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INVESTIGATION OF THERMODYNAMIC PERFORMANCE OF TURBOFAN ENGINE AT DIFFERENT FAN PRESSURE AND BYPASS RATIOS PART A: ENERGY ANALYSIS

FARKLI FAN BASINCI VE BYPASS ORANLARINDA TURBOFAN MOTORUNUN TERMODİNAMİK PERFORMANSININ İNCELENMESİ BÖLÜM A: ENERJİ ANALİZİ

Emine OĞUR[1] (ORCID:0000-0001-8020-9477)
Ali KOÇ[2]* (ORCID: 0000-0002-7388-2628)
Yıldız KOÇ[2] (ORCID: 0000-0002-2219-645X)
Özkan KÖSE[2] (ORCID: 0000-0002-9069-1989)
Hüseyin YAĞLI[3] (ORCID: 0000-0002-9777-0698)

[1]Iskenderun Technical University, Institute of Graduate Studies, Hatay, Türkiye
[2] Iskenderun Technical University, Department of Mechanical Engineering, Hatay, Türkiye
[3]Gaziantep University, Department of Mechanical Engineering, Hatay, Türkiye

*Sorumlu Yazar / Corresponding Author: Ali KOÇ, ali.koc@iste.edu.tr

ABSTRACT

This research is focused on analysing the thermodynamic performance results of the GE90 turbofan engine with different fan pressures and bypass air ratios. The paper analyses thrust force, thrust efficiency, thrust power, specific fuel consumption, heat input, fuel flow rate, fuel cost rates, emission amount, and cost. Accordingly, the thrust force of the turbofan engine increased as the fan pressure ratio increased, and the highest FBR is obtained as: 1.98 = 573.98 kN. While the highest thrust efficiency value is obtained at 37.22% at the FPR:1.66-BPR:7.4 ratios, the energy efficiency reached its maximum at 45.91% at the same values at the FPR:1.66-BPR:7.4 ratios. At the same rates, specific fuel consumption is calculated as 27.87 kg/kN.h, with its lowest value. The emission release amount of the turbofan engine and the cost of this amount are 49.48 tonCO_2/h and 74.21 \$/tonCO_2.h at the highest FPR:1.98-BPR:4.4 rates.

Keywords: turbofan, pressure ratio, energy, economy, emission

ÖZET

Bu araştırma, farklı fan basınçları ve baypas hava oranları ile GE90 turbofan motorunun termodinamik performans sonuçlarının analizine odaklanmıştır. Analizde itme kuvveti, itme verimliliği, itme gücü, özgül yakıt tüketimi, ısı girişi, yakıt akış hızı, yakıt maliyet oranları, emisyon miktarı ve maliyet analiz edilmiştir. Buna göre, turbofan motorunun itme kuvveti, fan basınç oranı arttıkça artmış ve en yüksek FBR; 1,98 = 573,98 kN olarak elde edilmiştir. En yüksek itme verimliliği değeri FPR:1,66-BPR:7,4 oranlarında %37,22 ile elde edilirken, enerji verimliliği aynı değerlerde FPR:1,66-BPR:7,4 oranlarında %45,91 ile maksimum değerine ulaşmıştır. Aynı oranlarda özgül yakıt tüketimi en düşük değeri ile 27,87 kg/kN.h olarak hesaplanmıştır. Turbofan motorunun emisyon salınım miktarı ve bu miktarın maliyeti en yüksek FPR:1.98-BPR:4.4 değerlerinde 49.48 tonCO_2/h ve 74.21 \$/tonCO_2.h olarak gerçekleşmektedir.

