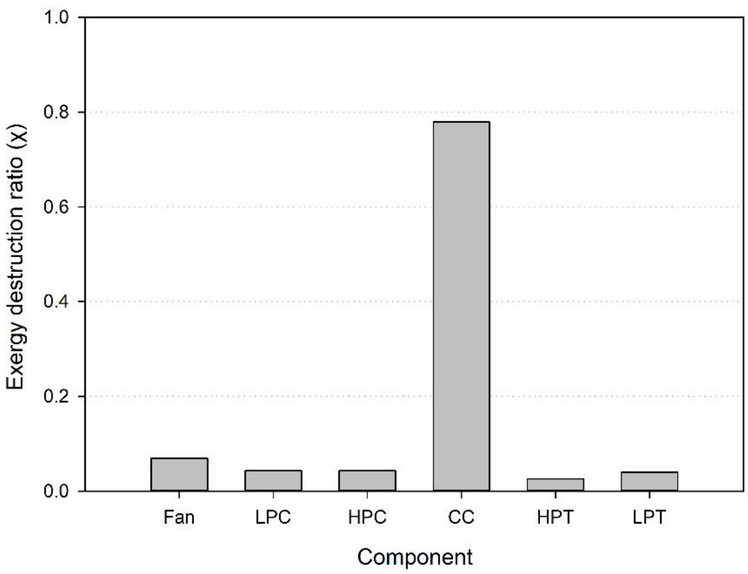

Figure 6. Exergy destruction ratios of the components

The productivity lack ratios are determined for Fan, LPC, HPC, CC, HPT, and LPT as shown in Figure 7. CC has a productivity lack ratio of 0.06. The productivity lack ratios of LPC, HPC, and LPT are approximately 0.003 and are very close to each other. It is understood that HPT has the minimum rate.

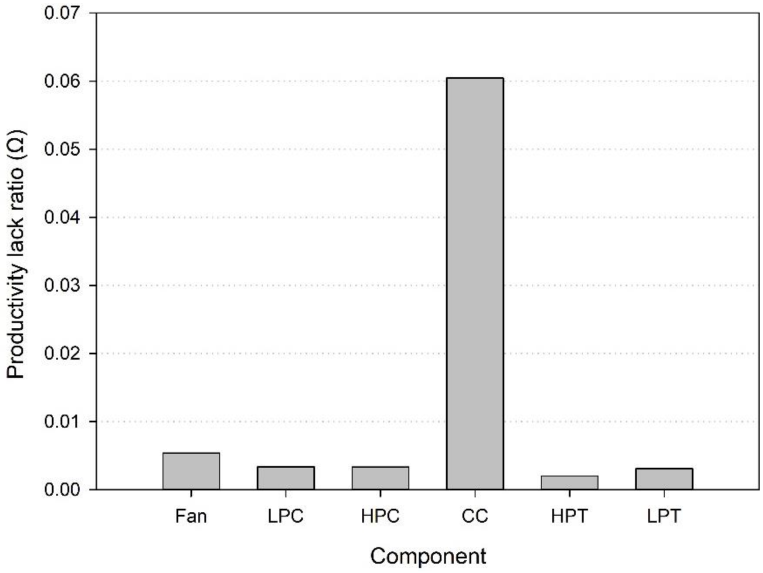

Figure 7. Productivity lack ratios of the components

Figure 8 represents the fuel depletion ratios of Fan, LPC, HPC, CC, HPT, and LPT. CC with a maximum fuel depletion ratio of 0.056 appears to have much greater fuel depletion ratio than other components. The minimum fuel depletion ratio is about 0.002 calculated for HPT. It is seen that Fan has the highest fuel depletion ratio of components other than CC.

