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EXERGETIC SUSTAINABILITY ASSESSMENT OF A GAS TURBINE JET ENGINE AT PART LOADS

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ABSTRACT

The sustainability performance of a jet engine was analyzed. To assess the jet engine's performance, four different operations at part loads are implemented (part load-1, part load-2, part load-3 and part load-4). The energy and exergy rates of the jet engine parts were studied. Sustainability indicators were used to understand the operating performance of the jet engine. Five exergetic sustainability indicators, exergy efficiency, waste exergy ratio, exergy destruction factor, environmental effect factor and exergetic sustainability indicator, were used to examine the exergetic performance of four different loads. The compressor, combustion chamber, turbine and nozzle of the jet engine were investigated. The exergy efficiency of the jet engine took the maximum value at part load-3 as 7.8%. The minimum waste exergy ratio (0.9) and exergy destruction factor (0.9) were calculated at part load-4. The minimum environmental effect factor and maximum exergetic sustainability factor belong to part load-3 case. They were found to be 12.029 and 0.0831, respectively. The exergy destructions caused by the combustion chamber were the maximum above all. It can be inferred from the analysis that the more loading applied to the jet engine the more the exergy rate obtained. Thus the resulting exergy destructions become higher. They were calculated as 48.96 kW, 57.14 kW, 67.93 kW and 74.38 kW, respectively.

Keywords: Energy analysis; Exergy analysis; Sustainability indicators; Gas turbine; Part load

1. INTRODUCTION

Gas turbine systems are used to generate mechanical energy for the propulsion of aircraft with propeller and jet engines. Gas turbines are required when higher power density, lower weight and quick starting are important. Contrary to piston engines, as fluid flow machines they permit high material flow rates with small dimensions. Thus, lighter weights and more powerful drives can be realized.

Moving parts of a gas turbine are subject to rotary motion. If the turbine is well balanced, it can run without any vibrations. There are some disadvantages because of the simultaneous connection to the atmosphere. These are high gas speeds and high noise emissions.

When compared to steam turbines, gas turbines work at higher temperatures but with lower pressures. The high temperatures affect the area of the turbine. Thus, heat resistant materials are required in the turbine area.

Jet engines are analyzed according to Brayton cycle. Expansion in the turbine is obtained only to operate compressor, a small generator and other support systems (hydraulic system etc.). In other words, net work for the propulsion cycle is zero. High pressure gases exiting from the turbine gain speed and the thrust is obtained to move the aircraft. Aircraft gas turbines work at higher pressure ratios like 10-25. Development of high pressure ratio turbojet engines lead to higher overall efficiencies [1].

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The work obtained in the turbine is equal to the work used in the compressor in ideal situations. The changes of state in diffuser, compressor, turbine and nozzle are also assumed to be isentropic. In the evaluation of real cycles, the irreversibilities in these systems are to be taken into consideration. The propulsion of an aircraft engine decreases because of the irreversibilities.

Sustainability aims to obtain sustainable outputs from the thermodynamic systems to use them at their optimum settings. It is related with environmental aspects as well as economic and social aspects. Responsible use of resources is another issue. When using sustainability parameters, one searches for low energy use, low exergy consumption, low cost, low environmental effects etc. Dincer and Rosen [2] explained that exergy methods can be used to improve sustainability. Cornelissen [3] expressed that the use of exergy analysis helps to achieve sustainable development.

Sustainability analysis of aircraft is relatively a new issue when compared to other energy using machines and systems. Turgut et al. [4] implemented an exergy analysis for a General Electric turbofan engine. Exergy efficiencies and exergy destructions were investigated for the turbomachinery components. The highest exergy losses were found in the fan and exhaust of the engine.

Altuntas et al. [5] studied the performance of piston prop aircraft engine including exergy, exergoeconomics and sustainability. The energy and exergy rates of the fuel were found. Energy and exergy efficiencies were determined. Cost analysis was also taken into consideration.

Aydın et al. [6] analyzed and discussed sustainability performance of an aircraft. This study applied for eight flight phases. Calculated exergy efficiencies took values between 0.274 and 0.284 from climb to maximum cruise. Highest exergy waste was found to be 79.4% for taxi and landing. Aydın et al. [7] developed theory, methodology and example application for a turbofan engine. Exergy analysis is performed and exergetic sustainability indicators are obtained in that paper. These are exergy efficiency, waste exergy ratio, exergy destruction factor, environmental effect factor and exergetic sustainability index.

