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Araştırma / Research

EKSERJİ ANALİZİ YÖNTEMİ KULLANILARAK BİR GAZ TÜRBİNLİ JET MOTORUNUN PERFORMANS ARAŞTIRMASI

Cem Tahsin YÜCER[1] (ORCID: 0000-0002-4848-867X)[*]

[1]National Defense University Air Force NCO Higher Vocational School, 35410 Gaziemir/ İzmir

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ÖZ

Bu çalışmada bir gaz türbinli jet motorunun üç farklı devir sayısı için performans analizi yapılmıştır. Çalışmanın amacı kompresör, yanma odası ve gaz türbini için teorik ve ölçüm sonucu elde edilen verilerin termodinamik süreçler dikkate alınarak incelenmesi ve jet motoru bileşenlerinin enerji ve ekserji dengelerinin elde edilmesidir. Ele alınan jet motorunun devir sayısı 120.000 d/d değerine kadar artırılabilmektedir. Ölçülen veriler basınç, sıcaklık, hava akımının debisi, yakıtın debisi ve itki değerleridir. Bu makalede jet motoruna ait ölçülen verilere ve analitik sonuçlara yer verilmiştir. Birinci kısmi yük için kompresör çıkış sıcaklığı en düşük olduğu için gaz türbininden elde edilen iş miktarı da en düşük değerdedir. Yanma odasının ekserji yıkım miktarları üç farklı yük değerinde de en yüksek değerlerdedir. Jet motorunun çalışma yükü artırıldıkça yakıttan daha fazla ekserji elde edilmektedir. Buna rağmen ekserji verimi ise çalışma yükü arttıkça azalmaktadır. Ekserji verimleri sırasıyla %7.1, %6 ve %5.5 olarak bulunmuştur.

Anahtar kelimeler: Jet motoru, Ekserji analizi, Enerji analizi, Kısmi yük.

INVESTIGATION OF THE PERFORMANCE FOR A GAS TURBINE JET ENGİNE BY USING EXERGY ANALYSIS METHOD

ABSTRACT

This study deals with a gas turbine jet engine module which was analyzed to investigate its performance at three different gas turbine speed values. The objectives are: to examine the thermodynamic processes involved, to determine the theoretical and measured data for the compressor, the combustion chamber and the gas turbine and to perform the energy and exergy balances on the jet engine components. The jet engine can operate up to the120000 rpm. The measured data include pressure, temperature, air flow rate, fuel flow rate and thrust values. This paper presents measured experiment data and analytical results of the jet engine. Since the compressor outlet temperature of the part load-1 is the minimum of all, it has the minimum work gained from the gas turbine. The exergy destructions caused by the combustion chamber were the maximum above all system components. It can be inferred from the analysis that the more loading applied to the jet engine the more exergy gained from the fuel. However the exergy efficiencies become lower. They were calculated as 7.1%, 6% and 5.5%, respectively.

Keywords: Jet engine, Exergy analysis, Energy Analysis, Part load.

1. INTRODUCTION

A small scale turbojet engine was used to carry out the experiments. The jet engine module has the maximum compressibility ratio capacity of 2.1. This compressibility ratio represents small scale gas turbine jet engines [1].

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[*]Corresponding author / Sorumlu yazar. Tel.: +90 232 251 16 00; e-mail / e-posta: tyucer@tekok.edu.tr

The engine consists of a single stage radial flow compressor, a single stage axial flow gas turbine and a reverse flow annular combustion chamber. The turbojet engine is of a single shaft design. The compressor and gas turbine are both rotating on the same shaft at the same speed. The turbojet engine was equipped with a data acquisition system to monitor the temperature, pressure, flow rates and thrust.

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. Development of high pressure ratio turbojet engines lead to higher overall efficiencies [2].

Dincer and Rosen explained the steps for exergy analysis on aircraft in [3]. 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. Exergy analysis of air vehicles took great attention to analyze the inefficient places in the system. Turan [5] studied energy and entropy analyses of an experimental turbojet engine. Brayton cycle results are simulated in P-v, T-s and h-s diagrams.

