SAKARYA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ DERGİSİ

Sakarya University Journal of Science
SAUJS

ISSN 1301-4048 e-ISSN 2147-835X Period Bimonthly Founded 1997 Publisher Sakarya University
http://www.saujs.sakarya.edu.tr/

Title: Dealing with Aspects of Performance and Environmental Impact of Aircraft Engine with Thermodynamic Metrics

Authors: Hakan AYGÜN

Recieved: 2022-10-21 00:00:00

Accepted: 2023-01-31 00:00:00

Article Type: Research Article

Volume: 27
Issue: 2
Month: April
Year: 2023
Pages: 370-385

How to cite
Hakan AYGÜN; (2023), Dealing with Aspects of Performance and Environmental Impact of Aircraft Engine with Thermodynamic Metrics . Sakarya University Journal of Science, 27(2), 370-385, DOI: 10.16984/saufenbilder.1192159
Access link
https://dergipark.org.tr/en/pub/saufenbilder/issue/76551/1192159

New submission to SAUJS
http://dergipark.gov.tr/journal/1115/submission/start

Sakarya University Journal of Science 27(2), 370-385, 2023

SAKARYA ÜNİVERSİTESİ

Dealing with Aspects of Performance and Environmental Impact of Aircraft Engine with Thermodynamic Metrics

Hakan AYGUN *1

Abstract

The limited energy source indicates the necessity of efficient energy consumption in every field of life. Especially, the prompt growth in aviation sector makes this issue more important. In this study, effects of power settings on several thermodynamic indicators regarding low by-pass turbofan engine (LBP-TFE) are investigated. For this aim, the energy and exergy analyses are implemented to the system of turbofan engine for eighteen operating points. According to performance analysis, thrust value of the LBP-TFE changes from 10.77 kN to 71.8 kN throughout RPM values. According to exergetic findings, relative exergy losses from Fan outlet decreases from 52.34 % to 30.58 % whereas exergy efficiency of the LBP-TFE increases from 10.9 % to 30.1 %. Considering improved exergy efficiency, it changes 25.03 % and 41.03 % at the same RPM intervals. As for environmental assessments, environmental effect factor (EEF) of LBP-TFE diminishes from 5.8 to 1.32 while ecological effect factor decreases from 9.16 to 3.31. Finally, specific irreversibility production of LBP-TFE decreases from 0.4811 MW/kN and 0.2716 MW/kN. Considering these outcomes, behaviour of the investigated metrics regarding main components is different from each other. Therefore, the results of these parameters calculated for the whole engine could help understanding optimum running point in terms of exergetic and environmental sustainability.

Keywords: Low by-pass turbofan, ecological effect factor, environmental effect factor, exergy

1. INTRODUCTION

In aviation sector, the dependency on fossil fuel consumption has increased in recent years due to an increasing aircraft fleet. It is estimated that the annual growth of aviation is approximately 5-6 % [1]. According to aviation authorities, the number of passengers conveyed with airline was figured out 3.53 billion in 2015 whereas it increased to 4.5 billion in 2019 [2]. This case corresponds to 27.4 % increment at four years. Therefore, this situation has triggered several issues such as environmental pollution, thereby global warming. Admittedly, CO_2 emissions from aviation activities are proportional with the

* Corresponding author: haygun@firat.edu.tr (H.AYGUN)
[1] Firat University
E-mail: haygun@firat.edu.tr
ORCID: https://orcid.org/0000-0001-9064-9644

Content of this journal is licensed under a Creative Commons Attribution-Non Commercial No Derivatives 4.0 International License.

quantity of fossil fuel consumption. To mitigate aircraft emissions, several policies have been brought forward by many foundations. The leading measure implemented in several countries is mitigation of CO_2 emissions with carbon taxes. To generate thrust or power is key role of propulsion system, however fuel efficiency of these systems while producing this power is affected from several factors such as design, weight and material of the engine. Commercial airline transportation is highly related to developments of the aviation sector [3]. However, compared with the earlier of invention of gas turbines, the current engines have undoubtedly designed more efficiently [4]. However, these developments could not eliminate impacts of emissions from air traffic [3, 5].

To alleviate effects of gas turbine engines on environment, these systems have been dealt with several approaches such as thermodynamic and optimization. The main challenge pertaining to aircraft system is to minimize environmental impact of engine by keeping system efficiency at the desired level [6]. To overcome this depends on finding optimum running point as well as lowering wasted exergy as possible. To design a competitive gas turbine engine in terms of environmental and performance could increase the interest of the users of this technology. Investigation of these systems under different conditions allows the designer to make decision more efficiently and economically. To meet the design requirements of novel aircraft missions, several elaborated studies along with many projects have been brought to light day by day. On the other hand, the main focusing point of the scientists is to improve energetic and exergetic performance of energy consuming systems due to the rising concern about the limited sources for two decades. For this aim, thermodynamics approaches which are significant tools are necessary for assessment of thermal systems. Comparison of similar systems is made by applying first and second laws of thermodynamics to the thermal systems. Considering the open literature, a number of studies involving exergy approach have existed. Especially, this method has commonly been implemented to gas turbine engine due to using many fields. In the present study, it is tried that the recent performed works about exergy of gas turbine engines are presented. Akdeniz and Balli [1] investigated the bypass effects on thermodynamic performance for JT3D-3B engine. They stated that exergy efficiency of the engine increases from 25.39 % (BPR:1.3) to 26.23 % (BPR:1.45) whereas energy efficiency of JT3D engine from 26.97% to 27.93% at the specified BPR values. Dinc et al. [7] conducted thermodynamic-based analyses for turboprop engine at several flight phase points. The authors stated that the combustor has the highest exergetic improvement potential ratio with 88.756% whereas for the intermediate pressure turbine, it is calculated lowest with 0.492% at phase point 3. Tuzcu et al. [8] searched turbofan engine in terms of efficiency and emission. Overall efficiency of the engine is found as 19.7%. CO_2 emission per day cyle was produced as 358.9 tonCO_2/day whereas its environmental damage cost is determined as 5742.52 US$/day. Moreover, Turan [9] dealt with exergetic parameters of JT9D engine producing thrust of 206 kN. According to the author, exergy efficiency of the engine was calculated as 29.6 % while its environmental effect factor was measured as 0.675. Furthermore, Balli et al. [10] implemented exergetic approach to TF33 low by-pass turbofan engine. The authors expressed that exergy efficiency of TF33 was gauged as 34.86% whereas its environmental effect factor was found as 1.868. On the other hand, Dinc et al. [11] examined three-spool turboprop engine with exergetic method at different flight points. They stated that exergy efficiency of the engine was computed as