Anahtar Kelimeler: turbofan, basınç oranı, enerji, ekonomi, emisyon

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INTRODUCTION

The most general operating principle of turbofan engines is to produce kinetic energy by burning the air/fuel mixture. This kinetic energy is converted into power in the turbine and creates the necessary thrust force for the aircraft (Liew, 2005). The most costly part of air transportation for airline companies comes from fuel. Costs for airline companies are increasing, especially for commercial aircraft that transport passengers and cargo on long-distance flights. Engineers and researchers are conducting many studies to improve engine performance by investigating the factors affecting the amount of fuel in turbofan engines (Dankanich and Peters, 2017). The main aim of aircraft design companies and scientists in these studies is to create a higher thrust force with lower specific fuel consumption. This means being able to produce maximum engine performance with lower fuel flow. Reducing fuel consumption is an important parameter not only for economic reasons but also to reduce the amount of emissions released into the environment. Additionally, the aircraft uses a smaller fuel tank with reduced fuel consumption. Accordingly, aircraft weight decreases, and a smaller engine may be needed. This reduces both noise and operating costs. Important thermodynamic values to increase the thermodynamic performance of an aircraft are thrust efficiency, thermal efficiency, and specific fuel consumption. In many studies, studies are carried out with parameters such as bypass air ratio (BPR), fan pressure ratio (FBR), high-pressure compressor pressure ratio (HPCPR), turbine inlet temperature (TIT) and Mach number (Ma), which have been determined to greatly affect these values (Xue et al., 2019). To increase thrust efficiency, engineers are trying to reduce the kinetic energy of the burned gas by providing a higher bypass air. However, these studies are limited in terms of today's engine technology and aircraft body weight. To increase thermal efficiency, they have approached making the material durability of high-pressure turbine blades suitable for high temperatures. However, this situation is limited in terms of material properties (Andriani, et al., 2022). There are many studies in the literature with similar results. Some of these are those Sabzehali et al. (2022) in a fighter plane examined the effect of Mach number on air mass flow rate, thrust force, thrust efficiency, specific fuel consumption, and exergy efficiency. For this purpose, they made a mathematical cycle model of the F135 PW100 engine. In the first stage, the authors determined the Mach number to be 2.5 and the flight distance to be 30000 m to enable supersonic aircraft to fly at high altitudes and to use hydrogen fuel to create a high thrust force. Accordingly, they are calculated for specific fuel consumption, thrust efficiency, thrust force, and exergy efficiency. Fan pressure ratio, bypass air ratio, turbine inlet temperature, and pressure ratio of the high-pressure turbine are used in the calculations. According to the results, the error rate is 5.02% in thrust force, 1.43% in specific fuel consumption, and 2.92% in exergy efficiency. Xue et al. (2019) examined the effect of fan pressure ratio and bypass air on Trent-XWB turbofan engine performance. The results are determined by first changing the bypass air and then the fan pressure air on the same engine. They determined that by changing the bypass ratios, they could obtain a high thrust force with a lower specific fuel consumption. However, the authors drew attention to drawbacks such as friction and aircraft weight during the design phase. Najjar et al. (2015) determined the turbine inlet temperature and compressor pressure as variables in a turbojet engine and argued that these variables affect thrust and specific fuel consumption. They have used a computer program called General Algebraic Modeling System (GAMS) in the calculations. They determined that the turbine inlet temperature significantly affected the specific fuel consumption and that there was a 10% decrease in the turbine inlet temperature. They calculated that specific fuel consumption decreased by 6.8% and thrust decreased by 6.7%. They showed that the compressor pressure ratio decreased by 11.43%. Under the operating conditions of the Turbojet engine at an altitude of 13000 m, Ma = 0.8 and turbine inlet temperature of 1700 K, the most appropriate compressor rust ratio is obtained as 14. Yucer. (2016) Exergy and energy analyses of the turbojet engine are carried out in a laboratory environment at different loads: idle, partial load, two partial loads, and full load. Parameters such as energy efficiency, specific fuel consumption, exergy destruction, and exergy recovery rate are examined separately under the influence of these four loads. According to the results, it reaches its maximum with values of 79.4% at partial load and 67.8% at idle load. The maximum value of exergy efficiency in the combustion chamber at full load is determined as 80.6%, and at partial load, two is determined as 81%. The exergy destruction rate in the combustion chamber, where the exergy loss is highest, is presented in the article as 35 kW at idle, 40.3 kW at partial load, 36.6 kW at partial load, and 47.9 kW at full load. Su et al. (2022) examined the thermodynamic analysis of a turbojet engine, a kerosene-fueled turbofan engine, and a hybrid turbofan engine at different pressure ratios. Parameters such as thrust force, energy efficiency, and fuel flow are examined. Two methods were tried in the study. In the first method, the combustion chamber pressure ratio was examined by keeping the total pressure constant. It was observed that the thrust force gave better results if the fuel consumption was reduced below 30% at high pressure. In the second method, the combustion chamber pressure ratio was examined by keeping the compressor pressure constant. In this section, the fuel flow rate was reduced by 20% or more, and thus, it was reported that lower energy was provided with higher thrust force. Zaid et al. (2018) An extensive literature study on the development process of the turbofan engine is presented. The authors then created software in the MATLAB program for the parameters that determine the performance analysis of the Rolls-Royce Trent 1000-A turbofan engine. The study wanted to determine the pressure ratio that would obtain maximum thrust, thrust, and energy efficiency with less specific fuel consumption by changing the fan pressure ratio, bypass ratio, Mach number, and turbine inlet temperature, based on take-off and cruise situations. Dankanich and Peters. (2017) investigated how changing the bypass ratio would affect the thermodynamic performance of a high-bypass turbofan engine. In addition, a low bypass turbofan engine consuming the same fuel was compared with a high bypass engine. A mathematical model was created, and calculations were made on this. It was shown how SFC decreases with increasing bypass ratio. Fuel costs were calculated accordingly. The range of BPR=0-12, turbine temperature, and compressor pressure ratio were kept constant. While the thrust force was 30,000 lbf at BPR=0, the thrust force was obtained as 60,000 lbf at BPR=12. SFC decreases as BPR increases. These values were calculated as 1.316 at BPR=0 and =0.695 at BPR=12. Fuel costs for the turbojet engine were calculated as 6.78 $/h. The actual fuel cost for this 5-hour flight is $71,640, while the engine cost is $122,040. Akdeniz and Balli. (2021a). examined the exergic analysis of the turbofan engine used in the JT3D-3B military aircraft with varying bypass air. They change it in the range of BPR = 1.30-145. According to the results, the highest energy efficiency is calculated as 27.93% at BPR = 1.45, and the lowest is 26.97% at BPR = 1.30. By increasing the bypass ratio by 0.04 in the range of 135 -1.45, the energy and exergy efficiency and exergy destruction rate increased, while the exergy improvement potential, fuel exergy waste rate, and efficiency deficiency rate decreased. The authors argued that the study will contribute to the future turbofan engine design.

When the studies in the literature were analysed, there were limited studies on analysing the effect of fan pressure ratio and bypass air on the system performance. Also, it was observed from the literature that there is a need for a comprehensive analysis of the effect of fan pressure on specific fuel consumption. In addition to all these, considering emission together with performance-affecting parameters will be a key study for the literature. This article examines how the thermodynamic performance of a turbofan engine is affected when the fan pressure ratio and bypass air of a turbofan engine change. In addition, the effect of the change in fan and bypass pressure ratios on the specific fuel consumption and thrust force of the kerosene-fueled turbofan engine is observed. Then, the effect of the change in pressure ratio on emissions and emission costs is evaluated. As a result of the analysis, the best FBR and BPR rates and their environmental impact are examined.

