Exergetic Performance of a Low Bypass Turbofan Engine at Takeoff Condition

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4 authors, including:

T. Hikmet Karakoc
Eskisehir Technical University

Adnan Midilli
Istanbul Technical University

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Hakan Aydın
TUSAS Engine Industries (TEI), TR-26003, Eskisehir, Turkey
E-mail: tei.hakan@gmail.com

Onder Turan
Faculty of Aeronautics and Space Sciencies,
Anadolu University, TR-26470 Eskisehir, Turkey
E-mail: onderturan@anadolu.edu.tr

Adnan Midilli
Advanced Energy Technologies,
Energy Division, Mechanical Engineering Department, Faculty of Engineering, Recep Tayyip Erdogan University, Rize, 53000, Turkey
E-mail: adnan.midilli@erdogan.edu.tr

T. Hikmet Karakoc
Faculty of Aeronautics and Space Sciencies,
Anadolu University, TR-26470 Eskisehir, Turkey
E-mail: hikmetkarakoc@gmail.com

ABSTRACT

In this article, exergetic methodology is applied for a low bypass turbofan engine at maximum power setting. The engine is a low-bypass (0.96 to 1) turbofan engine and its variants fitted to the 737-100/200 all comprise six low-pressure compressor (LPC) stages, seven high pressure compressor (HPC) stages, a single HP turbine (HPT), and finally three LPT stages. At the end of the analysis, the most irreversible units in the system are found to be the combustor and the fan/low pressure compressor, with exergy loss rates of 18.7 MW and 2.486 MW, respectively. The exergy efficiencies of the fan/LPC, the HPC and combustor are 0.856, 0.845 and 0.744, respectively. For the HPT and LPT, the exergy efficiencies are calculated to be 0.98 and 0.963, respectively.

INTRODUCTION

With over two billion people travelling safely around the world every year and some 23,000 aircraft in commercial service. 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 (Boeing, 2011; Enviro, 2011; IATA, 2005; Lee et al., 2007; USHP, 2006). Total scheduled world revenue tonne 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 (Macintosh and Wallace, 2008). 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 (Ahmadi et al., 2011; Ptasinski et al., 2006).

Energy intensity can be related to some important measures operational and technological efficiency in the aircraft and its propulsion system. An aero-engine converts the flow of chemical energy contained in the kerosene fuel and the air drawn into the engine into propulsion power. Nearly one-fourth or one-third of fuel energy is used to propel the aircraft. The remaining energy is expelled as waste heat in the exhaust. Specific fuel consumption (SFC) is more relevant to consider propulsion power in terms of payload carried per unit range. Energy intensity (E_I) is a suitable parameter with comparing efficiency and environmental impact. It consists of two components- energy use, E_U and load factor, L_f as shown in Eq.1 (Joosung et al., 2004).

$$E_I = \frac{E_U}{L_f} = \frac{MJ}{RPK} = \frac{MJ}{ASK} / \frac{RPK}{ASK} \qquad (1)$$

Where MJ is mega joules of kerosene fuel energy, RPK is revenue passenger-kilometers, ASK is available seat- kilometers, and L_f is load factor. To have a model of aircraft, it is necessary to show E_I as a function of the engine, aerodynamic, and structural efficiency of the aircraft system as well as load factor. These parameters play important role in the energy intensity of an aircraft. 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, which is limited by materials and cooling technology, and improving engine component efficiencies. 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 (Joosung et al., 2004).

The environmental impact of emissions can be reduced by increasing the efficiency of resource utilization (Rosen, 2002). 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 (Ao et al., 2008; Dincer and Rosen, 1998; Midilli and Dincer, 2009, 2010; Norberg et al., 2009). 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 (Aydin et al., 2012a, 2012b; Ballı et al., 2008; Bejan and Seems, 2001; Brilliant, 1995; Cesare et al., 2010; Diango et al., 2011; Etele and Rosen, 2001; Figliola, 2003; Riggins, 1996; Roth and Mavris, 2000, 2001; Schiffmann and Favrat, 2010; Turan, 2012a, 2012b).

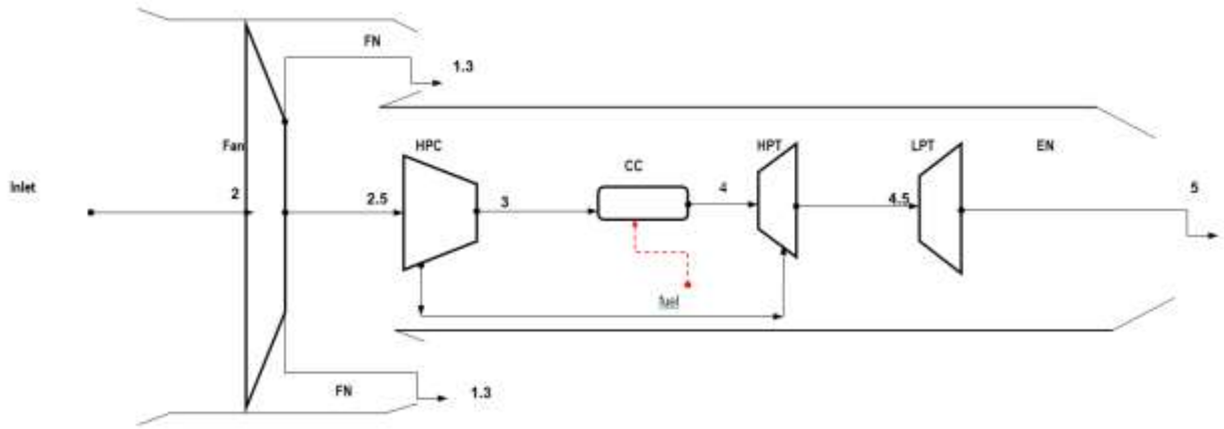
Through a literature review, it is noticed that there is no work to be studied about exergy analysis for a low bypass turbofan engines in the open literatures. The present assessment, therefore, aims to provide a practical framework for the use of such exergy analysis in low bypass engines. Lack of exergy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

In this paper, first the detailed exergy analysis of JT8D low bypass turbofan engine has been performed. In this analysis, exergy efficiency, exergy losses/destructions have been calculated at maximum power setting, i.e. takeoff condition. Exergy analysis of JT8D has first been studied in this paper. Moreover, there is no previous work about exergy related to low bypass turbofan engine in the aircraft engine in the literature.

