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Some Exergetic Measures of a JT8D Turbofan Engine

Onder Turan
Faculty of Aeronautics and Astronautics, Anadolu University, TR-26470 Eskisehir, Turkey
Email: onderturan@anadolu.edu.tr

Hakan Aydın, T. Hikmet Karakoc, and Adnan Midilli
TUSAS Engine Industries (TEI), TR-26003, Eskisehir, Turkey
Faculty of Aeronautics and Astronautics, Anadolu University, TR-26470 Eskisehir, Turkey
Advanced Energy Technologies, Energy Division, Mechanical Engineering Department, Faculty of Engineering, Recep Tayyip Erdogan University, Rize, 53000, Turkey
Email: {tei.hakan, hikmetkarakoc}@gmail.com; adnan.midilli@erdogan.edu.tr

Abstract—**In this article, some exergetic measures are calculated for a JT8D turbofan engine at takeoff. Selected exergetic measures in this study are as follows: fuel depletion ration, productivity lack ratio, fuel exergy factor, product exergy factor and improvement potential rates. The engine has low-pressure compressor (LPC) stages, high pressure compressor (HPC) stages, a single HP turbine (HPT), and finally three LPT stages. The exergetic assessment of the JT8D turbofan components provided here should be helpful for designing turbofan engines. Results from this study also evaluate effects of the maximum power setting on the exergetic measures of the engine components commonly used in medium range commercial aircrafts.**

Index Terms—**low bypass turbofan, exergy, propulsion, commercial aircraft, improvement potential rates**

I. INTRODUCTION

Energy efficiency in commercial aircrafts is improved by averaging 1.5% percent annually with the introduction of bypass turbofan engines. However, as the bypass ratio increased, engine diameter has also increase, leading to an increase momentum drag. Other way to propulsion system improvement is to increase turbine inlet temperature. Between the introduction B707 and B777, commercial aircrafts have been constructed exclusively of aluminum and are currently about 90% metallic by weight. So improvements of structural efficiency are less evident [1].

Worldwide passenger traffic will average 5.1 percent growth and cargo traffic will average 5.6 percent growth 2–5% of the world energy consumption belongs to aviation industries [2]-[6]. Total scheduled world revenue ton kilometers (RTK) increased by 119 per cent, with scheduled passenger revenue passenger kilometers (RPK) and cargo (RTK) traffic rising by 108 and 140 per cent, respectively [7]. Effects of energy consumption in aviation sector give rise to potential environmental hazards. Therefore energy consumption plays a crucial importance role to achieve sustainable development; balancing economic and social development with environmental protection. The importance of energy efficiency is also linked to environmental problems, such as global warming and atmospheric pollution [8], [9].

The environmental impact of emissions can be reduced by increasing the efficiency of resource utilization [10]. Using energy with better efficiency reduces pollutant emissions. Energy and exergy concepts have been utilized in environmental sustainability, economics and engineering. Exergy is a quantity which follows from the First and Second Laws of Thermodynamics and analyses directly impact process design and improvements because exergy methods help in understanding and improving efficiency, environmental and economic performance as well as sustainability. The potential usefulness of exergy analysis in addressing sustainability issues and solving environmental problems is substantial [11]-[15]. The exergy studies related to gas turbines have first been done on stationary gas turbines. In the literature, the various exergy and exergo-economic analysis of aero engines have been reported [16]-[30].

Through a literature review, it is noticed that there is no work to be studied about exergetic measures for a JT8D turbofan engine in the open literatures. The present assessment, therefore, aims to provide a practical framework for the use of such exergy analysis in low bypass engines. Lack of exergy analysis for low bypass turbofan engine makes the paper original and becomes main motivation.

In this paper, the detailed exergetic parameters of JT8D low bypass turbofan engine have been performed. In this analysis, fuel depletion ration, productivity lack ratio, fuel exergy factor, product exergy factor and improvement potential rates have been calculated at maximum power setting, i.e. takeoff condition. These exergetic parameters of JT8D have first been studied in this paper.