Aydın et al. [8] performed a detailed exergy analysis based on engine test cell parameters. Six exergetic sustainability indicators were applied by using the exergy analysis results. Exergetic sustainability index was calculated as 0.46 and it showed that the turbofan engine did not have good sustainable level for environment.

Balli and Hepbasli [9] carried out a study to assess the performance of a turboprop engine. Under different power loadings exergoeconomic, sustainability and environmental damage cost analyses were investigated. The gas turbine was determined as having the highest sustainability index.
Turan [10] developed a new methodology and proposed the use of exergy parameters for mapping exergy flows in the turbofan engine. The sustainability analysis resulted with the findings as exergy efficiency of 29.6% and exergy destruction factor of 0.5037.

Kaya et al. [11] investigated an UAV by implementing exergetic sustainability parameters. Hydrogen was used as a fuel for the turbofan engine of UAV. Maximum instant exergetic efficiencies found to be ranging from 35% to 36.7%. Environmental effect factors and exergetic sustainability indices were calculated as 0.98 and 1.035 respectively for almost all flight phases.

Several studies were conducted for jet engine systems by using sustainability indicators. To the best of the author's knowledge, this paper is the first that a small scale jet engine's part load performance was analyzed by implementing exergetic sustainability indicators. In this paper, sustainability assessment is applied via exergetic metrics. The main objectives of this paper are (i) to use exergy analysis method for the analysis of the jet engine by (ii) to obtain the energy flows, exergy flows and exergy destructions in the engine's components (iii) to use exergetic sustainability indicators for the evaluation of the jet engine and (iv) to compare the jet engine's performance at various loads.

2. SYSTEM DESCRIPTION

The jet engine consists of a compressor, a combustion chamber and a turbine. The schematic view of the jet engine module is shown in Figure 1. In the jet engine, the ambient air is compressed to a higher pressure in the compressor (1-2). Then heat addition is provided in the combustion chamber to increase the temperature of the air. It is assumed that 20% of the air was used as primary air to light the fuel. During the combustion 20% of air, secondary air, was transferred into the combustor. Fuel and air are mixed and burned in this process which also increased the enthalpy of the working fluid (2-3). In the turbine, work extraction is achieved for compression (3-4). Finally, the exiting stream goes through the nozzle and the speed of gases increase (4-5).

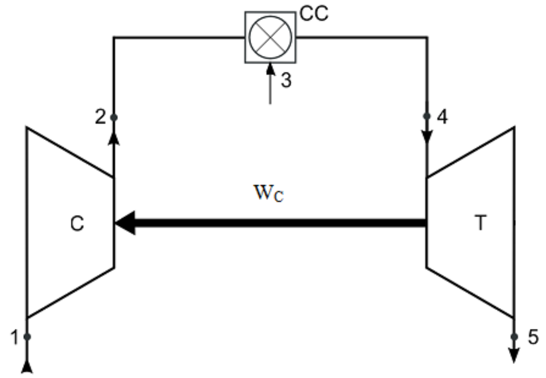

Figure 1. Open gas turbine system

In open cycles, the system is open to atmosphere. The working fluid is taken from and returned to atmosphere. In the open cycle, adiabatic compression of the of ambient air is obtained from outside pressure ($P_{C,in}$) to pressure ($P_{C,out}$) and the temperature rise from $T_{C,in}$ to $T_{C,out}$ is achieved.

Air is heated at isobaric state to increase temperature from $T_{CC,in}$ to $T_{CC,out}$. The heat is resulted from ignition of fuel with the oxygen in the combustion chamber. The hot gases expand in the turbine and thus pressure decreases. At the turbine outlet pressure is equal to the atmospheric pressure. The temperature decreases from T_3 to T_4 during this condition.

3. ANALYSES

3.1. Energy Analysis

In this paper, the jet engine's components are studied. The energy balance for the control volume can be formulated as,

$$\Delta E = Q - W \tag{1}$$

The difference between heat and work interactions is caused by energy rate change between the inlet and outlet streams.

$$E_i = m_i . c_{p,i} . T_i \tag{2}$$

According to the ideal gas law, the energy rate at state i is equal to the multiplication of mass flow rate, specific heat rate and temperature at state i.
To analyze the jet engine; the enthalpy rates, heat rates and work rates at the inlet and outlet streams of each engine components were constructed by the following equations. The equations were inspired from Yucer [12].