SYSTEM DESCRIPTION

GE Aviation'ın aldığı GE90 turbofan motoru, 2 motorlu, baypas havası oranı: 8.4, itme gücü 375.30 kN olan yüksek bypasslı ticari bir uçak motorudur. The turbofan engine is an axial flow turbofan engine consisting of a fan drawing 1350 kg of air flow, a 3-phase low-pressure compressor, a 10-phase high-pressure compressor, a 2-phase low-pressure turbine, and a 6-phase high-pressure turbine. These engines stand out as environmentally friendly engines with low fuel consumption, high efficiency, quiet operation of the fan, and low carbon emissions (General Electric, 1997). Engine data of the turbofan engine obtained from the literature are presented in Table 1.

Table 1. GE90 Turbofan Engine Specifications (General Electric, 1997; EASA, 2019)

Thrust force	375.30 kN	HPT inlet temperature	1592 K
Bypass air rate	8:4	SFC	7.91 mg/Ns
Engine Total Pressure ratio (OPR)	39.97	Compressor isentropic efficiency ($\eta_{s,c}$)	0.91
LPC pressure ratio (Pr)	1.10	Turbine isentropic efficiency ($\eta_{s,t}$)	0.93
HPC Pressure ratio (Pr)	23	Mechanical efficiency ($\eta_{s,m}$)	0.99
Fan pressure ratio (Pr)	1.58	Fuel combustion efficiency ($\eta_{s,cc}$)	0.99
Air mass flow	1350 kg/s	Combustion pressure loss (ΔP_{fd})	0.05
Fuel flow	2.968 kg/s	Isentropic nozzle efficiency ($\eta_{s,n}$)	0.95
Fan isentropic efficiency ($\eta_{s,f}$)	0.93		

A simplified schematic diagram and parameter descriptions of the turbofan engine are given in Figure 1.

Mathematical Modeling

The first law of thermodynamics is taken as the basis for the in terms of thermodynamic study of turbofan engines. Atmospheric conditions are acceptable for gas turbine engines, which are a closed system. The cycle analysis of each component for the simplified turbofan engine shown in Figure 1 is presented below (Akdeniz, 2021b; Arslan, 2022; Artaş, 2023; Balli, 2017; Coban, 2017; Çengel, 2011; Çoban, 2018; Ekrataleshian, 2020; Fetahi, 2020; Küçük, 2023; Oğur, 2023; Ping, 2021; Sürer, 2024; Yapicioglu, 2018);

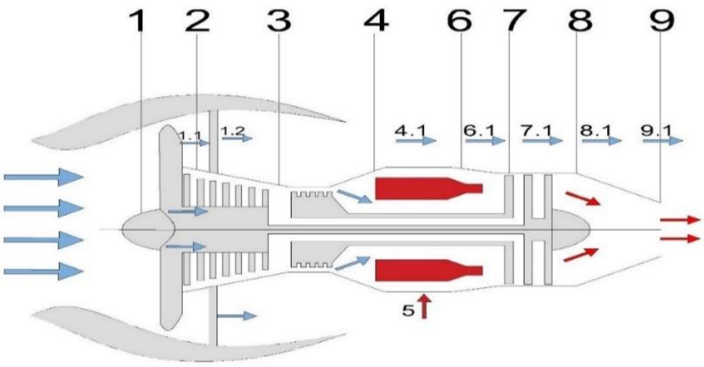

Figure 1. Cutaway Diagram of GE90 Turbofan Engine

<u>Fan (1-2)</u>;

$$T_1 = T_{atm} \tag{1}$$

$$P_1 = P_{atm} \tag{2}$$

$$T_2 = T_1 * Pr^{\frac{k-1}{k}} \tag{3}$$

$$P_2 = P_1 * Pr_{fan} \tag{4}$$

$$T_2 = T_{1.1} \qquad P_2 = P_{1.1} \tag{5}$$

$$\dot{W}_{FAN} = \dot{m}_1 * (Cp_2 * T_2 - Cp_1 * T_1) \tag{6}$$

<u>Fan Duct (1.1-1.2)</u>;

$$P_{1.2} = P_{1.1} * (1 - \Delta P_{fd}) \tag{7}$$

$$T_{1.2} = T_{1.1} * (\frac{P_{1.2}}{P_{1.2}})^{\frac{k-1}{k}} \tag{8}$$

<u>Low-Pressure Compressor (2-3)</u>;

$$T_3 = [1 + \left(\frac{Pr^{\frac{k-1}{k}} - 1}{\eta_{s,c}}\right)] * T_2 \tag{9}$$

$$P_3 = P_2 * Pr_{lpc} \tag{10}$$

$$\dot{W}_{LPC} = \dot{m}_2 * (Cp_3 * T_3 - Cp_2 * T_2) \tag{11}$$

<u>High-Pressure Compressor (3-4)</u>;

$$T_4 = [1 + \left(\frac{Pr^{\frac{k-1}{k}} - 1}{\eta_{s,c}}\right)] * T_3 \tag{12}$$

$$T_4 = T_{4.1}; P_4 = P_{4.1} \tag{13}$$

$$P_4 = P_3 * Pr_{hpc} \tag{14}$$

$$\dot{W}_{HPC} = \dot{m}_3 * (Cp_4 * T_4 - Cp_3 * T_3) \tag{15}$$

Combustion chamber (4-6-5F);

$$\dot{Q} = [(\dot{m}_6 * Cp_6 * T_6 + (\dot{m}_{6.1} * Cp_{6.1} * T_{6.1})] - [(\dot{m}_4 * Cp_4 * T_4 + (\dot{m}_{4.1} * Cp_{4.1} * T_{4.1})] \tag{16}$$