The papers [6-7] investigated the the exergetic performances of turbojet and turboprop engines thermodynamically. Bahete and Gilani [8] studied the perfromance of a gas turbine at part loads. Hayes et al. [9] performed exergy analysis for aerospace use.

Ekici et al. [10] studied the sustainability indicators of a small scale turbojet engine. Exergetic performance of the turbojet engine was investigated to obtain exergy efficiency, waste exergy ratio, environmental effect factor, exergy destruction factor and exergetic sustainability index. Şöhret [11] performed a comprehensive assessment on a turbojet. He derived novel measures to understand the irreversiblities in turbojet and its components. The highest endogenous and avoidable irreversibilities belong to turbine and compressor, respectively. Coban et al. [12] investigated the exergetic assessment of an indigenous mini class gas turbine engine. Exergetic efficiencies of centrifugal compressor, combustion chamber and high pressure turbine were calculated as 74.04%, 56.06% and 98.98%, respectively.

This study justifies how thermodynamic exergy analysis has the potential to facilitate a breakthrough in the optimization of aerospace vehicles based on a system of energy systems. Jet engines operate at higher performance standards when the load is increased. However, part load-3 performance is not the best case according to the calculated exergy metrics. In this paper, the main objectives of this contribution are (i) to examine the performance of a small gas turbine jet engine using exergy analysis method (ii) to calculate the energy and exergy flows, as well as the exergy efficiencies and exergy destructions of the jet engine components under three part loads and (iii) to compare the effect of load on the exergetic performance of the jet engine components.

2. MATERIAL AND METHOD

Jet engine module is comprised of an axial turbine with a direct coupled radial compressor and an annular combustion chamber. The turbine and compressor wheels are fitted to a common shaft. The engine is fully throttleable from an idle speed of 35000 rpm to a maximum speed to 120000 rpm.

The jet engine module operates according to the open cycle, in which the working medium is taken from the environment and returned to it. The air in the cycle is subject to the following changes: i) Adiabatic compression of the air in the compressor from ambient pressure (P_1) to pressure (P_2) and related temperature rise from T_1 to T_2. ii) Isobaric heating of air between temperatures T_2 and T_3 as a result ofthe combustion process. iii) Non adiabatic expansion of the hot air in the turbine results in pressure decrease. Turbine outlet expands to ambient pressure. During this process temperature decreases from T_3 to T_4.

In this study, a complete energy analysis is applied to the jet engine components. Each of the components and the jet engine itself were investigated. Certain parameters were selected to understand operation performance of the jet engine. These are specific fuel consumption and energy efficiencies which are the key parameters. Heat losses and air-fuel ratio were also studied. Performance according to three different gas turbine speeds was analyzed to compare the findings. Examined components are compressor, combustion chamber and gas turbine.

Gas turbine drives the compressor. Fig. 1 illustrates the energy rate flows in the control volume of the compressor.

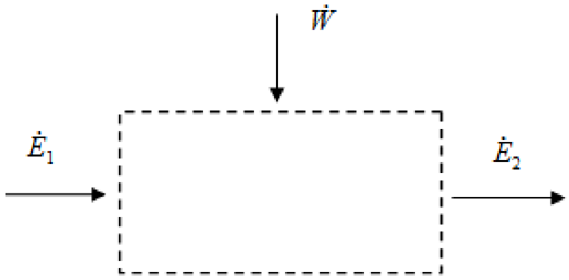

Figure 1. The control volume of the compressor

The work obtained from gas turbine rotates the gas turbine shaft. Then it forms the required energy to operate the compressor. Similarly the energy balances for the other components are illustrated in Figs. 2-3.