29.11% at take-off and 34.69% at cruise phase. Balli and Caliskan [12] was investigated of JTD15 turbofan engine generating thrust of 9.79 kN in terms of energetic and exergetic. According to the authors, exergy efficiency of the whole engine was estimated as 19.91%, whereas environmental effect factor of JTD15 was found as 4.02. According to the studies about exergy analysis of gas turbine engines considered, the most of studies about gas turbine engine in the literature are performed at one-point. This study differs from this aspect. Namely, exergetic parameters are calculated for eighteen running points instead of one case. Thus, exergy and environmental behaviour of the engine against to RPM variations can be observed and compared with each other. This comparison is of high importance since the engine is not operated at only one point in the real world. On the other hand, exergetic and environmental indicators are computed for both the whole engine and its six components. Main novelty of the study is that specific irreversibility production (SIP) index is firstly calculated for the engine which is very similar to JT8D engine. As a conclusion, the current study has differences from following points:

- To calculate exergetic metrics involving exergy efficiency, wasted exergy ratio, fuel exergy waste ratio, improved exergy, exergetic improvement potential for turbofan and its six components
- To compute environmental parameters incorporating environmental effect factor, exergetic sustainability index ecological effect factor and sustainable efficiency factor
- To measure firstly specific irreversibility production for LBP-TFE
- To compare exergetic and environmental indicator for eighteen running points.

2. SYSTEM DESCRIPTION

In this study, gas turbine engine that is the very similar to JT8D engine is dealt with so as to be analyzed. JT8D engine has proven durability and reliability by flying more than 673 million hours since starting operation. However, nowadays, these engines are known as ‘the old engines’. Up to date, the number of JT8D engines used exceeds to 14,750. According to the literature, 2400 of these engines are still employing in the aircraft. There are the eight models of JT8D family [13]. Thrust range of these engines are between 62 kN and 96 kN. JT8D engines have been installed in B-727/737, DC-9 and MD-80. These engines have front-mounted fan with two stages, low pressure compressor with four stages, combustor, high pressure compressor with seven stage combustor, high-pressure turbine with one stage and low-pressure turbine with three stages [14]. Overall pressure ratio for JT8D family engines has ranges from 15.8 to 21 whereas their by-pass ratio varies between 1 and 1.7.

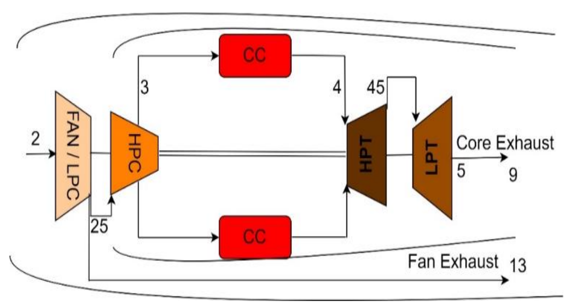

Figure 1 Cross section of JT8D engine

The representative drawing for typical low bypass turbofan engine is illustrated in Figure 1. Table 1 presents several versions of JT8D engine with their key features.

Table 1 Several models and features of the JT8D low by-pass turbofan engine [15]

Versions	By-pass ratio	Overall pressure ratio	Rated thrust	General Applications
JT8D-11	1	17.17	66.72	Boeing 727 Boeing 737-100 Boeing 737-100 Boeing MD-80 DC-9
JT8D-15	1.03	16.81	68.94	
JT8D-17	1.02	17.01	71.17	
JT8D-209	1.8	18.3	85.6	
JT8D-217	1.73	19.66	92.74	
JT8D-219	1.7	20.27	96.52	
JT8D-7 series	1.05	15.82	62.27	
JT8D-9 series	1.04	15.88	64.5	

Table 2 The engine input parameters for performing exergy analysis throughout eighteen RPM values

RPM (%)	Fan air mass flow (kg/s)	Core air mass flow (kg/s)	Fuel flow (kg/s)	Fan exhaust velocity (m/s)	Core exhaust velocity (m/s)
50.29	64.824	28.266	0.179	160.103	173.126
55.32	74.628	32.808	0.222	182.525	203.323
59.93	83.271	36.833	0.266	202.003	231.316
64.3	90.98	40.591	0.31	218.555	257.43
68.4	98.056	44.076	0.354	233.486	282.049
71.99	104.605	47.401	0.4	246.75	305.66
75.25	110.699	50.571	0.445	258.65	327.812
78.18	116.466	53.64	0.492	269.52	349.892
80.77	121.919	56.612	0.539	279.439	371.075
83.05	127.079	59.501	0.587	288.438	392.602
85.13	131.976	62.323	0.636	296.623	413.148
87.09	136.622	65.063	0.686	304.124	433.452
89.02	141.035	67.72	0.738	311.04	453.094
90.92	145.156	70.282	0.792	317.262	473.554
92.76	149.016	72.736	0.848	322.901	483.445
94.75	152.591	75.086	0.91	328.045	488.983
97.19	155.726	77.256	0.983	332.741	495.849
100	158.392	79.197	1.066	337.029	504.257

3. METHODOLOGY BACKGROUND

Once performing exergy analysis, potential improvements and environmental impacts of the system considered can be estimated. However, first law of thermodynamics could not gain comprehensive point of view. Therefore, second law of the thermodynamics is required so as to quantify environmental impacts and sustainability level. Namely, the irreversibility of processes can be assessed by means of the exergy approach that includes computation of these irreversibilities. Magnitudes of wastes, destructions and losses of energy occurred in the system are measured with this approach [7]. Table 2 gives air and fuel mass flows as well as fan and core velocity, which is obtained from parametric cycle equations [16, 17].

3.1. Exergy Analysis

Fuel-Product law is employed so as to compute exergy destruction occurred in the system or the component [18].

$$\sum \dot{E}x_F - \sum \dot{E}x_{Pr} = \sum \dot{E}x_D \tag{1}$$

where F represents ‘fuel’ whereas Pr denotes ‘product’. Also, D specifies ‘destruction’.