- Compressor (C)

$$m_{C,in} = m_{C,out} = m_{air} \tag{3}$$

$$W_C = m_{air}\left(c_{p,2}.T_2 - c_{p,1}.T_1\right) \tag{4}$$

Here m_{air} and W_C indicate mass flow rate of the air and the compressor work rate. The compression process is assumed as adiabatic.

- Combustion chamber (CC)

$$E_{fuel} = m_{fuel}.H_U \tag{5}$$

$$m_{air} + m_{fuel} = m_{gas} \tag{6}$$

$$E_2 + E_{fuel} = E_3 \tag{7}$$

m_{fuel}, H_U and m_{gas} indicate mass flow rate of fuel, heating value of fuel and mass flow rate of combustion gas.

- Turbine (T)

$$m_{T,in} = m_{T,out} = m_{gas} \tag{8}$$

$$W_T = m_{gas}\left(c_{p,3}.T_3 - c_{p,4}.T_4\right) - Q_{loss} \tag{9}$$

$$W_T = W_C \tag{10}$$

W_T stands for the work rate of the turbine. The process in the turbine is assumed as non-adiabatic and the turbine work rate is equal to the compressor work rate.

- Nozzle (N)

$$E_k = m_g.\frac{v_{out}^2}{2} \tag{11}$$

$$E_4 = E_k + Q_{ex,loss} \tag{12}$$

$$F = m_g.(v_{out} - v_{in}) \tag{13}$$

The energy stream exiting from turbine is converted to kinetic energy in the nozzle in which the exhaust gases flow at a high speed. E_k , $Q_{ex,loss}$ and F indicate kinetic energy rate, exhaust heat loss rate and the thrust. Thrust is simply calculated by the principle of linear momentum from the mass flow rate and the speed of the fluid inlet and outlet of the jet engine. v_{out} and v_{in} are the outlet and the inlet speeds of the jet engine.

3.2. Exergy Analysis

Exergy analysis is directly related with the second law of thermodynamics. The energy rate of a flow can not be transformed into work without losses. Energy balance does not provide information on the degradation of energy. Exergy quantifies the usefulness or quality of energy and material flows through a system. The aim is to minimize the irreversibilities to get benefit from the work potential. The components of the jet engine is studied as follows,

$$Ex_{i,in} = Ex_{i,out} + Ex_{i,D} \tag{14}$$

$$Ex_i = m_i.[c_{p,i}(T_i - T_0) - T_0(s_i - s_0)] \tag{15}$$

$$s_i - s_0 = \left[c_{p,i}.\ln\frac{T_i}{T_0} + R.\ln\frac{P_i}{P_0}\right] \tag{16}$$

Exergy equations consist of exergy destruction ($Ex_{i,D}$), inlet ($Ex_{i,in}$) and outlet ($Ex_{i,out}$) flows in the examined open system at state i. s denotes the entropy at state i. Ex_i is the exergy rate at state i and R is the ideal gas constant of air. The exergy balance equations are constructed in the below formulas. The below equations were derived from Yucer [12].

- Compressor (C)

$$Ex_{C,in} = 0 \tag{17}$$

$$W_C + Ex_{C,in} = Ex_{C,out} + Ex_{C,D} \tag{18}$$

The inlet of compressor is in outside conditions, so there is not any work potential.

- Combustion chamber (CC)

$$\varepsilon_{fuel} = \varphi.H_U \tag{19}$$

$$Ex_{fuel} = m_{fuel}.\varepsilon_{fuel} \tag{20}$$

$$Ex_{CC,in} + Ex_{fuel} = Ex_{CC,out} + Ex_{CC,D} \tag{21}$$

Ex_{fuel}, ε_{fuel} and φ and indicate the exergy rate of fuel, the specific exergy and the chemical exergy factor. The exergy rate of the combustion gases entering the turbine yields the turbine work rate and the thrust of the jet engine.

- Turbine (T)

$$Ex_{T,in} = Ex_{T,out} + W_T + Ex_{T,D} + Ex_Q \tag{22}$$

The combustion gases leaving the turbine are at high temperature and cause high exergy rate losses. The exergy rate of heat loss (Ex_Q) in the non-adiabatic turbine is formulated in Eq.(22).