II. SYSTEM DESCRIPTION JT8D TURBOFAN ENGINE

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JT8D series engines are one of the most popular modern commercial engines ever made. More than 14,750 of them have been built, amassing more than 673 million hours of reliable service since 1964. The eight models that make up the JT8D family cover a thrust range from 62 to 76 kN. The newer JT8D-200 engine offers 18,500 to 21,700 pounds of thrust, and is the exclusive power for the popular MD-80 aircraft [31].

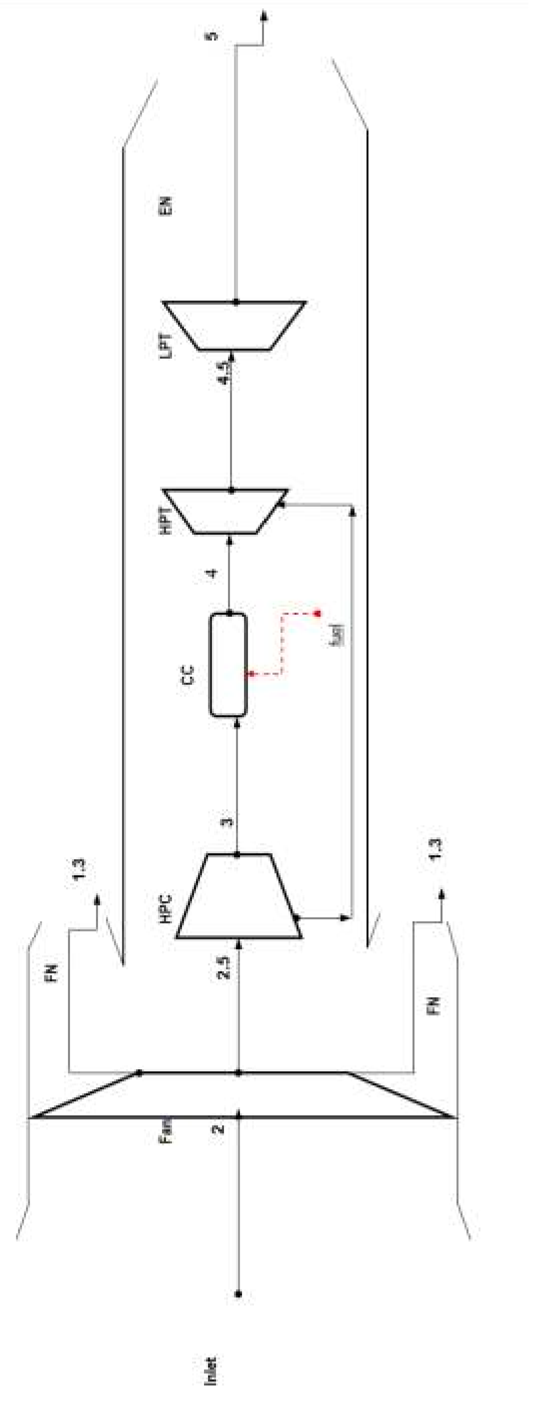

Figure 1. Main components of JT8D engine

An illustrated diagram, station numbering and main component of the high bypass turbofan engine is shown in Fig. 1. It consist of fan (F), axial low pressure compressor (LPC), axial high pressure compressor (HPC), an annular combustion chamber, high-pressure turbine (HPT) and low pressure turbine (LPT).

This engine operates according to the Brayton cycle, which includes four processes under the ideal conditions given below:

a. isentropic compression (fan and HPC)
b. combustion at constant pressure (CC)
c. isentropic expansion (HPT and LPT)
d. heat transfer at constant pressure (EN and FN).

There are two drive shafts in this engine. The first, N_2, connects the HPT and HPC and constitutes the HP system, while the second, N_1, connects the LPT to the fan and constitutes the LP system. While the high pressure turbine runs the high pressure compressor, fuel pump, starter generator and reduction gearbox, LPT runs the fan.

III. EQUATIONS FOR THERMODYNAMIC ANALYSIS

Thermodynamic first-law analysis is energy-based approach in thermal systems. It is based on the principle of conservation of energy applied to the system. For a general steady state, steady-flow process, the four balance equations (mass, energy, entropy and exergy) are applied to find the work and heat interactions, the rate of exergy decrease, the rate of irreversibility, the energy and exergy efficiencies [32]-[34].