Kinetic exergy or product exergy obtained from the engine is calculated as:

$$\dot{E}x_{PR,engine} = (\dot{m}_F + \dot{m}_a)\frac{V_{exhaust}^2}{2} \quad (2)$$

Exergy rates for air and exhaust gases are found from following equation. However, specific heat value is separately computed for air and gases [19].

$$\dot{E}x = \dot{m}\left[c_{p(T)}\left[T\text{-}T_0\text{-}T_0 ln\left(\frac{T}{T_0}\right)\right] + RT_0 ln\left(\frac{P}{P_0}\right)\right] \quad (3)$$

For air and gases, specific heat value is calculated from [20]:

$$C_{p,air}(T) = 1.04841 - 0.000383719(T) + \frac{9.45378(T^2)}{10^7} - \frac{5.49031(T^3)}{10^{10}} + \frac{7.92981(T^4)}{10^{14}} \quad (4)$$

$$C_{p,gas}(T) = 0.9910 + \frac{3.606(T)}{10^5} + \frac{1.552(T^2)}{10^7} - \frac{6.76(T^3)}{10^{11}} \quad (5)$$

Fuel exergy is calculated from:

$$\dot{E}x_F = \dot{m}_F \dot{Q}_{LHV} \xi_F \quad (6)$$

where ξ_F represents liquid fuel exergy grade function [21]. For liquid fuels ($C_a H_b$), its formula is:

$$\xi_F \cong 1.04224 + 0.011925\frac{b}{a} - \frac{0.042}{a} \quad (7)$$

Wasted exergy of turbofan engine is computed from difference between fuel exergy and product exergy of the engine. It is written as:

$$\dot{E}x_{WE,engine} = (\dot{E}x_F + \dot{E}x_1) - \dot{E}x_{PR,engine} \quad (8)$$

Total exergy destruction consists exergy destruction of fan, low pressure compressor, high pressure compressor, combustor, high pressure turbine and low pressure turbine. It is written as:

$$\dot{E}x_{D,engine} = \sum \dot{E}x_D = \dot{E}x_{D,components} \quad (9)$$

There are several ways that exergy efficiency is formulated for thermal systems. These can be seen in detail elsewhere. In the current study, exergy efficiency is expressed as the ratio of product exergy to fuel exergy [12, 22].

$$\eta_{ex} = \frac{\dot{E}x_{Pr}}{\dot{E}x_F} \quad (10)$$

Waste exergy ratio is calculated by dividing wasted exergy in the kth component to total wasted exergy occurred in overall system. It is written as:

$$WExR_k = \frac{\dot{E}x_{WE,k}}{\dot{E}x_{WE,engine}} = \frac{\dot{E}x_{D,k} + \dot{E}x_{L,k}}{\dot{E}x_{WE,engine}} \quad (11)$$

Fuel exergy waste ratio is computed by dividing wasted exergy in the kth component to fuel exergy entering the system. It is written as [23]:

$$FExWR_k = \frac{\dot{E}x_{WE,k}}{\dot{E}x_{F,engine}} = \frac{\dot{E}x_{D,k} + \dot{E}x_{L,k}}{\dot{E}x_{F,engine}} \quad (12)$$

Moreover, exergetic improvemental potential is found from exergy destruction and exergy efficiency. It means how much exergy destruction could be recovered in the any system. It is expressed as [24]:

$$ExIP_k = (1-\eta_{ex})\dot{E}x_{D,k} \tag{13}$$

Improved exergy efficiency is firstly proposed by Balli [25]. It is determined by inserting exergetic improvemental potential to exergy efficiency. This metric means that how much exergy efficiency increases due to recovering exergy destruction. It is presented as:

$$\Psi = \frac{\dot{E}x_{Pr}}{\dot{E}x_F - \dot{E}xIP} \tag{14}$$

3.2. Environmental and Sustainability Parameters

The term sustainability means the usage of energy sources with the lowest negative environmental impacts as possible. Therefore, to consume energy efficiently is of high importance for sustainability [26]. Also, the higher the energy efficiency, the lower the environmental damage. In this context, gas turbine engines have a key role so as to quantify the sustainability of aircraft. For this aim, four different parameters that are commonly used in the literature are dealt with in the present study.

Ecological effect factor is computed by taking the reciprocal of the exergy efficiency. This parameter is adversely proportional with exergy efficiency. It is written as:

$$EcoEF_k = \frac{\dot{E}x_F}{\dot{E}x_{Pr}} = \frac{1}{\eta_{ex,k}} \tag{15}$$

Environmental effect factor (EEF) is computed by dividing fuel exergy waste ratio to exergy efficiency. It means damage of environmental of the engine or the component. It is expressed as [27]:

$$EEF_k = \frac{FExWR_k}{\eta_{ex,k}} \tag{16}$$

Besides, exergetic sustainability index is found by taking the reciprocal of the EEF. This metric shows the level of sustainability of the engine or the component. It is presented as [27]:

$$ExSI_k = \frac{1}{EEF_k} \tag{17}$$

On the other hand, sustainable efficiency factor (SEF) is determined from exergy efficiency. Namely, its value depends on exergy efficiency. It is written as[12]:

$$SEF_k = \frac{1}{1-\eta_{ex,k}} \tag{18}$$

Finally, specific irreversibility production is firstly implemented to the low by-pass turbofan in the present study. It is computed by dividing total exergy destruction to net thrust of the engine. Thanks to this metric, irreversibility performance of the gas turbine engine could be gauged at any operation conditions. Namely, different running points could be compared in terms of irreversibility. It is expressed as follows:

$$SIP_{engine} = \frac{\sum \dot{E}x_D}{\tau_{engine}} \tag{19}$$

where τ_{engine} denotes net thrust of the engine**.**

4. RESULTS AND DISCUSSION

This section covers the outcomes of exergetic and environmental for low by-pass turbofan and its six components. These computations are carried out for eighteen relative RPM values starting from 50.29 % to 100 %. To clearly be understood, this section could be divided to three subsections. Firstly, variations of performance metrics such as thrust and specific fuel consumption (SFC) against RPM values are presented in Figure 2. Secondly, exergetic parameters pertaining to

LBP-TFE and its components are evaluated in Figures 3-8. Thirdly, environmental parameters of the system along with its components are evaluated with Figures 9-13.