$$\dot{Q} = \dot{m}_5 * LHV * \eta_{s,cc} \tag{17}$$

$$\mathrm{P}_6 = \mathrm{P}_4 * (1 - \Delta\mathrm{P}_{\mathrm{fd}}) \tag{18}$$

$$P_6 = P_{6.1} \tag{19}$$

High Pressure Turbine (6-7);

$$T_7 = T_6 - \left(\frac{\dot{W}_{HPC}}{\dot{m}_6 * Cp_6 * \eta_{s,m}}\right) \tag{20}$$

$$P_7 = P_6 * \left(1 - \left(\frac{T_6 - T_7}{T_6}\right) * \left(\frac{1}{\eta_{s,t}}\right)^{\frac{kg}{kg-1}}\right) \tag{21}$$

$$T_7 = T_{7.1} \qquad P_7 = P_{7.1} \tag{22}$$

$$\dot{W}_{HPC} = \dot{W}_{HPT} * \eta_{s,m} \tag{23}$$

Low Pressure Turbine (7-8);

$$T_8 = T_7 - \left(\frac{\dot{W}_{LPC}}{\dot{m}_7 * Cp_7 * \eta_{s,m}}\right) \tag{24}$$

$$P_8 = P_7 * \left(1 - \left(\frac{T_7 - T_8}{T_7}\right) * \left(\frac{1}{\eta_{s,t}}\right)^{\frac{kg}{kg-1}}\right) \tag{25}$$

$$T_8 = T_{8.1} \qquad P_8 = P_{8.1} \tag{26}$$

$$(\dot{W}_{LPC} + \dot{W}_{FAN}) = \dot{W}_{LPT} * \eta_{s,m} \tag{27}$$

Exhaust Duct (8-9);

$$\mathrm{T}_9 = \mathrm{T}_8 \tag{28}$$

$$\mathrm{P}_9 = \mathrm{P}_8 * (1 - \Delta\mathrm{P}_{\mathrm{ed}}) \tag{29}$$

If the exhaust duct is choked, the pressure ratio is calculated as follows;

$$P_{ch} = \left(\frac{k_g + 1}{2}\right)^{\frac{k_g}{k_g - 1}} \tag{30}$$

$$P_{9s} = \frac{P_9}{P_{ch}} \tag{31}$$

Here, P_{9s} is the exhaust duct outlet static pressure. If $\frac{\mathrm{P}_9}{\mathrm{P}_{\mathrm{atm}}} > \mathrm{P}_{\mathrm{ch}}$, the exhaust duct is choked. Thus, the output becomes Mach=1. Accordingly, the static temperature is expressed as follows;

$$T_{9s} = \left(\frac{T_9}{1 + \frac{k_g - 1}{2}}\right) \tag{32}$$

Cp values of exhaust gas and air temperature at the inlet and outlet points of turbofan engine components are calculated as follows;

$$C_{12}H_{23} + \delta\left(17.75 * (O_2 + 3.762N_2)\right) \rightarrow 12CO_2 + 11.5H_2O + (\delta - 1) * (17.75O_2) + \delta * 17.75 * 3{,}762N_2 \quad (33)$$

The kerosene combustion equation given above includes %75.76 N_2, %4.65 CO_2, %13.29 O_2, and %6.30 H_2O. Depending on the gas percentages in the fuel component of kerosene fuel, the specific heat capacity values of air and fuel are determined according to the equations taken from (Çengel, 2011)

$$C_p = a + bT + cT^2 + dT^3 \quad (34)$$

The specific heat capacity of air is shown by the following equation (Oğur, 2023);

$$C_{p.air=}1.04841 - \left(\frac{3.83719.T}{10^4}\right) * \left(\frac{9.45378T^3}{10^7}\right) - \left(\frac{5.49031T^2}{10^{10}}\right) + \left(\frac{7.92981T^4}{10^{14}}\right) \quad (35)$$

The following formula is used to calculate thrust force in turbofan engines (Ballı and Çalışkan, 2021b);

$$ET = \dot{m}_{1.2} * (V_{1.2} - V_1) + (\dot{m}_9 + \dot{m}_{9.1}) * (V_9 - V_1) + A_{1.2} * (P_{1.2} - P_1) + A_9 * (P_9 - P_1) \quad (36)$$

The thrust force is written with the following formula (Akdeniz and Ballı, 2021a);

$$\dot{W}_p = ET * V_1 \quad (37)$$

Thrust efficiency, which has a significant impact on determining the performance of the turbofan engine, is expressed as follows (Oğur, 2023);

$$\eta_{ET} = \frac{\dot{W}_p}{\dot{Q}_{in}} \quad (38)$$

The energy efficiency of a turbofan engine expresses the ratio of kinetic energy to heat input and is written as follows (Akdeniz, 2021a; Ballı, 2017; Andriani, 2011; Tiwari, 2024);

$$\eta_{th} = \frac{\dot{W}_p + E_{KN}}{\dot{Q}_{in}} \quad (39)$$

$$E_{KN} = \dot{m}_1 * \frac{V_1^2}{2} \quad (40)$$

Specific fuel consumption is the amount of fuel consumed per unit thrust force and is an important parameter for businesses. Specific fuel consumption is expressed as follows (Yüksel, 2020; Ballı, 2021b);

$$SFC = \frac{\dot{m}_5}{ET} \quad (41)$$

Energetic and exergic fuel costs are calculated as follows (Ekrataleshian, 2020; Aygün, 2020; Atilgan, 2020; Dişlitaş, 2021;Ballı, 2021b; Kocaman, 2022; Köse, 2021; Oğur, 2024);

$$C_{en} = PR * \dot{m}_f * 3600 * \lambda \quad (42)$$

$$C_{ex} = \frac{C_{en} * LCV}{ex_{fuel}^{ch} * \lambda} \quad (43)$$

$$ex_{fuel}^{-ch} = -(AG)_f + \sum_P n_k(ex_{k,P}^{-ch}) - \sum_R n_k(ex_{k,R}^{-ch} \quad (44)$$

$$\Delta G_{fuel} = \sum_P \dot{n}_{k,P} \Delta g_{fuel,k,P} - \sum_R \dot{n}_{k,R} \Delta g_{fuel,k,R} \quad (45)$$