- Nozzle (N)

In the nozzle of the jet engine, the speed of gases is increased. The thrust is obtained by the momentum of the combustion gases.

$$Ex_{N,in} = Ex_{N,out} + Ex_{N,D} \tag{23}$$

$$Ex_{N,out} = \frac{1}{2}.m_{gas}.v_{out}^2 \tag{24}$$

3.3. Exergetic Sustainability Indicators

The exergetic sustainability indicators are exergy efficiency, exergy destruction factor, waste exergy ratio, environmental effect factor and exergetic sustainability index. The below formulas used to calculate the indicators were derived from [6].

Exergy efficiency (EE) is one of the most important factors that investigates the ratio between the availabilities of our purpose of energy and the used energy. It is simply calculated as

$$\psi = \frac{W}{Ex_{in}} \tag{25}$$

W represents the shaft power generated. Ex_{in} is the input exergy rate of the jet engine.

Exergy destruction factor (EDF) can be defined as the ratio between the exergy destruction and the input exergy. It is formulated as,

$$f = \frac{Ex_D}{Ex_{fuel}} \tag{26}$$

Waste exergy ratio (WER) is defined as the ratio between the waste exergy and the input exergy. In the jet engine, the waste exergy is in unusable category since exhaust gases can not be recovered.

$$r = \frac{Ex_D + Ex_L}{Ex_{in}} \tag{27}$$

The sum of exergy destruction rates and exergy loss rates are equal to the waste exergy of the jet engine.

Environmental effect factor (EEF) is an important indicator. It investigates damage that the engine causes because of the waste exergy output. It is the ratio between waste exergy ratio and the exergy efficiency.

$$e = \frac{r}{\psi} \tag{28}$$

Exergetic sustainability index (ESI) is defined as the inverse of the environmental effect factor. Low environmental damage means high sustainability capacity.

$$\theta = \frac{1}{e} \tag{29}$$

4. AN EXPERIMENTAL STUDY FOR THE JET ENGINE

The analyzed thermodynamic system belongs to a gas turbine jet engine. It is a test cell for thermodynamic analysis. The jet engine has a single stage axial flow turbine. The compressor is a radial flow type. The combustion chamber is an annular type. The engine is of single shaft design. Both the compressor and turbine rotate on the shaft at the same speed. The jet engine is fully throttleable from idle speed of 25,000 rpm to a maximum speed up to 120,000 rpm. This study gives the researcher the opportunity to investigate the effect of various loads on the sustainability assessment of the jet engine. The following assumptions are taken into consideration.

The jet engine was operated in a steady-state. Ideal gas laws were implemented to the working fluid. The fuel used in the combustion chamber was kerosene. The heating value of kerosene was used as 42,580 kJ/kg. The velocity of inlet air flow was taken zero. The temperature and the pressure of the dead state (ambient) were measured to be 288.15 K and 102 kPa.

The measured experimental data were compressor outlet temperature, combustion chamber pressure and temperature, gas turbine outlet temperature, mass flow rate of air and fuel, gas turbine speed and thrust.

4.1. Experimental Study

Having implemented the study, the resultant data are measured and presented in Table 1. According to four part load settings, performance assessment was carried out. A jet engine experiences a lower efficiency at part loads. To operate at part load, the fuel flow rate was adjusted. Gas turbine speeds were measured to be 35215 1/min. for part load-1, 44074 1/min. for part load-2, 50039 1/min. for part load-3 and 57667 1/min. for part load-4. As percentage ratios, part loads can be written 29% for part load-1, 37% for part load-2, 42% for part load-3 and 48% for part load-4. The turbine inlet temperature varied between 1037.25 K and 1119.24 K from part load to full load. Thrust values were measured to be from 6.64 N to 15.23 N.