Table 3 Exergy destruction of main components throughout eighteen RPM values

RPM (%)	FAN (MW)	LPC (MW)	HPC (MW)	CC (MW)	HPT (MW)	LPT (MW)
50.29	0.194	0.129	0.432	3.621	0.633	0.172
55.32	0.251	0.167	0.516	4.16	0.809	0.249
59.93	0.309	0.204	0.595	4.677	0.987	0.325
64.3	0.366	0.239	0.672	5.163	1.167	0.388
68.4	0.423	0.273	0.744	5.631	1.346	0.444
71.99	0.47	0.3	0.807	6.093	1.52	0.512
75.25	0.506	0.321	0.868	6.544	1.691	0.578
78.18	0.534	0.337	0.928	6.995	1.863	0.639
80.77	0.555	0.348	0.991	7.435	2.036	0.697
83.05	0.567	0.354	1.054	7.876	2.211	0.751
85.13	0.573	0.359	1.117	8.311	2.38	0.811
87.09	0.578	0.363	1.18	8.748	2.548	0.866
89.02	0.585	0.368	1.243	9.182	2.716	0.918
90.92	0.598	0.377	1.304	9.63	2.888	0.966
92.76	0.613	0.388	1.363	10.087	3.058	1.01
94.75	0.657	0.413	1.425	10.567	3.234	1.045
97.19	0.782	0.477	1.497	11.072	3.416	1.093
100	0.984	0.577	1.583	11.604	3.604	1.145

Table 3 presents exergy destruction for six different components. According to this, the lowest exergy destruction takes place in LPC whereas the combustor has the highest irreversibility value. ExD of components increases when RPM is elevated. However, it does not mean that the higher RPM value leads to deteriorate exergetic performance of the engine. To make decision for this, exergetic parameters are calculated for eighteen running points. In this regard, the ExD of the combustor increases from 3.621 MW to 11.604 MW whereas that of the whole engine raises from 5.18 MW to 19.5 MW throughout RPM values.

Table 4 gives the results of exergetic improvement potential for each component. These outcomes indicate that the combustor amongst the components has the highest potential to be enhanced. The second highest potential belongs to the HPT unit. Considering total improvement rate, it is observed to vary from 1.098 MW to 2.331 MW when RPM is increased from the lowest value to the highest one. Additionally, the combustor consists 84.51 % at 50.29 % RPM and 64.82 % at 100 % RPM of total exergetic improvement potential.

Fuel exergy and product exergy of components are tabulated in Table 5. The term fuel exergy means input exergy whereas the term product exergy represents output exergy. The difference between fuel exergy and output exergy gives exergy destruction.

Table 6 gives exergy losses of Fan outlet and exhaust outlet. This exergy loss is calculated from between wasted exergy and exergy destruction. Considering relative exergy losses, it decreases from 52.34 % to 30.58 % at Fan outlet whereas it increases from 47.65 % to 69.41 % at exhaust outlet when RPM is varied from 50.29 % to 100 %. At 50.29 %

RPM, the difference between losses of Fan outlet and exhaust outlet is calculated as 0.042 MW while it is computed as 5.707 MW at 100%. Considering these findings, to determine the lowest exergy losses depends on determining optimum RPM value.

Table 4 Exergetic improvement potential of main components throughout eighteen RPM values

RPM (%)	FAN (MW)	LPC (MW)	HPC (MW)	CC (MW)	HPT (MW)	LPT (MW)
50.29	0.035	0.018	0.036	0.928	0.067	0.013
55.32	0.04	0.021	0.04	0.963	0.086	0.019
59.93	0.045	0.024	0.044	1.003	0.107	0.024
64.3	0.05	0.026	0.049	1.039	0.129	0.028
68.4	0.055	0.029	0.052	1.076	0.152	0.03
71.99	0.058	0.03	0.055	1.115	0.173	0.035
75.25	0.058	0.03	0.058	1.153	0.195	0.039
78.18	0.057	0.03	0.061	1.193	0.217	0.042
80.77	0.056	0.029	0.064	1.231	0.24	0.045
83.05	0.053	0.028	0.068	1.27	0.263	0.048
85.13	0.049	0.026	0.071	1.308	0.284	0.052
87.09	0.047	0.025	0.074	1.347	0.306	0.055
89.02	0.044	0.024	0.078	1.385	0.327	0.058
90.92	0.043	0.024	0.081	1.425	0.35	0.06
92.76	0.043	0.024	0.084	1.468	0.372	0.062
94.75	0.047	0.025	0.087	1.511	0.395	0.063
97.19	0.063	0.032	0.09	1.551	0.416	0.065
100	0.094	0.044	0.095	1.588	0.438	0.068

Table 5 The outcomes of fuel and product exergy for six components throughout eighteen RPM values

	FAN		LPC		HPC		CC		HPT		LPT	
RPM (%)	**F (MW)**	**Pr (MW)**	**F (MW)**	**Pr (MW)**	**F (MW)**	**Pr (MW)**	**F (MW)**	**Pr (MW)**	**F (MW)**	**Pr (MW)**	**F (MW)**	**Pr (MW)**
50.29	1.077	0.883	0.935	0.805	5.179	4.747	14.132	10.51	5.956	5.322	2.27	2.097
55.32	1.567	1.316	1.321	1.153	6.597	6.081	17.964	13.804	7.562	6.753	3.25	3.001
59.93	2.102	1.792	1.723	1.519	7.92	7.325	21.799	17.121	9.052	8.064	4.29	3.964
64.3	2.652	2.286	2.13	1.89	9.223	8.55	25.636	20.473	10.52	9.352	5.341	4.952
68.4	3.228	2.804	2.542	2.269	10.463	9.719	29.465	23.834	11.918	10.571	6.416	5.971
71.99	3.803	3.333	2.947	2.647	11.667	10.86	33.303	27.209	13.292	11.771	7.473	6.96
75.25	4.374	3.867	3.344	3.022	12.841	11.973	37.13	30.586	14.634	12.942	8.521	7.942
78.18	4.943	4.408	3.735	3.397	14.005	13.076	41.015	34.02	15.966	14.102	9.568	8.928
80.77	5.507	4.952	4.116	3.768	15.159	14.168	44.899	37.463	17.271	15.235	10.602	9.904
83.05	6.057	5.49	4.487	4.132	16.312	15.258	48.831	40.955	18.563	16.352	11.609	10.857
85.13	6.594	6.021	4.85	4.491	17.47	16.352	52.79	44.478	19.877	17.497	12.578	11.767
87.09	7.122	6.543	5.207	4.844	18.627	17.447	56.801	48.053	21.19	18.642	13.526	12.66
89.02	7.642	7.056	5.56	5.191	19.786	18.543	60.861	51.678	22.503	19.787	14.461	13.543
90.92	8.146	7.548	5.907	5.529	20.954	19.649	65.044	55.414	23.814	20.926	15.368	14.401
92.76	8.632	8.019	6.244	5.856	22.112	20.749	69.299	59.211	25.115	22.056	16.248	15.237
94.75	9.126	8.468	6.593	6.18	23.327	21.901	73.872	63.304	26.48	23.245	17.158	16.112
97.19	9.67	8.887	6.988	6.511	24.67	23.173	79.022	67.949	28.004	24.588	18.149	17.055
100	10.257	9.272	7.422	6.844	26.136	24.553	84.765	73.161	29.62	26.015	19.225	18.08