Emission gases, which contribute greatly to global warming, have been the subject of many studies in the aviation sector, as in all sectors. Engine companies have made advances to reduce emissions. But these are still insufficient. Some formulas obtained from the studies are presented below (Caliskan, 2015; Kanbur, 2018; Koc, 2020; Tuzcu, 2020; Atilgan, 2020; Dişlitaş, 2021; Ballı, 2021b; Köse, 2021; Oğur, 2025a, Oğur, 2025b).

$$XCO_2 = YCO_2 * \dot{m}_5 \tag{46}$$

Cost of the amount of carbon released by the fuel ($\mathrm{CCO_2}$);

$$\mathrm{CCO_2} = \mathrm{XCO_2} * \mathrm{NCO_2} \tag{47}$$

$\mathrm{NCO_2}$ is Turkey's CO_2 price per ton and is accepted as 1.5$ (Kyoto Protocol).

RESULTS AND DISCUSSIONS

This article aims to investigate the changes in the performance of a turbofan engine using kerosene fuel by changing the fan pressure ratio in the range of 1.26-1.98 and the bypass air ratio in the range of 4.4-11.6. In the study, firstly, mathematical modeling is made for the thermodynamic analysis of the GE90 turbofan engine using data obtained from the literature. In the first stage, thrust force, thrust efficiency, specific fuel consumption, thrust power, energy efficiency, heat input, and fuel flow rate are calculated. Then, fuel costs, environmental impact, and its cost to the business, which are important for businesses, are examined. These results are presented in Table 2. In the last stage of the study, the fan pressure ratio and bypass air ratio are changed in the above-mentioned ratios, and the results are compared with the calculated values obtained from the engine's literature data. Accordingly, the graphs of the thrust efficiency, thrust force, and specific fuel consumption of the turbofan engine are presented in Figure 2.

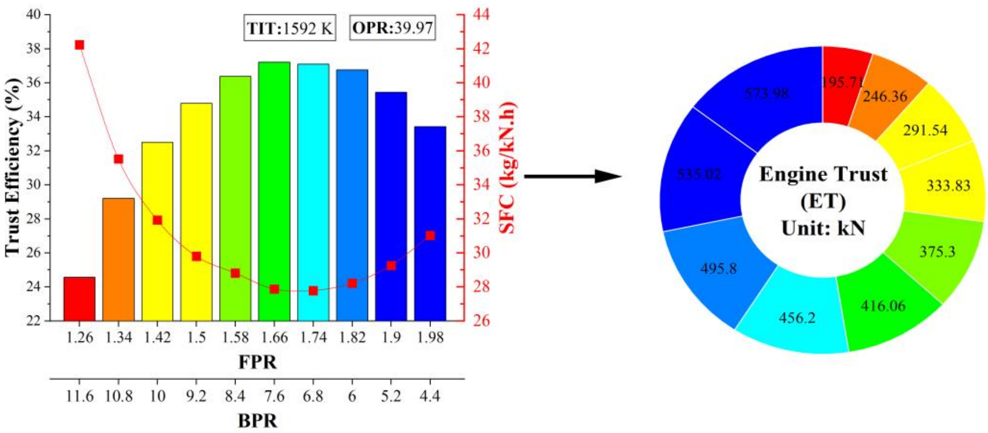

Figure 2. Change in Specific Fuel Consumption, Thrust Efficiency and Thrust of the Turbofan Engine

Fan pressure ratio is obtained by dividing the ratio of the highest pressure to the lowest pressure of the general pressure ratio, which expresses the part from the fan inlet to the outlet of the high-pressure compressor. Fan pressure ratio is an important parameter in turbofan engines. Because the suction pressure decreases in a small diameter fan, it draws in less air. The fan pressure ratio increases, and the speed of the air fluid increases. However, in a large diameter fan, a lower fan pressure ratio is achieved with a higher air flow rate. This is where bypass air comes into play. Approximately 80% of the thrust force is provided by bypass air. Another 10% is used to cool the engine core. To move a large amount of air, the fan needs the fan blades to rotate at a higher speed, which creates high tension on the blades and causes friction. Another negative effect is that as the fan diameter increases, the weight of the fan increases. As seen in Figure 2, as the fan pressure ratio increased, the thrust force increased. However, thrust efficiency does not increase in the same way. While the highest thrust efficiency of 37.22% is achieved at the ratios FPR:1.66-BPR:7.6, the thrust force at this point is calculated as 416.06 kN. After this value, thrust efficiency decreased with increasing fan pressure ratio. After this value, thrust efficiency decreased with increasing fan pressure ratio. While the highest thrust force is obtained as 573.98 kN at the FPR:1.98 BPR:7.6 ratios, the thrust efficiency decreased to 33.43%. Bypass air is an important parameter in specific fuel consumption. While the specific fuel consumption reaches its highest value of 42.23 kg/kN.h at the ratios of FPR:1.26-BPR:11.6, the decrease at this point is the high energy consumption to provide the decreasing thrust force as a result of the low fan pressure ratio. In the study, the most ideal specific fuel consumption is calculated as 27.87 kg/kN.h with the ratios FPR:1.66-BPR:7.6. In high bypass air, it uses a higher amount of air around the engine, using less air for expansion within the engine core. It is more suitable for specific fuel consumption due to the combination of less fuel flow and more air flow. Thrust force can be produced from the sum of a higher air flow rate and a lower fuel flow rate. The thrust power and energy efficiency results of the turbofan engine are presented in Figure 3.