Table 1. Experimental data of the part loads

Load type	Part load-1	Part load-2	Part load-3	Part load-4
Compressor outlet temperature (K)	297.75	303.03	305.96	311.24
Combustion chamber temperature (K)	1037.3	1088.2	1095.2	1119.2
Turbine outlet temperature (K)	686.85	678.65	654.6	656.94
Combustion chamber pressure (kPa)	109.81	113.6	118.85	123.73
Mass flow rate of air (kg/s)	0.0151	0.0239	0.0278	0.036
Mass flow rate of fuel (kg/s)	0.00115	0.00138	0.00164	0.00183
Turbine speed (1/sec)	586.92	734.58	834	961.14
Thrust (N)	6.64	9.57	13.086	15.23

4.2. Determination of Specific Heat Capacity

The specific heat capacity of the combustion gases were calculated by [13],

$$c_{p,g}(T) = 0.9874 + 0.0000544T + \frac{1.48}{10^7}T^2 - \frac{6.57}{10^{11}}T^3 \tag{30}$$

The air specific heat capacity can be found by [13],

$$c_{p,a}(T) = 1.04841 - 0.000383719T + \frac{9.45378}{10^7}T^2 - \frac{5.49031}{10^{10}}T^3 + \frac{7.92981}{10^{14}}T^4 \tag{31}$$

where the temperature unit is in K. The specific heat capacity values are presented in Table 2.

Table 2. Specific heat capacity results

		$c_{p,a}$ (kJ/kg.K)		$c_{p,g}$ (kJ/kg.K)	
State		Compressor inlet	Compressor outlet	Turbine inlet	Turbine outlet
Load type	**Part load-1**	1.00375	1.00410	1.12631	1.046
	Part load-2	1.00375	1.00433	1.13727	1.0441
	Part load-3	1.00375	1.00448	1.13876	1.03853
	Part load-4	1.00375	1.00475	1.14379	1.03908

5. RESULTS AND DISCUSSION

5.1. Energy and Exergy Analyses Results

The analyses show that the increase in the fuel flow rate results in increase for energy and exergy rates. The work obtained by the jet engine shaft takes higher values since the turbine inlet temperature changes.
The turbojet engine characteristics at four different part loads are studied to assess the jet engine's performance. In the energy analysis, it is aimed to analyze the thermodynamic properties of the streams at each component to calculate work rates and energy rates.

The energy rates at part load-1 for the compressor outlet, the turbine inlet and the turbine outlet were calculated as 4.51 kW, 18.98 kW and 11.67 kW. The energy rate results increase as the gas turbine speed increases. Likewise, the work rate obtained from the gas turbine increases from part load-1 to part load-4. The work rate at part load-1 was calculated as 0.15 kW, since the entering and exiting energy rates are at lower temperatures when compared to higher part loads. With the increase in the fuel flow rate, the heat transfer from the combustion chamber increases. Thus, the work rates calculated from other part loads were higher and at part load-4 it was found to be 0.85 kW. The calculated data regarding the energy figures are presented in Table 3.

Table 3. Energy and exergy flow rates (kW) of the part loads

	Part load-1		Part load-2		Part load-3		Part load-4	
State	**Energy rate**	**Exergy rate**	**Energy rate**	**Exergy rate**	**Energy rate**	**Exergy rate**	**Energy rate**	**Exergy rate**
Compressor Inlet	4.367	0	6.913	0	8.04	0	10.412	0
Compressor Outlet	4.514	0.096	7.274	0.226	8.544	0.372	11.258	0.617
Combustion Chamber	48.967	52.297	58.76	62.756	69.831	74.58	77.924	83.22
Turbine Inlet	18.984	7.628	31.284	13.19	36.717	15.676	48.429	21.174
Turbine Outlet	11.674	2.819	17.913	4.311	20.014	4.642	25.823	6.151

The air stream entering the compressor was in dead state, thus the exergy rate was equal to zero. The magnitudes of exergy rates were much more lower than that of energy rates. This is because of high energy losses and irreversibilities in the engine components. The exergetic findings are listed in Table 4.

Table 4. Exergy destruction rates (kW) of the part loads

Load Types	Compressor	Combustion Chamber	Turbine
Part load-1	0.051	48.96	0.04
Part load-2	0.135	57.138	0.112
Part load-3	0.131	67.934	0.169
Part load-4	0.228	74.383	0.322

The exergy destructions in the jet engine components increase from part load-1 to part load-4. The gas turbine speed characteristic and total exergy destruction is presented in Fig.2. The relationship between exergy efficiency and shaft torque is demonstrated in Fig.3. The compressor exergy increases as the part load increases. Likewise the combustion chamber and the gas turbine. The temperature and pressure values increase because of the increase in gas turbine speed.