Table 6 Exergy losses from Fan outlet and exhaust outlet

RPM (%)	Fan outlet losses (MW)	Exhaust outlet losses (MW)	Fan Relative exergy losses (%)	Exhaust Relative exergy losses (%)
50.29	0.468	0.426	52.34	47.65
55.32	0.696	0.682	50.5	49.49
59.93	0.947	0.992	48.83	51.16
64.3	1.203	1.355	47.02	52.97
68.4	1.471	1.767	45.42	54.57
71.99	1.741	2.232	43.82	56.17
75.25	2.011	2.741	42.31	57.68
78.18	2.281	3.313	40.77	59.22
80.77	2.549	3.934	39.31	60.68
83.05	2.811	4.631	37.77	62.22
85.13	3.064	5.373	36.31	63.68
87.09	3.309	6.176	34.88	65.11
89.02	3.546	7.027	33.53	66.46
90.92	3.768	7.969	32.1	67.89
92.76	3.976	8.599	31.61	68.38
94.75	4.17	9.085	31.45	68.54
97.19	4.343	9.618	31.1	68.89
100	4.497	10.204	30.58	69.41

To evaluate energetic performance of the engine, thrust and specific fuel consumption metrics regarding LBP-TFE are employed. These parameters are presented in Figure 2. As seen in Figure 2, when the relative RPM is increased from 50.2 % to 100 %,

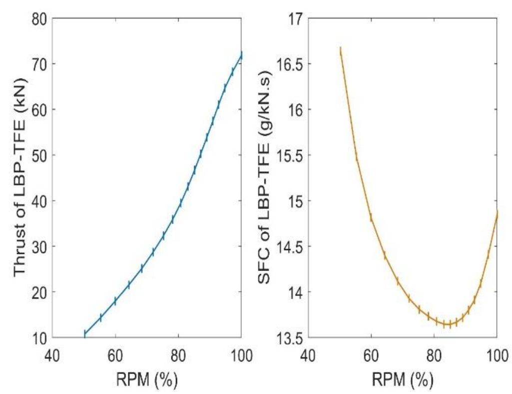

Figure 2 Variation of thrust and SFC regarding LBP-TFE against RPM values

the thrust of LBP-TFE raises from 10.7 kN to 71.8 kN whereas the SFC does not continuously decreases with rising RPM. Namely, it diminishes from 16.63 g/kN.s (at 50.2 % RPM) to 13.644 g/kN.s (at 85.13 % RPM). After that point, it increases up to 14.85 g/kN.s at 100% RPM.

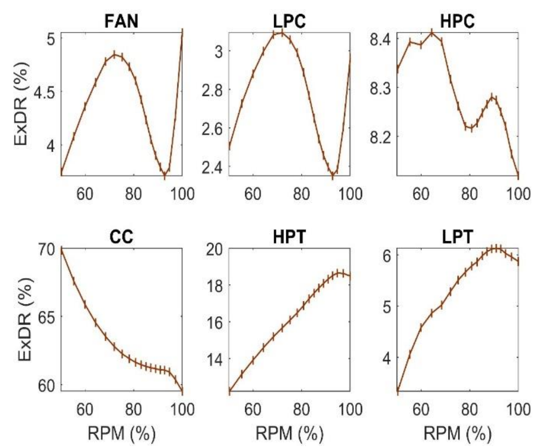

Figure 3 Variation of exergy destruction ratio pertaining to six components against RPM values

Figure 3 shows how exergy destruction ratio (ExDR) of major components changes according to RPM value. As seen in, the ExDR of Fan, LPC and HPC fluctuate throughout RPM values. Therefore, effect of power setting on this metric may not be distinct. However, the trend of ExDR of the combustor is apparent and it amongst other components has highest ratio changing from

69.85% to 59.51% owing to rising RPM. One can infer from this finding is that exergy destruction of the combustor accounts for highest share of total irreversibility. When regarding maximum RPM, ExDRs of the Fan, LPC and HPC are figured out as 5.05%, 2.96% and 8.12% while those of CC, HPT and LPT are estimated as 59.51%, 18.49% and 5.87%, respectively.

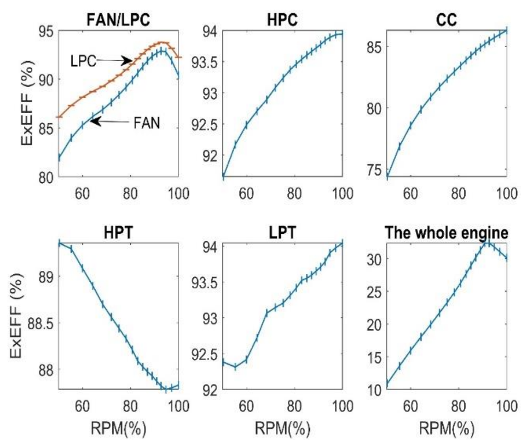

Figure 4 Variation of exergy efficiency pertaining to six components against RPM values

To measure exergetic performance of LBP-TFE and its components, several exergetic parameters are computed for eighteen throttle settings. Firstly, exergy efficiency of the system is presented in Figure 4. As can be understood, variations of exergy efficiency of Fan and LPC have similar trend by an increase in the RPM. Considering only component exergy efficiency, effects of power setting could not be understood. Therefore, exergy efficiency is also examined for the whole engine. This approach is implemented for the other metrics regarding LBP-TFE. Except HPT unit, exergy efficiency of components generally increases due to rising RPM. The lowest exergy efficiency belongs to the combustor, which raises from 74.31% to 86.37%. The highest exergy efficiency for the whole engine is calculated as 32.4% at 92.76 % RPM. In this context, this parameter regarding LBP-TFE varies from 10.91% to 30.14% throughout all RPM values.

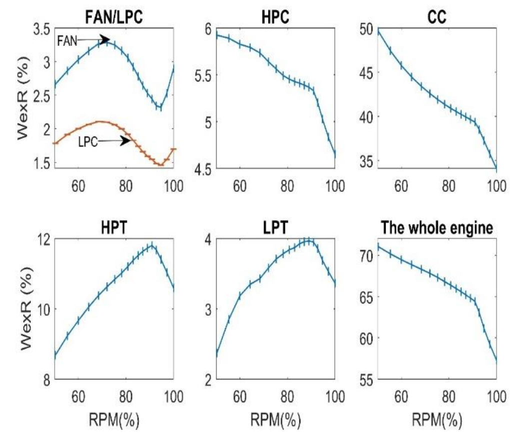

Figure 5 Variation of wasted exergy ratio pertaining to six components against RPM values

As for another significant indicator, wasted exergy ratio of LBP-TFE and its components are given in Figure 5, It is desired that WExR becomes the lowest value. In terms of environmental sustainability, this parameter related to the whole engine is favorably affected at elevated RPM values. Namely as the relative RPM is increased it decreases from 71.04% to 57.31%. This important decrement proves that operation points close to idle RPM lead to inefficiently consume fuel. Furthermore, significant part of this wasted exergy originates from the combustor. As seen in, the decrement curve of WExR of the combustor is similar with that of the whole engine. In this context, WExR of the combustor decreases from 49.62% to 34.1% throughout RPM values. The decrement curve of WExR regarding LBP-TFE is less susceptible to variations of power setting from 50.52% up to 90.92% RPM. This could be attributed to increment in WExRs of HPT and LPT at the specified ranges.