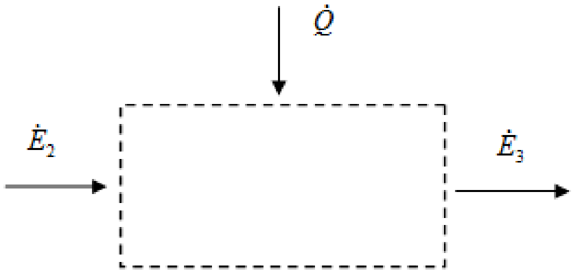

Figure 2. The control volume of the combustion chamber

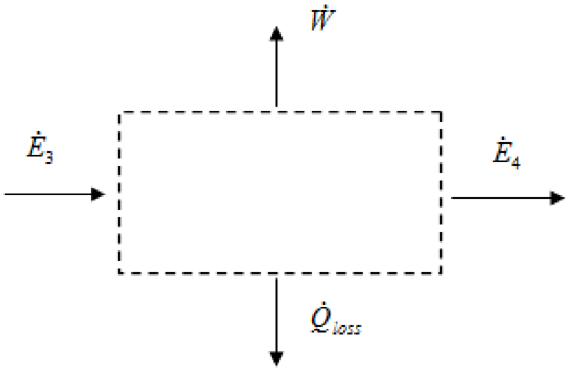

Figure 3. The control volume of the gas turbine

2.1 Energy Analysis

In the energy analysis, the first law of thermodynamics is applied. The portions of energy of a flow are formulated as follows,

$$\dot{H}_i = \dot{m}_i . h_i \tag{1}$$

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

$$\dot{E}_{k,i} = \frac{1}{2} \dot{m}_i . v_i{}^2 \tag{3}$$

$$\dot{E}_{P,i} = \dot{m}_i . g . z_i \tag{4}$$

$$\dot{E}_i = \dot{H}_i + \dot{E}_{k,i} + \dot{E}_{p,i} \tag{5}$$

$\dot{H}_i$, $\dot{m}_i$, h_i, $c_{p,i}$, T_i, v_i, z_i, $\dot{E}_{k,i}$, $\dot{E}_{p,i}$ and $\dot{E}_i$ are enthalpy rate, mass flow rate, specific enthalpy, specific heat ratio at constant pressure, temperature, velocity, height from a reference level, kinetic energy rate, potential energy rate and total energy rate of state i. g denotes the gravitational acceleration.

To model jet engine module; the values of enthalpy rate, heat energy rate, work rate at the inlet and at the outlet stream of each component were calculated with the following equations. The examined gas turbine jet engine components are compressor, combustion chamber and gas turbine.

- Compressor (C)

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_{air} \tag{6}$$

$$\dot{W}_C = \dot{m}_{air}(c_{p,2}.T_2 - c_{p,1}.T_1) \tag{7}$$

Here $\dot{m}_{air}$ and $\dot{W}_C$ indicate mass flow rate of air and compressor work rate. The compressor is assumed to be adiabatic.

- Combustion chamber (CC)

$$\dot{E}_{fuel} = \dot{m}_{fuel}.LHV \tag{8}$$

$$\dot{E}_{fuel} + \dot{E}_2 = \dot{E}_3 \tag{9}$$

$$\dot{m}_{air} + \dot{m}_{fuel} = \dot{m}_{gas} \tag{10}$$

$\dot{m}_{fuel}$, LHV and $\dot{m}_{gas}$ stand for mass flow rate of fuel, lower heating value of fuel and mass flow rate of gas (combustion product).

- Gas turbine (GT)

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_{gas} \tag{11}$$

$$\dot{W}_{GT} = \dot{m}_{gas}.\left(c_{p,3}.T_3 - c_{p,4}.T_4\right) - Q_{loss} \tag{12}$$

$$\dot{W}_{GT} = \dot{W}_C \tag{13}$$

$\dot{W}_{GT}$ is the work rate of gas turbine. The gas turbine is assumed as non-adiabatic. This is the case in similar laboratory experiments as in [13]. Heat loss takes place because of the significant heat release from the combustion chamber. Then the work obtained is equal to the compressor work.

2.2 Exergy Analysis

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,

$$\dot{E}x_{i,in} = \dot{E}x_{i,out} + \dot{E}x_{i,D} \tag{14}$$

$$\dot{E}x_i = \dot{m}_i.[c_{p,i}.(T_i - T_0 - T_0.(s_i - s_0)] \tag{15}$$

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

Exergy equations consist of exergy destruction ($\dot{E}x_{i,D}$), inlet ($\dot{E}x_{i,in}$) and outlet ($\dot{E}x_{i,out}$) flows in the examined open system at state i. s denotes the entropy at state i. $\dot{E}x_i$ 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 [14].