First Law or 'energy' analysis takes no account of the energy source in terms of its thermodynamic quality. It enables energy or heat losses to be estimated, but yields only limited information about the optimal conversion of energy.

In contrast, the Second Law of Thermodynamics indicates that, whereas work input into a system can be fully converted to heat and internal energy, not all the heat input can be converted into useful work [37]. The exergy loss in a system or component is determined by multiplying the absolute temperature of the surroundings by the entropy increase [37]-[39]. Exergy methods also help in understanding and improving efficiency, environmental and economic performance as well as sustainability [40].

Note that, whereas energy is a conserved quantity, exergy is not and is always destroyed when entropy is produced. In the absence of electricity, magnetism, surface tension and nuclear reaction, the total exergy of a system $\dot{E}x$ can be divided into four components, namely (i) physical exergy $\dot{E}x^{PH}$ (ii) kinetic exergy $\dot{E}x^{KN}$ (iii) potential exergy $\dot{E}x^{PT}$ and (iv) chemical exergy $\dot{E}x^{CH}$ [37].

Numerous ways of formulating exergy (or second-law) efficiency for various energy systems are given in detail elsewhere [41]. It is very useful to define efficiencies based on exergy. There is no standard set of definitions in the literature. Here, exergy efficiency is defined as the ratio of total exergy output to total exergy input, i.e.

$$\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \tag{1}$$

This improvement potential in the rate form, denoted $\dot{IP}$, is given by

$$I\dot{P} = (1-\eta_{ex})(\dot{E}x_{in} - \dot{E}x_{out}) \tag{2}$$

Fuel depletion ratio (δ_k) expresses the exergy destruction for a system unit as a percentage of the total fuel exergy, and can be written as [42]

$$\delta_k = \frac{\dot{E}x_{dest,k}}{\dot{F}_{tot}} \tag{3}$$

Productivity lack, which is similar to the fuel depletion ratio, gives the product loss in the form of exergy destruction or shows how much product exergy potential is lost due to exergy destructions. Productivity lack ξ is expressible as [42];

$$\xi_k = \frac{\dot{E}x_{dest,k}}{\dot{P}_{tot}} \tag{4}$$

Fuel and product exergy factors measure the parts of the fuel and product exergy values for a component as a fraction of the total fuel and product exergy values for the engine, respectively. These factors provide useful information about the consumed and produced exergy quantities inside the system, on a component by component basis. The fuel exergy factor *f* can be written as [42];

$$f_k = \frac{\dot{F}_k}{\dot{F}_{tot}} \tag{5}$$

and the product exergy factor *p* as [42];

$$p_k = \frac{\dot{P}_k}{\dot{P}_{tot}} \tag{6}$$

IV. ANALYSIS

The total airflow mass is 142.7 kg/s that includes 74.74 kg/s fan air and 67.95 kg/s core air. Air is taken into LPC at ambient temperature of 288.15 K and ambient pressure of 101.35 kPa. In gas turbine engines, a part of compressed air is extracted to use for ancillary purposes, such as cooling, sealing and thrust balancing. In this study the cooling airflow is neglected since it doesn't have meaningful effect on exergy and sustainability analyses.

In this study, the assumptions made are listed below

(a) The air and combustion gas flows in the engine are assumed to behave ideally.

(b) The combustion reaction is complete

(c) Compressors and turbines are assumed to be adiabatic

(d) Ambient temperature and pressure values are 288.15 K and 101.35 kPa, respectively.

(e) The exergy analyses are performed for the lower heating value (LHV) of kerosene (JET A1) which is accepted as 42,800kJ/kg.

(h) Engine accessories, pumps (fuel, oil and hydraulic) are not included in the analysis

(i) The kinetic and potential exergies are neglected

(j) Chemical exergy is neglected other than combustor.

As fuel the kerosene (JET A) is burned. Its chemical formula is as $C_{12}H_{23}$. The value of LHV is 42,800 kJ/kg. Fuel flow is 1.05 kg/s that results in air/fuel ratio as 64.

The exergy analysis of JT8D gas turbine engine's Fan, HPC, combustor, HPT and LPT will be performed.