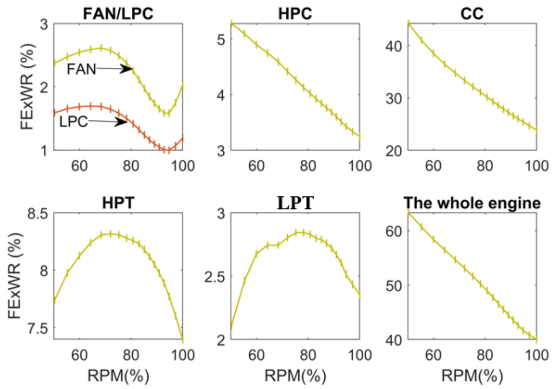

Figure 6 Variation of fuel exergy waste ratio pertaining to six components against RPM values

Variations of Fuel exergy waste ratio of the components are presented in Figure 6. This metric measures wasted exergy rate per unit fuel exergy. As understood in, FExWR of the Fan is higher than that of the LPC. However, their responds against to RPM variation bear resemblance. In this context, the FexWR of the LBP-TFE decreases from 63.28% to 40.02 % whereas that of the combustor diminishes from 44.2% to 23.81% due to rising RPM from 50.2% to 100%.

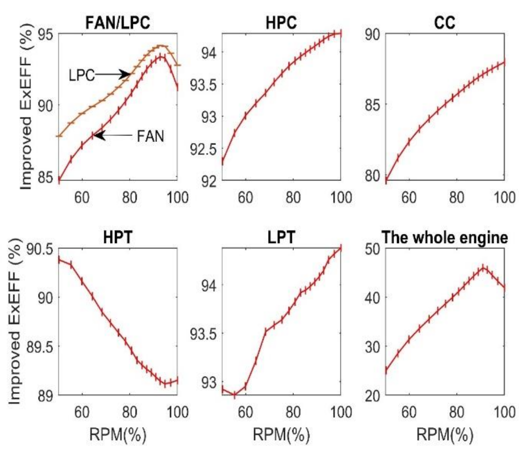

Figure 7 Variation of improved exergy efficiency pertaining to six components against RPM values

Figure 7 presents improved exergy efficiency (IMPExEFF) pertaining to LBP-TFE and its components. This indicator means that if exergetic improvement for each component is achieved, it specifies how much exergy efficiency of the considered unit enhances. When compared with real exergy efficiency, variation curve of improved exergy efficiency against to RPM is same, but its magnitude is higher than real one for each component as expected. In this sense, the IMPExEFF of the combustor increases from 79.6% to 87.96%. The increment averagely occurs 2.64% whereas the IMPExEFF related to the whole engine is computed to vary from 25.03% to 41.88%. Compared with real exergy efficiency, the increase takes place about 14.25% throughout the whole RPM values.

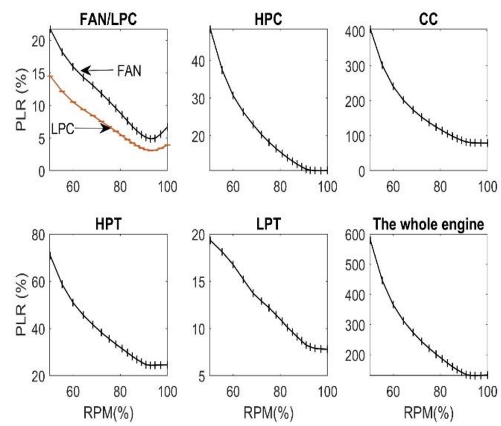

Figure 8 Variation of productivity lack ratio pertaining to six components against RPM values

To investigate exergetic performance in detail, productivity lack ratio of components are also calculated in Figure 8. It gauges exergy destruction per unit product (or useful) exergy. Except the combustor, PLR values of the other components are less than 100 %. It means that magnitude of product exergy is lower than that of exergy destruction. However, it does not hold for the combustor and the whole engine. Moreover, increment of power setting highly affects this metric. Namely, PLR of the combustor decreases from 404.74 % to 78.93 %. Similarly, the PLR of the whole engine diminishes from 560.13 % to 124.84 % as the RPM increases from 50.2 % to 100 %. As seen in, the PLRs of all components demonstrate similar trend by increase in the RPM.

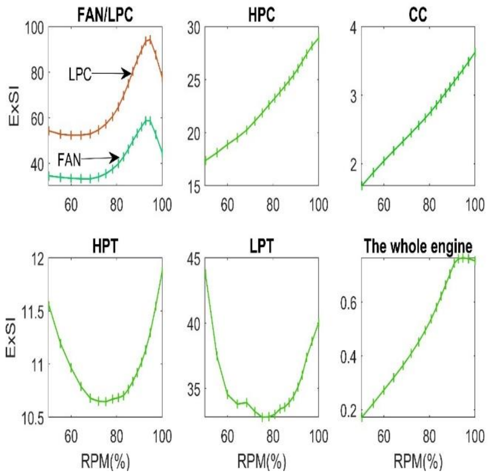

Figure 9 Variation of exergetic sustainability index pertaining to six components against RPM values

In the present study, well-known two parameters are dealt with for evaluating the engine sustainability. Firstly, curves of exergetic sustainability index against RPM variation are obtained in Figure 9. To measure high ExSI, two conditions that are high exergy efficiency and low WExR are necessary. Increasing RPM value leads to enhance ExSI of the whole engine. Namely, its value is found to be 0.1724 at 50.2 % RPM and 0.7533 at 100% RPM. Moreover, the ExSI of the combustor varies from 1.68 to 3.62 throughout RPM values. As seen in Figure 9, ExSI values of Fan, LPC, HPT and LPT fluctuate with variation of RPM. To make decision which point is suitable for sustainability, the ExSI of the whole engine plays key role for determining optimum power setting.