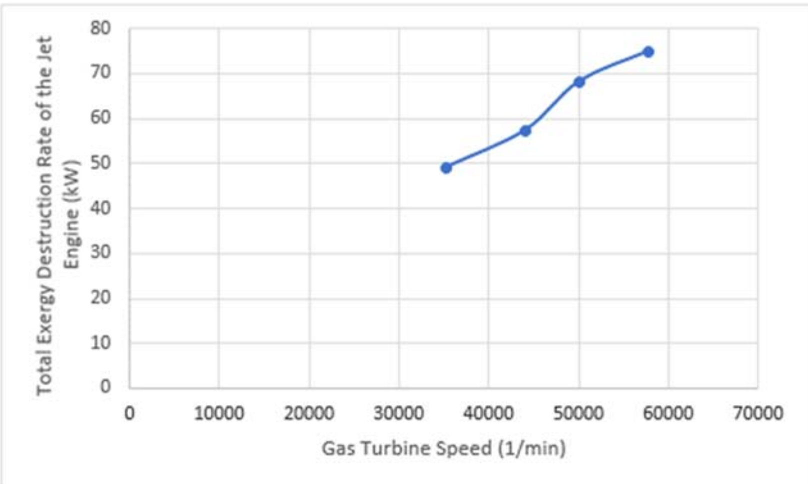

Figure 2. Total exergy destruction of the jet engine vs. gas turbine speed

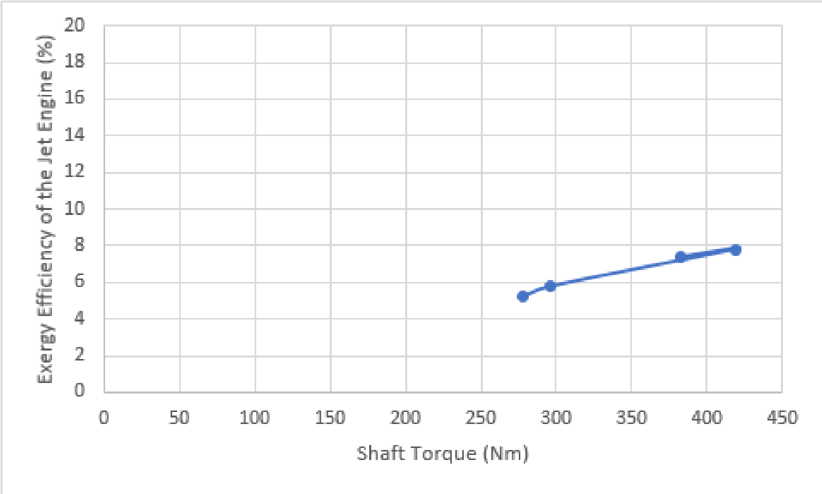

Figure 3. Exergy efficiency of the jet engine vs. shaft torque

The exhaust heat loss vs. gas turbine speed is shown in Fig.4. The exhaust gas speed exiting from the nozzle was calculated as 408.61 m/s at part load-1. The speed changes according to the enthalpy rate at the turbine outlet stream. It reaches the value of 444.5 m/s at part load-3. The increase in the gas turbine speed results in increase in thrust power and it is measured as 15.23 N at part load-4. The thrust nozzle speeds, kinetic exergy rates, exhaust losses and shaft torques of the jet engine are presented in Table 5 for part loads.

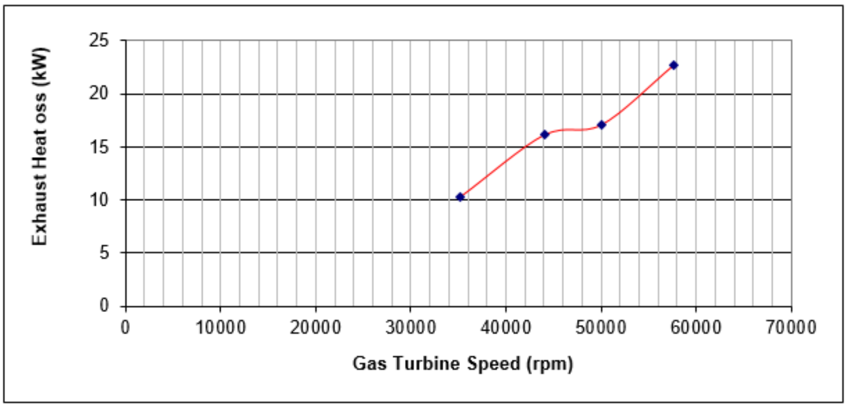

Figure 4. Exhaust heat loss vs. gas turbine speed.