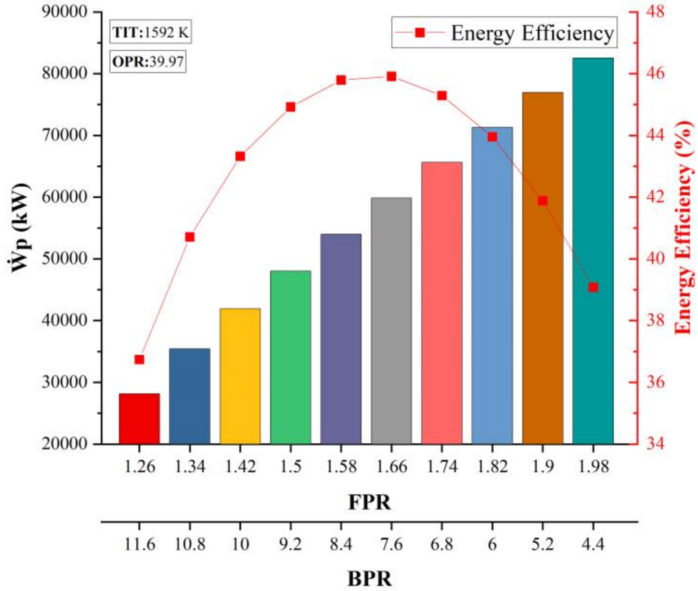

Figure 3. Thrust Power and Thermal Efficiency Change of the Turbofan Engine

In the thrust power and energy efficiency values presented in Figure 3, the highest thrust power is calculated as 82546.5 kW at the ratios FPR: .98-BPR:4.4. As the fan pressure ratio increased, the thrust power increased. While the energy efficiency reached the highest value with 45.91% at the ratios of FPR: 1.66-BPR:4.4, it started to decrease after this value as the BPR decreased. Bypass air has a high impact on energy efficiency. While most of the bypass air is used for thrust force, some of it passes through the engine combustion chamber and turbine blades, allowing the engine to cool, thus providing a higher efficiency. However, as the fan diameter increases, friction occurs on the end surfaces of the blades as a result of the increase in rotation speed. This has a limited increasing effect on efficiency. The fuel flow rate and heat input results of the turbofan engine are presented in Figure 4.

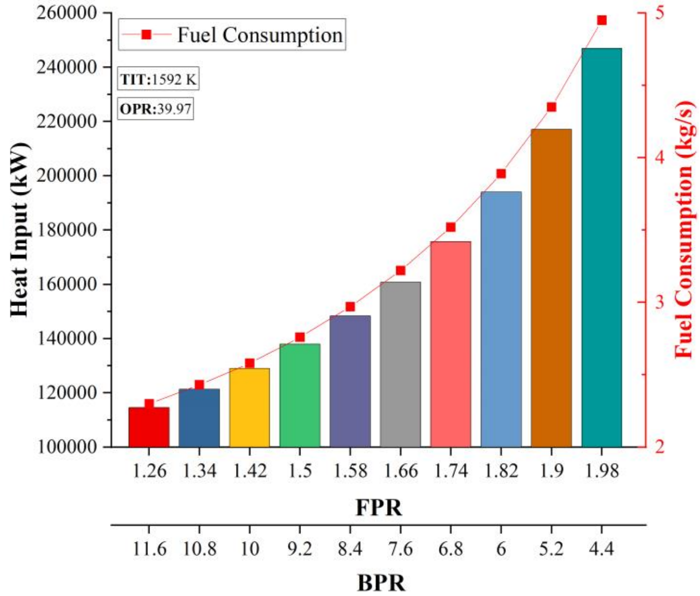

Figure 4. Heat Input and Fuel Flow Change of the Turbofan Engine

The heat input and fuel flow rate presented in Figure 4 increased with the increase of the fan pressure ratio. Accordingly, it is calculated as 246959.62 kW at the highest FPR:1.98-BPR:4.4 ratios. The fuel flow rate calculated based on heat input increased in the same direction as the fan pressure ratio increased. These values are highest at 4.95 kg/s at FPR:1.98-BPR:4.4 rates and lowest at 2.30 kg/s at FPR:1.26-BPR:11.6 rates. Although increasing the fan pressure ratio increases the amount of heat produced, this situation has negative aspects. A higher fan housing means a higher fan speed. This requires a higher turbine body due to the low-pressure turbine shaft to which it is connected. There is a certain limit to both the composite fan blade material and the turbine blade materials that will produce high power. This situation is not compatible with the engine design. The results of the energetic and exergetic fuel cost ratios determined according to the fuel flow rate of the turbofan engine are presented in Figure 5.