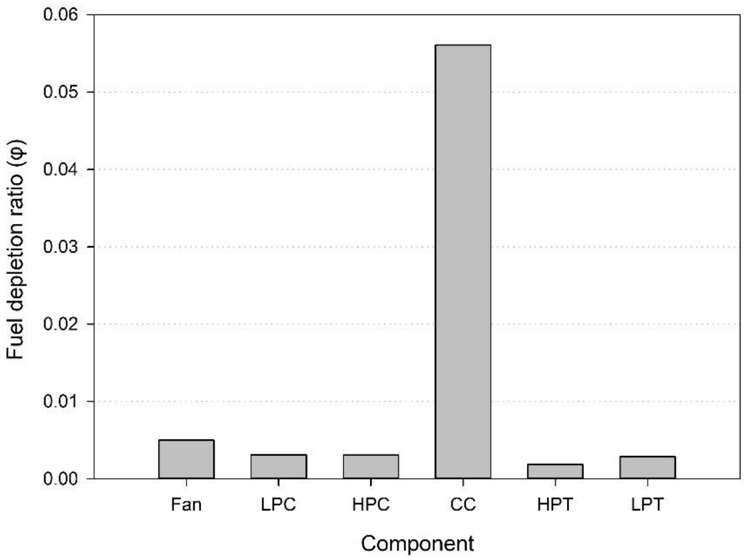

Figure 8. Fuel depletion ratios of the components

4.2. Effect of BPR on Engine Performance

Net thrust and specific fuel consumption (SFC) are indeed critical parameters in the field of aviation and aerospace engineering [30]. These parameters play a crucial role in determining the performance and efficiency of aircraft and other propulsion systems. The net thrust is a crucial performance parameter as it directly affects the aircraft's acceleration, climb rate, and maximum speed. Higher net thrust values generally result in better aircraft performance. On the other hand, SFC is a measure of the fuel efficiency of an aircraft's engine or propulsion system. It represents the amount of fuel consumed per unit of thrust or power produced. A lower SFC value indicates higher fuel efficiency, as it means the engine is producing more thrust or power with less fuel consumption. Fuel efficiency is a critical factor in the aviation industry due to its impact on operating costs and environmental considerations. Figure 9 depicts the net thrust and SFC variation according to BPR for CFM56-5A3 turbofan engine model. As the engine design, which is normally BPR= 6, decreases towards BPR=1, it is seen that the net thrust increases significantly. As the BPR increases towards 10, a less rapid decrease in net thrust is observed. It is also clear that while BPR decreases, SFC also increases parabolically. When BPR is reduced by 1 from 6, net thrust and SFC increases by 141% and 45%, respectively. When BPR increases from 6 to 10, net thrust and SFC decreases by 28% and 12%, respectively.

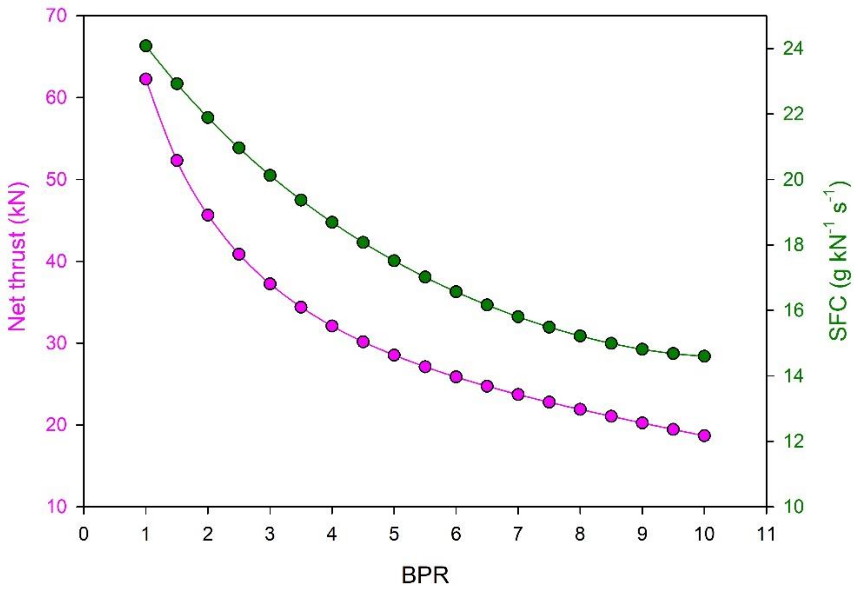

Figure 9. Net thrust and SFC variation relative to BPR

5. CONCLUSIONS

This study presents a thermodynamic model, and exergy analysis for a commercial turbofan engine (CFM56-5A3). Besides, a parametric study is conducted to show how the bypass ratio affects net thrust and specific fuel consumption. The concluding remarks can be summarized as follow,

- The net thrust and SFC values of the modeled engine and the actual engine are compared. 14.0% and 7.2% errors occur for net thrust and SFC selected for validation parameters, respectively.
- The fuel exergy, the product exergy, and the exergy destruction are calculated for Fan, LPC, HPC, CC, HPT, and LPT.
- The air inlet temperature reached its maximum value of 1265 °C at the CC outlet. On the other hand, the air total pressure reaches its maximum value of 1742 kPa at the CC outlet.
- The maximum exergy efficiency occurs at HPT as 0.992.
- HPT has the minimum exergy development potential of 1528.5 kW.

- The productivity lack ratios of LPC, HPC, and LPT are approximately 0.003 and are very close to each other.
- CC with a maximum fuel depletion ratio of 0.056 appears to have much greater fuel depletion ratio than other components.
- When BPR is reduced by 1 from 6, net thrust and SFC increases by 141% and 45%, respectively. When BPR increases from 6 to 10, net thrust and SFC decreases by 28% and 12%, respectively.

The modeling and exergy analysis discussed can be applied to many different jet engines. The effects of many parameters used in the design of jet engines on engine performance can be evaluated in different studies. Optimization studies that evaluate the effects of these parameters on engine performance can also be performed.

Declaration of Ethical Standards

The author declares that the study complies with all applicable laws and regulations and meets ethical standards.

Credit Authorship Contribution Statement

The author contributed to the design and modelling of the system, the analysis of the results and the writing of the manuscript.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Research data has not been made available in a repository.

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