Table 5. Exhaust nozzle calculated figures

Load Types	Speed (m/s)	Kinetic Energy Rate (kW)	Exhaust Heat Loss Rate (kW)
Part load-1	408.615	1.357	10.318
Part load-2	378.56	1.811	16.101
Part load-3	444.497	2.908	17.106
Part load-4	402.59	3.066	22.757

5.2. Exergetic Sustainability Indicator Results

In this study, it is aimed to assess the inefficiencies and sustainability performances within the jet engine. To analyze the jet engine according to sustainability issue, five exergetic sustainability indicators are implemented. By using the measured data, the indicators were derived for each part load of the jet engine cycle are summarized in Table 6.

Table 6. Exergetic sustainability findings at four load types

Load Types	EE	WER	EDF	EEF	ESI
Part load-1	0.052	0.966	0.938	18.618	0.054
Part load-2	0.058	0.954	0.914	16.53	0.06
Part load-3	0.078	0.938	0.915	12.029	0.083
Part load-4	0.074	0.9	0.9	12.221	0.082

The exergy efficiency of the jet engine increases from part load-1 to part load-3. It slightly decreases at part load-4. Because of the high exergy destruction rates in the combustion chamber, the exergy efficiencies are at low ratios. The maximum EE was calculated as 7.79% at part load-3. Minimum EE value was found to be 5.19% at part load-1.

Waste exergy ratios (WER) express the ratio between exergy consumptions and exergy input. Most of the exergy input of the fuel was consumed in the combustion chamber for all part loads. But, it decreases as the load increases. The ratios for the four loads are 0.966, 0.954, 0.938 and 0.9 respectively.

As the loading increased, jet engine components consume more exergy. Exergy destruction factor (EDF) decreased from part load-1 to part load-4, as 0.938, 0.914, 0.914 and 0.9, respectively. Similarly, for the gas turbine, the fuel exergy depletion values increased. They were calculated as 0.131, 0.159, 0.208 and 0.219, respectively.

Environmental effect factor (EEF), examines the system whether it damages environment or not. The maximum environmental effect was determined at part load-1. Because it has the minimum exergy efficiency among the part loads. EEF follows a decreasing trend. At part load-3, the minimum EEF was calculated as 12.029. This part load is the most efficient of all.

Exergetic sustainability index (ESI), explains the environmental damage potential. High ESI means low EEF. Part load-3 has the maximum ESI as 0.083. This is not surprising, because both the maximum EE and the minimum EEF belong to part load-3. The minimum ESI was found to be 0.054 at part load-1. Like the EE, ESI has an increasing trend as the part load increased. But at part load-4, the jet engine has slightly lower ESI when compared with part load-3.

6. CONCLUSIONS

In this paper, energy and exergy analyses were implemented to a jet engine to analyze sustainability performances at various part loads. The energy rates, exergy rates and exergetic sustainability indicators were obtained according to the part loads.

Some concluding remarks of the study were as follows:

(a) The maximum exergy destructions were observed in combustion chamber. These are 48.96 kW, 57.14 kW, 67.93 kW and 74.38 kW for the four loadings, respectively.

(b) The maximum kinetic exergy and exhaust loss were observed at part load-4 as 3.06 kW and 22.75 kW, respectively.

(c) The maximum shaft torque was calculated at part load-3. It was 418.47 Nm.

(d) The maximum exergy efficiency of the jet engine was observed at part load-3, as 7.8%. The minimum exergy efficiency was found to be 5.2% at part load-1.

(e) The minimum WER value was calculated as 0.9 at part load-4.

(f) The maximum EDF value was determined at part load-1. It was calculated as 0.938.

(g) The minimum EEF value took place at part load-3 as 12.03.

(h) The maximum ESI was found at part load-3 as 0.083.

(i) In this study, the sustainability assessment of a gas turbine jet engine was analyzed. For a future work, exergetic optimization according to sustainability issue of the jet engines is planned to investigate.

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