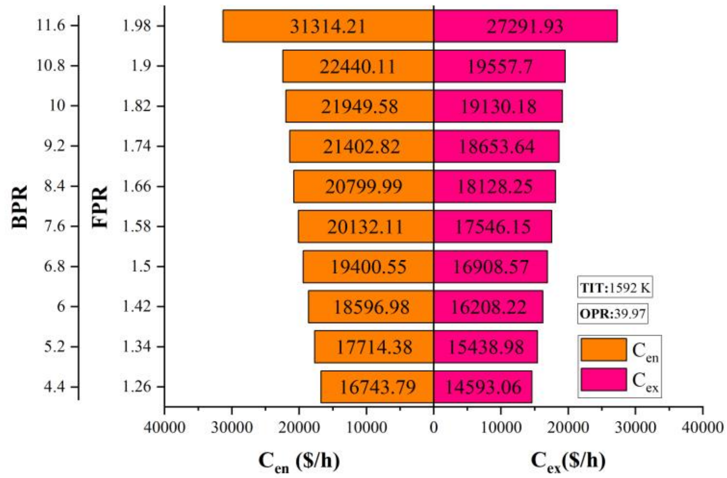

Figure 5. Energetic and Exergetic Fuel Cost Variation of the Turbofan Engine

As seen in Figure 5, as the fan pressure ratio increases, fuel cost also increases due to the increasing fuel flow rate. The highest fuel cost is calculated as C_{en}: 31314.21$/h and C_{ex}: 27291.93$/h at the rates FPR:1.98-BPR:4.4. The lowest values are obtained as C_{en}:16743.79$/h and C_{ex}:14593.06$/h at the rates FPR:1.26-BPR:11.6. As the fan pressure ratio increases, higher engine power and therefore higher heat production is required. Considering today's fuel costs, high values are a great burden for businesses. Increasing fan diameter is also a negative factor in that it increases fuel costs. The calculated emission release amount, depending on the fuel flow rate of the turbofan engine and the cost of this released emission amount, is presented in Figure 6.

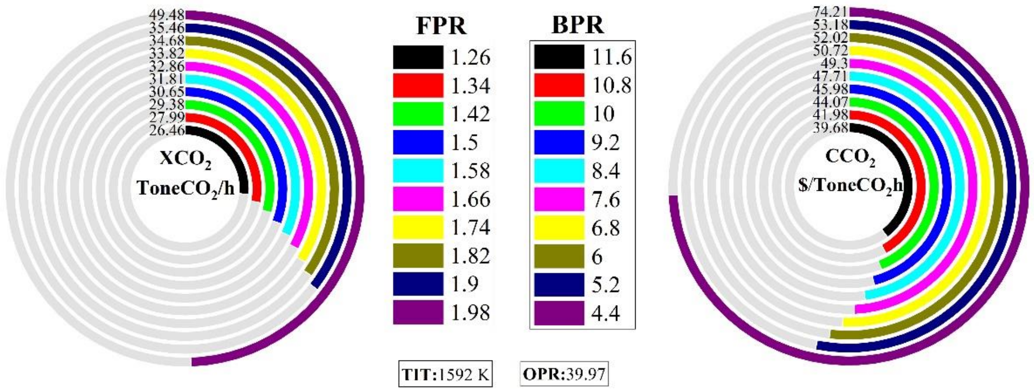

Figure 6. Change in Emission Amount and the Emission Cost of the Turbofan Engine

As seen in Figure 6, the amount of emissions sent to the atmosphere from a kerosene-fueled turbofan engine increases with the increase in the fan pressure ratio. The highest value is calculated as 49.48 tonCO_2/h and 74.21 $/ton$CO_2$.h in the ratios of FPR:1.98-BPR:4.4. The lowest emission release amount and cost at FPR:1.26-BPR:11.6 rates are calculated as 26.46 tonsCO_2/h and 39.68 $/ton$CO_2$.h.Considering the damage that greenhouse gases cause to the planet and living things, all businesses and researchers accept how important it is to reduce these gases and are working on reducing them. There are certain limits for increasing or decreasing the fan pressure ratio and bypass air. Taking these values into consideration, businesses and engineers make their calculations. The change in exhaust gas outlet temperature depending on the fan pressure ratio and bypass air change of the turbofan engine is presented in Figure 7.

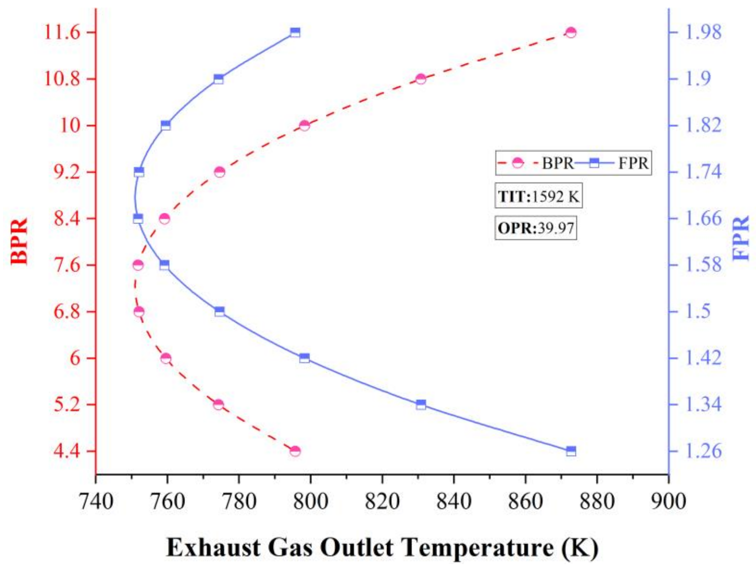

Figure 7. Exhaust Gas Outlet Temperature Change of the Turbofan Engine

As seen in Figure 7, the exhaust gas outlet temperature decreased with the increase of the fan pressure ratio. The highest value is obtained as 872.74 K at the ratios FPR:1.98-BPR:4.4. The lowest value is 751.8 K at the rates FPR:1.74-BPR:7.6 has been calculated. Depending on the fan pressure ratio reduced to increase the bypass air, the pressure ratio of the high-pressure compressor increases. This ensures that the air and fuel flow entering the combustion chamber are mixed in better proportions. This high pressure occurring in the combustion chamber increases the expansion of the burned gas and converts a higher amount of the enthalpy of this gas into kinetic energy, allowing the engine to operate at a high efficiency. This also causes the exhaust gas to exit the exhaust duct at a higher speed, thus creating a high thrust force. Thermodynamic parameters for each point and thermodynamic performance results of the turbofan engine are given in Tables 2 and 3, respectively.