V. RESULTS AND CONCLUSIONS

In this paper, some exergetic parameters of JT8D turbofan engine at takeoff thrust power have been carried out. In this analysis, these parameters are fuel depletion ration, productivity lack ratio, fuel exergy factor, product exergy factor and improvement potential rates. Now, it is necessary to definite the phases of flight for an aircraft. Considering the flight phases as a function of engine power, the flight phases can be split into seven parts in this study: a) landing b) climb c) maximum cruise d) normal take-off e) maximum continuous f) automatic power reverse g) maximum take-off.

Fig. 2 demonstrates the fuel depletion of the fan, HPC, combustor, HPT, LPT and JT8D turbofan engine at takeoff condition.

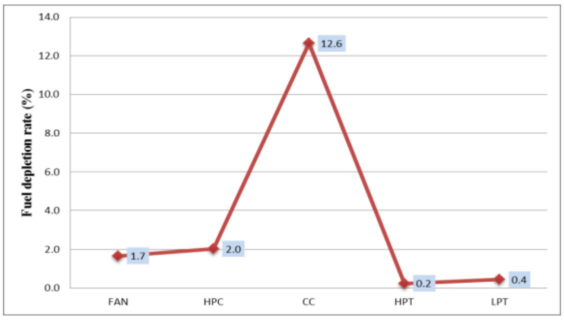

Figure 2. Fuel depletion rate of JT8D engine components.

Fig. 3 also illustrates the productivity lack ratio of the fan, HPC, combustor, HPT, LPT and JT8D turbofan engine at takeoff condition.

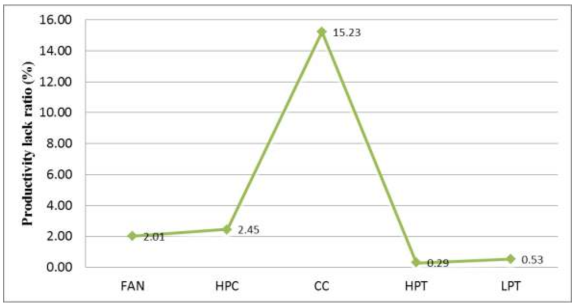

Figure 3. Productivity lack ratio of JT8D engine components.

Fuel exergy factor of the fan, HPC, combustor, HPT, LPT and JT8D turbofan engine at takeoff condition is given in Fig. 4.

Fig. 5 also shows the productivity exergy factor of the fan, HPC, combustor, HPT, LPT and JT8D turbofan engine at takeoff condition.

Finally, Fig. 6 also illustrates the improvement potential rates of the fan, HPC, combustor, HPT, LPT and JT8D turbofan engine at takeoff condition.

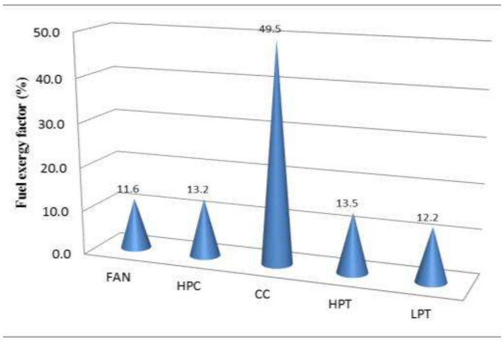

Figure 4. Fuel exergy factor of JT8D engine components.

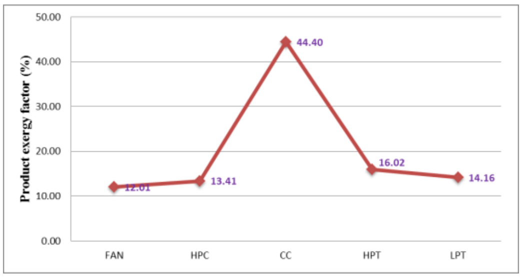

Figure 5. Product exergy factor of JT8D engine components.

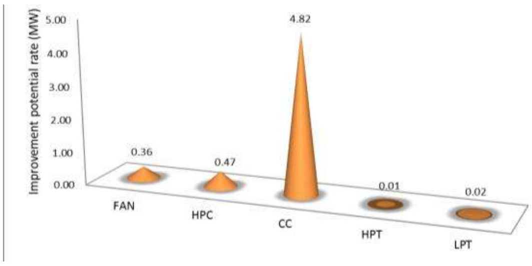

Figure 6. Improvement potential rates of JT8D engine components.