As for another index pertaining to sustainability shown in Figure 10, sustainable efficiency factor is proposed in the open literature. This parameter is associated with exergy efficiency. As the exergy efficiency increases, the SEF is found to be higher. Up to 92.76 % RPM, the SEF of LBP-TFE increases from 1.1225 to 1.4793. At 100 % RPM, its value is computed as 1.4315. The reason for this decrement could be decrement of the SEF of Fan and LPC. Besides, the SEF of combustor is observed to vary from 3.902 to 7.304 due to rising RPM.

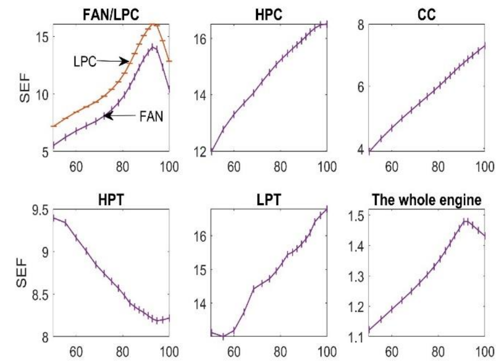

Figure 10 Variation of sustainable effect factor pertaining to six components against RPM values

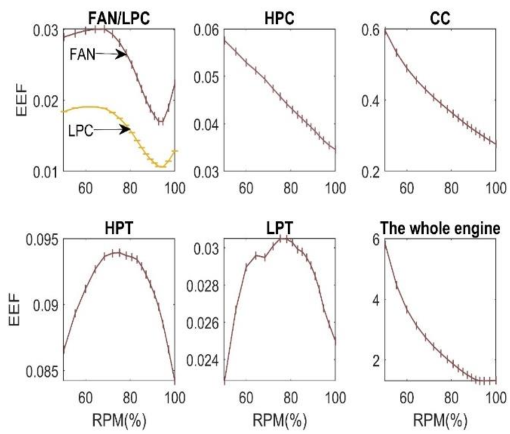

Figure 11 Variation of environmental effect factor pertaining to six components against RPM values

In the current study, there are exergetic indicators related to environmental impact. Firstly, environmental effect factor regarding the engine and its components is investigated for eighteen RPM values in Figure 11. Similar to the previous comments made, EEF value of the overall engine should be considered so as to clearly understand effect of throttle setting. In this context, the EEF of LBP-TFE is estimated to change from 5.8 to 1.32 whereas that of the combustor varies from 0.594 to 0.275 by an increase in the RPM. Moreover, as seen in figure 11, the EEF of LPC is lower than that of the Fan. It can be partly attributed that exergy destruction of Fan is higher than that of LPC.

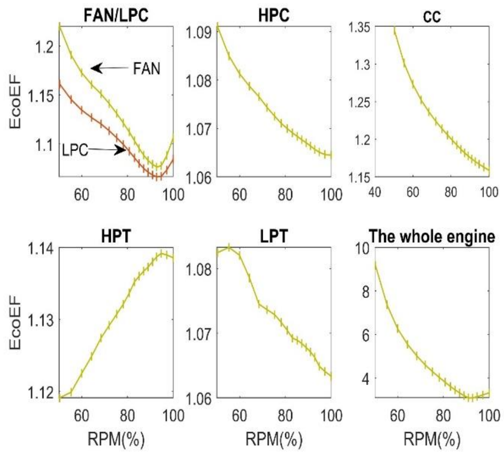

Figure 12 Variation of ecological effect factor pertaining to six components against RPM values

Figure 12 demonstrates how EcoEF regarding components vary according to RPM value. As can be understood, there are non-linear EcoEF curves. Effect of power setting on this index is very obvious. Namely, the EcoEF value pertaining to overall engine decreases from 9.16 to 3.31 while that the combustor is observed to change from 1.344 to 1.158 owing to the elevated RPM step by step.

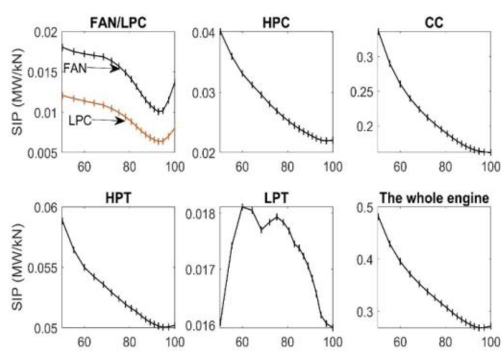

Figure 13 Variation of specific irreversibility index pertaining to six components against RPM values

Finally, specific irreversibility index for each component is calculated for eighteen operating points in Figure 13. This parameter measures exergy destruction per unit thrust. The SIP of the LBP-TFE decreases from 0.481 MW/kN to 0.271 MW/kN. It corresponds 43.6 % decrement. Furthermore, the SIP of the combustor is observed to decrease from 0.336 MW/kN to 0.161 MW/kN. As can seen in, the general trend of SIP for each component is prone to diminish with rising RPM.

5.CONCLUSION

This study dealt with exergetic and environmental metrics regarding low by-pass turbofan engine at several RPM values. The main aim is to evaluate effects of power settings for LBP-TFE and its six components. For this goal, specific code related to exergetic relations was written so as to calculate these parameters for each RPM value at MATLAB environment. Thermodynamic performance of the engine considered is measured with a set of exergetic and exergo-sustainability parameters for the LBP-TFE and its six components. Exergetic metrics evaluated in this study involve exergy efficiency, exergy destruction ratio, wasted exergy ratio, fuel exergy waste ratio, improved exergy efficiency and productivity lack ratio whereas environmental metrics incorporate exergetic sustainability index, environmental effect factor, sustainable efficiency factor and ecological effect factor. The main contribution of this study is to observe behaviours of performance, exergetic and environmental throughout eighteen RPM values. This analysis involving different running points can help understanding optimum RPM value for environmental sustainability. Additionally, firstly, the index ‘specific irreversibility production’ was computed for the LBP-TFE. Thanks to this metric, irreversibility of the engine per unit thrust is measured. Several significant findings can be highlighted from the current study as following:

i. The thrust of the LBP-TFE non-linearly increases throughout RPM values. Namely, the thrust value of the engine changes from 10.77 to 71.8 kN throughout RPM values.

ii. Exergy efficiency of the LBP-TFE is favourably affected from increase in RPM. Its value increases from 10.91 % to 30.14 % throughout RPM values. However, the highest exergy efficiency is computed as 32.4 % at 92.76 % RPM.

iii. Fuel exergy waste ratio of the engine decreases from 63.28 % to 40.02 % when the relative RPM is increased from 50.29 % to 100 %. This means that irreversibility per unit fuel exergy significantly diminishes.

iv. Improved exergy efficiency of the LBP-TFE is observed to change from 25.03 % to 41.88 %. It can deduced that compared with real exergy efficiency, exergy efficiency can be improved between 11.73 % and 15.55 % throughout RPM values.

v. Environmental efffect factor of the LBP-TFE decreases from 5.8 to 1.32 with increment of power setting. However the lowest value is 1.30 at 92.76 % RPM. It means that determining optimum RPM value leads to find the point where minimum environmental damage occurs.

vi. Finally, the results of specific irreversibility production for the engine verify findings of exergetic parameters. Namely, SIP value decreases due to rising RPM. It means that the engine produces less irreversibility at elevated RPMs.