- Compressor (C)

$$\dot{E}x_{C,in} = 0 \tag{17}$$

$$\dot{W}_C + \dot{E}x_{C,in} = \dot{E}x_{C,out} + \dot{E}x_{C,D} \tag{18}$$

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

- Combustion Chamber (CC)

$$\dot{\varepsilon}_f = \varphi.\,LHV \tag{19}$$

$$\dot{E}x_{fuel} = \dot{m}_{fuel}.\,\dot{\varepsilon}_{fuel} \tag{20}$$

$$\dot{E}x_{CC,in} + \dot{E}x_{fuel} = \dot{E}x_{CC,out} + \dot{E}x_{CC,D} \tag{21}$$

- Gas Turbine (GT)

$$\dot{E}x_{GT,in} = \dot{E}x_{GT,out} + \dot{W}_{GT} + \dot{E}x_{GT,D} + \dot{E}x_Q \tag{22}$$

The combustion gases leaving the gas turbine are at high temperature and cause high exergy loss rates. The exergy rate of heat loss ($\dot{E}x_Q$) in the non-adiabatic turbine is formulated in the above equation.

3. RESULTS AND DISCUSSION

The turbojet engine characteristics at three 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. For the investigated part loads, the speed of the turbine changed from 42,175 rpm to 58,207 rpm.

The energy rates at part load-1 for the compressor outlet, the turbine inlet and the turbine outlet were calculated as 5.8 kW, 25.12 kW and 15 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-3. The work rate at part load-1 was calculated as 0.25 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-3 it was found to be 0.84 kW. The observed data of the part load operation, the energy and exergy results and exergy destruction values are presented in Table 1-4 respectively.

Table 1. Experimental Data

Measured Data	**Units**	**Part Load-1**	**Part Load-2**	**Part Load-3**
T_2	K	301.25	306.55	312.4
T_3	K	1072.95	1096.39	1096.39
T_4	K	693.85	648.74	644.63
P_2	kPa	113.47	119.33	122.48
$\dot{m}_{air}$	kg/s	0.0192	0.0337	0.0462
$\dot{m}_{fuel}$	kg/s	0.00148	0.00159	0.00185
Turbine speed	1/min	42175	51093	58207
Thrust	N	9.96	12.5	15.039

Table 2. Energy Flow Rates (kW)

State	**Part Load-1**	**Part Load-2**	**Part Load-3**
1	5.541	9.761	13.369
2	5.795	10.390	14.206
3	25.12	44.134	59.978
4	15	23.780	32.613

Table 3. Exergy Flow Rates (kW)

State	**Part Load-1**	**Part Load-2**	**Part Load-3**
1	0	0	0
2	0.174	0.457	0.724
3	9.686	17.441	23.785
4	3.298	4.616	6.436

Table 4. Exergy Destruction Rates (kW)

Load Type	**Compressor**	**Combustion Chamber**	**Gas Turbine**
Part load-1	0.079	65.284	6.135
Part load-2	0.172	55.550	12.196
Part load-3	0.113	61.270	16.512

4. CONCLUSION

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

Some concluding remarks of the study were as follows:

- The work rate increased as the part load increased. it changed from 0.25 kW to 0.84 kW.
- The maximum exergy destructions were observed in combustion chamber. These are 65.284 kW, 55.55 kW and 61.27 kW for the three loadings, respectively.
- The maximum exergy rate input in the combustion chamber was calculated at part load-3. It was 84.33 kW.
- The maximum exergy efficiency of the jet engine was observed at part load-1, as 7.1%. The minimum exergy efficiency was found to be 5.5% at part load-3.

In this study, the energy and exergy analyses of a gas turbine jet engine was investigated. For a future work, exergetic optimization of the jet engine is planned to investigate.

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