The exergetic parameters studied in this paper, important indicators for the sustainability of the engine, is mainly based on the exergy input and the required output. It is noticed that the exergy efficiency of the turbofan engine highly affected by the input-output exergetic values of the each engine component at all phases of a flight. The results in Fig. 2 show that the fuel depletion ratio values ranges from 0.2% to 12.6% in engine components. As can be seen in Fig. 2, HPT and LPT are good fuel depletion ratios changes between 0.2-0.4 due to higher isentropic efficiencies. For the fan and HPC, fuel depletion ratios are found to be 1.7% and 2%, respectively. On the other hand, maximum fuel depletion ratio is observed in combustor (to be 12.6%) due to internal irreversibilites in CC.

The unit with productivity lack ratio is found to be CC (to be 15.3%) as shown in Fig. 3. The productivity lack ratio for the other units are found to be HPC (to be 2.45%), fan (to be 2.01%), LPT (to be 0.53%) and HPT (to be 0.29).

Greatest fuel exergy factor is calculated in the CC (to be 49.5%) as shown in Fig. 4. It is clear from Fig. 4 that fan fuel exergy factor with value of 11.6%. For the product exergy factor, CC has maximum value (to be 44.4%) as shown in Fig. 5.

Finally, in the last figure, minimum improvement potential rate is found in HPT with the value of 0.01 MW. For the other low improvement potential rates are calculated to be 0.02 MW for the LPT, 0.36 MW for the fan and 0.47 MW for the HPC as shown in Fig. 6. On the other hand, improvement potential rate is observed in combustor (to be 4.82 MW) due to irreversibilites in CC.

The results should provide a realistic and meaningful in the thermodynamics second law evaluation of JT8D low bypass turbofan engine, which may be useful in the analysis of similar propulsion systems. In a future study, we will focus on exergo-environmental and exergo-sustainability analysis of the low bypass turbofan engine. It is noted that, to obtain more comprehensive conclusions, exergo-economics must be considered. In particular, an exergo-economic analysis would be useful. An exergo-environmental analysis can help improve the environmental performance of the low bypass engine, and consequently should be considered in future assessments.

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Onder Turan is an Assist. Prof. in the School of Civil Aviation. He received his BSc and MSc in the School of Civil Aviation and Graduate School of Sciences at Anadolu University in 1998 and 2000, respectively. He received his PhD in 2007 under the supervision of Dr. Hikmet Karakoc. He has published many papers at various national and international conferences. He is also a member of many journals and associations. His research areas include aviation, energy and energy economy, gas turbine engines, aircraft propulsion systems and fuels.

Hakan Aydin works at TUSAS Engine Industries (TEI) as an aeronautical engineer in Eskisehir, Turkey, while he makes his PhD thesis under the supervision of Dr. Onder Turan in Anadolu University, Eskisehir, Turkey. He has published several articles in various prestigious international journals and conferences.

T. Hikmet Karakoc is a Full Professor of School of Civil Aviation at Anadolu University, Eskisehir, Turkey. He received his MSc and PhD in 1983 and 1987, respectively. He has published many papers at various national and international conferences, while he has authored several books. He is also a member of many journals and associations. His research areas include aviation, energy and energy economy, gas turbine engines, fuels, isolation and installation.

Adnan Midilli is a professor of Marine Engineering Department in Turgut Kiran Maritime College of Recep Tayyip Erdogan University, Rize,Turkey between 1993–2010, he worked in Mechanical Engineering Department at the Faculty of Engineering of the Nigde University, Nigde, Turkey. He has authored/co-authored books and book chapters, many journal and conference papers and numerous technical reports. He has chaired many conferences, symposia, workshops and technical meetings. He is an active member of various international scientific organizations and societies and serves as the Associate Editor and Editorial Board member of various prestigious international journals. He is a recipient of several research, teaching and service awards. He has been an active Researcher and Supervisor. His research areas include energy and sustainability.