As a conclusion, to find minimum and maximum points of exergetic values, the engine should be operated at relatively the lowest and the highest points. This study could guide the researchers to detect optimum RPM values in terms of environmental impact of the gas turbine engine. As a next study, exergetic and environmental parameters regarding LBP-TFE could be estimated with several prediction methods such as long-short term memory and supported vector machine. The modeling of performance parameters depending on RPM value could be performed. Also, effects of power settings on exergo-economic analysis metrics can be researched.

Funding
The author has no received any financial support for the research, authorship or publication of this study.

The Declaration of Conflict of Interest/ Common Interest
No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval
The author declare that this study does not require an ethics committee approval or any special permission.

The Declaration of Research and Publication Ethics
The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

REFERENCES

[1] H.Y. Akdeniz, O. Balli. "Effects of Bypass Ratio Change Trend on Performance in a Military Aircraft Turbofan Engine With Comparative Assessment". Journal of Energy Resources Technology. vol.143 no.12, pp. 120905, 2021.

[2] https://www.icao.int/sustainability/pages/factsfigures.aspx. (Last accessed 05 11 2022)

[3] K. Kayaalp, S. Metlek, S. Ekici, Y. Sohret. "Developing a model for prediction of the combustion performance and emissions of a turboprop engine using the long short-term memory method".Fuel. vol.302, pp. 121202, 2021.

[4] M. Z. Sogut. "New approach for assessment of environmental effects based on entropy optimization of jet engine".Energy. vol.234, pp. 121250, 2021.

[5] A. Dinc, I. Elbadawy. "Global warming potential optimization of a turbofan powered unmanned aerial vehicle during surveillance mission" . Transportation Research Part D: Transport and Environment. vol.85: pp. 102472, 2020.

[6] O. Balli. "Advanced exergy analyses of an aircraft turboprop engine (TPE)".Energy. vol.124, pp. 599-612, 2017.

[7] A. Dinc, H. Caliskan, S. Ekici, Y. Sohret. "Thermodynamic-based environmental and enviroeconomic assessments of a turboprop engine used for freight aircrafts under different flight phases".Journal of Thermal Analysis and Calorimetry. vol.147 no.22, pp. 12693-12707, 2022.

[8] H. Tuzcu, Y. Sohret, H. Caliskan. "Energy, environment and enviroeconomic analyses and assessments of the turbofan engine used in aviation industry".Environmental Progress & Sustainable Energy. vol.40 no.3,pp. e13547, 2020.

[9] O. Turan. "An exergy way to quantify sustainability metrics for a high bypass turbofan engine".Energy. vol.86, pp. 722-736, 2015.

[10] O. Balli, S. Ekici, T.H. Karakoc. "TF33 Turbofan engine in every respect: Performance, environmental, and sustainability assessment". Environmental Progress & Sustainable Energy. vol.40 no.3, pp. e13578, 2021.

[11] A. Dinc, Y. Sohret, S. Ekici. "Exergy analysis of a three-spool turboprop engine during the flight of a cargo aircraft".Aircraft Engineering and Aerospace Technology.vol.92 no.10,pp.1495-1503, 2020.

[12] O. Balli, H. Caliskan. "Turbofan engine performances from aviation, thermodynamic and environmental perspectives".Energy. vol.232, pp. 121031, 2021.

[13] https://prattwhitney.com/products-and-services/products/commercial-engines/jt8d. (Last accessed 09 11 2022)

[14] O. Turan, H. Aydin. "Exergy-based sustainability analysis of a low-bypass turbofan engine: A case study for JT8D". Energy Procedia. vol.95, pp. 499-506, 2016.

[15] https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank. (Last accessed 01 12 2022)

[16] J. D. Mattingly, Elements of propulsion: gas turbines and rockets. 2006: American Institute of Aeronautics and Astronautics.

[17] A. F. El-Sayed, Aircraft propulsion and gas turbine engines. 2008: CRC press.

[18] O. Balli, H. Caliskan. "On-design and off-design operation performance assessmentsof an aero turboprop engine used on unmanned aerial vehicles (UAVs) in terms of aviation, thermodynamic, environmental and sustainability perspectives". Energy Conversion and Management. vol.243, pp. 114403, 2021.

[19] H. Aygun, O. Turan. "Exergetic sustainability off-design analysis of variable-cycle aero-engine in various bypass modes". Energy. vol.195, pp. 117008, 2020.

[20] Y. A. Cengel, M. A. Boles, Thermodynamics: An Engineering Approach 6th Editon (SI Units). 2007: The McGraw-Hill Companies, Inc., New York.

[21] T. J. Kotas, The exergy method of thermal plant analysis. 1995: Krieger.

[22] H. Aygun. "Investigation of effects of several design parameters on exergo-sustainability metrics for twin-spool turbojet engine at different flight conditions". International Journal of Exergy. vol.37 no.2, pp. 200-213, 2022.

[23] H. Aygun. "Thermodynamic and environmental considerations of small turbojet engine under different design variables".Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2021. https://doi.org/10.1080/15567036.2021.1985019

[24] W. Van Gool, "Energy Policy: Fairy Tales and Factualities". Innovation and Technology — Strategies and Policies, O.D.D. Soares, A.M. da Cruz, G.C. Pereira, I.M.R.T. Soares, and A.J.P.S. Reis, Editors., Springer Netherlands: Dordrecht. 1997, pp. 93-105.

[25] O. Balli. "Exergy modeling for evaluating sustainability level of a high by-pass turbofan engine used on commercial aircrafts". Applied Thermal Engineering. vol.12, pp. 138-155, 2017.

[26] G. P. Hammond. "Energy and sustainability in a complex world: Reflections on the ideas of Howard T. Odum".International Journal of Energy Research. vol.31 no.12, pp. 1105-1130, 2007.

[27] H. Aydin, O. Turan, T. H. Karakoc, A. Midilli. "Exergetic sustainability indicators as a tool in commercial aircraft: a case study for a turbofan engine".International journal of green energy. vol.12 no.1, pp. 28-40, 2015.