Table 2. Thermodynamic Parameters for Each Point in the Turbofan Engine: FBR:1.58-BPR:8.4

No	Fluid type	T (K)	P (kPa)	ṁ (kg/s)	Cp (kJ/kg.K)
1	Fan air input	288.15	101.33	1350	1.0040
1.1	Fan duct air input	331.41	160.10	1206.38	1.0060
1.2	Fan duct air output	330.50	158.50	1206.38	1.0060
2	Low-pressure compressor air input	331.41	160.10	143.62	1.0060
3	High-pressure compressor air input	341.46	176.11	143.62	1.0068
4	Combustion chamber air input	885.34	4050.57	129.26	1.1174
5	Fuel	298.15	2500.00	2.97	-
6	High-pressure turbine exhaust gas inlet input	1592	3807.53	132.23	1.3343
7	Low-pressure turbine exhaust gas inlet input	1103.36	766.18	132.23	1.2493
8	Exhaust duct exhaust gas inlet	759.18	149.27	132.23	1.1672
9	Exhaust duct exhaust gas outlet	759.18	141.81	132.23	1.1672
4.1	Combustion chamber cold air input	885.34	4050.57	14.36	1.1174
6.1	High-pressure compressor cold air input	973.87	3807.53	14.36	1.1355
7.1	Low-pressure compressor cold air input	1103.36	766.18	14.36	1.1559
8.1	Exhaust duct cold air input	759.18	149.27	14.36	1.0881
9.1	Exhaust duct cold air outlet	759.18	141.81	14.36	1.0881

Table 3. Thermodynamic Performance Results of the Turbofan Engine

$\dot{Q}_{in}$ kW	$\dot{W}p$ kW	ET kN	SFC kg/kN.h	η_{ET} %	η_{th} %	C_{en} \$/h	C_{ex} \$.h	XCO_2 ton.CO_2/h	CCO_2 \$/tonCO_2.h
148369.21	53973.83	375.30	28.81	36.38	45.79	20132.11	17546.15	31.81	47.71

CONCLUSION

In this work, the performance of the turbofan engine was investigated by changing the fan pressure ratio and bypass air ratio of the GE90 turbofan engine. The conclusions obtained from the performance analysis results of the turbofan engine are as follows;

- The highest thrust efficiency of the engine is obtained as 37.22% at FPR: 1.66-BPR: 7.6 ratios. As the fan pressure ratio increased, the thrust force increased. The lowest thrust efficiency is obtained as % 24.56 at the ratios FPR:1.26-BPR:11.6.
- The highest specific fuel consumption of the engine is 42.23 kg/kN. h at FPR: 1.26-BPR: 11.6, while the lowest value is 31.03 kg/kN.h at FPR: 1.74-BPR: 6.8.
- The highest thermal efficiency of the engine was obtained as 45.91% at FPR:1.66-BPR:7.6 rates.
- The fuel cost obtained in the turbofan engine was obtained as the highest with C_{en} :31314.21 $/h and C_{ex} :27291.93 $/h at FPR:1.98-BPR:4.4 rates, and the lowest with C_{en}:16743.79 $/h and C_{ex} : 14593.06 $/h at FPR:1.26-BPR:11.6 rates.
- The amount of emissions released and the cost of this amount were calculated as 49.48 tons.CO_2/h and 74.21 $/tonCO2.h at the highest rates of FPR: 1.98-BPR: 4.4. The lowest emission release amount and cost values are obtained as 26.46 ton.CO_2/h and 39.68 $/ton$CO_2$.h in the ratios of FPR:1.26-BPR:11.6.

Engine manufacturing companies want to produce the most suitable engine in terms of both design and thermodynamic performance. Thermodynamic performance parameters increase with increasing fan pressure ratio, but engine designs suitable for these conditions may be limited. As fan pressure increases, bypass air decreases. To increase the fan pressure, it is necessary to reduce the fan diameter. This causes less air fluid to be taken in. The air fluid begins to rotate faster at a higher pressure rate, which increases the fluid speed. This creates a high friction resistance within the fan duct. As the fan pressure ratio increases, the fuel flow rate increases, but there may not be a good mixture due to the low amount of air trapped in the engine core. Therefore, it may not be an inefficient combustion. Increasing bypass air increases thrust and reduces the fuel flow rate used. However, to get a high amount of airflow, we need to increase the fan diameter. This means greater power production.

To produce this high power, a large-diameter turbine is required. These situations both cause the engine to operate noisily and increase the weight of the engine. This article provides important data to the literature in terms of design parameters and operating performance in aircraft engine studies. It will contribute to the environmental and economic analysis of exergy, exergy sustainability for aircraft engines in future studies.

NOMENCLATURE

BPR	bypass air rate
C_p	specific heat capacity (kJ/kgK)
CCO_2	emission Cost ($/ton$CO_2$. h)
ET	engine thrust (kN)
E_{KN}	kinetic energy
FPR	fan pressure ratio
g	gravity (m/s^2)
$\dot{m}$	mass flow rate (kg/s)
P_0	atmospheric pressure (kPa)
P	pressure (kPa)
PLR	productivity lack rate (%)
R	gas constant (kj/kgK)
SEF	sustainability efficiency factor (-)
PR	engine fuel cost ($)
$\dot{Q}$	heat flow (kW)
T_0	atmospheric temperature (K)
T	temperature (K)
V	velocity (m/s)
$\dot{W}$	power (kW)
XCO_2	amount of released carbon (tonCO_2/h)

Greek letters

η	efficiency (%)

Subscripts

atm	atmosphere
ch	chemical
in	input
k	the kth component
nk	mole value of the ideal gas
out	output
P	product
ph	physical
R	reactant
t	working hour
th	thrust

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