SYSTEM DESCRIPTION FOR LOW BYPASS TURBOFAN ENGINE

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 (B-1-7.pdf)

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).



HPC: *High pressure compressor*; **CC:** *combustion chamber*; **HPT:** *High pressure turbine*; **LPT:** *Low pressure turbine*; **EN:** *Exhaust nozzle*; **FN:** *Fan nozzle*

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.

In the schematic diagram of the high bypass turbofan engine given in Fig. 1, the bypass ratio is defined as

$$\alpha = \frac{\text{Bypass airflow}}{\text{Primary airflow}} = \frac{\dot{m}_{fan}}{\dot{m}_{core}} = \frac{\dot{m}_{cold}}{\dot{m}_{hot}} \qquad (2)$$

Thus if the air mass through the core (HPC) is $\dot{m}_{core}$, then the bypass air mass flow rate is $(\alpha\ \dot{m}_{core})$.

MATHEMATICAL FRAMEWORKS FOR THERMODYNAMIC ANALYSIS

The energy and exergy methods in practice: some useful tools and definitions

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 (Balkan et al., 2005; Dincer et al., 2004; Wall, 2003).

The mass balance equation can be expressed in the rate form as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad , \tag{3a}$$

where $\dot{m}$ is the mass flow rate, and the subscript in stands for inlet and out for outlet. The general energy balance can be expressed below as the total energy inputs equal to total energy outputs.

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{3b}$$

Energy conservation suggests that for a steady-state process the First Law may be represented by (Hammond and Stapleton, 2001):

$$\sum (h + ke + pe)_{in} \dot{m}_{in} - \sum (h + ke + pe)_{out} \dot{m}_{out} + \sum \dot{Q} - \dot{W} = 0 \tag{3c}$$

where $\dot{m}_{in}$ and $\dot{m}_{out}$ denote the mass flow rate across the system inlet and outlet, respectively, $\dot{Q}$ represents the heat transfer rate across the system boundary, $\dot{W}$ is the work rate (including shaft work, electricity, and so on) transferred out of the system, and *h*, *ke*, and *pe* denote the specific values of enthalpy, kinetic energy, and potential energy, respectively.

This energy balance can be simplified, assuming negligibly small changes in kinetic and potential energy and no heat or work transfers, to (Hammond and Stapleton 2001):

$$\sum H_{i,in} = \sum H_{j,out} \tag{3d}$$

where $H_{i,in}$ represents the various energy (or enthalpy) streams flowing into the system, and $H_{j,out}$ the different energy outputs.

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 (Hammond, 2007). The exergy loss in a system or component is determined by multiplying the absolute temperature of the surroundings by the entropy increase (Hepbasli, 2008; Hermann, 2006; Kilkis, 1999). Exergy methods also help in understanding and improving efficiency, environmental and economic performance as well as sustainability (Genoud and Lesourd, 2009).

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 $\dot{E}x^{CH}$ (Hepbasli, 2008).

$$\dot{E}x = \dot{E}x^{PH} + \dot{E}x^{KN} + \dot{E}x^{CH} + \dot{E}x^{PT} \tag{4a}$$

Although exergy is extensive property, it is often convenient to work with it on a unit of mass or molar basis. The total specific exergy on a mass basis may be written as follows (Hepbasli, 2008):

$$ex = ex^{PH} + ex^{KN} + ex^{CH} + ex^{PT} \tag{4b}$$

The general exergy balance can be written as follows (Hepbasli, 2008):

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} + \sum \dot{E}x_{loss} \tag{5a}$$

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,in} - \dot{E}x_{mass,out} = \dot{E}x_{dest} + \dot{E}x_{loss} \tag{5b}$$

$$\dot{E}x_{heat} = \sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k \, , \tag{5c}$$

$$\dot{E}x_{work} = \dot{W}\ ,\tag{5d}$$

$$\dot{E}x_{mass,in} = \sum \dot{m}_{in}\psi_{in}\ ,\tag{5e}$$

$$\dot{E}x_{mass,out} = \sum \dot{m}_{out}\psi_{out}\ .\tag{5f}$$

where $\dot{Q}$ is the heat transfer rate through the boundary at temperature T_k at location k and $\dot{W}$ is the work rate. The flow (specific) exergy is calculated as follows:

$$ex = (h - h_0) - T_0(s - s_0)\tag{6}$$

where *h* is enthalpy, *s* is entropy, and the subscript zero indicates properties at the restricted dead state of P_0 and T_0.

The rate form of the entropy balance can be expressed as (Hepbasli, 2008)

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = 0\tag{7}$$

where the rates of entropy transfer by heat transferred at a rate of $\dot{Q}_k$ and mass flowing at a rate of $\dot{m}$ are $\dot{S}_{heat} = \dot{Q}_k / T_k$ and $\dot{S}_{mass} = \dot{m}s$, respectively (Hepbasli, 2008).

Taking the positive direction of heat transfer to be to the system, the rate form of the general entropy relation given in Eq. (7) can be rearranged to give (Hepbasli, 2008)

$$\dot{S}_{gen} = \sum \dot{m}_{out}s_{out} - \sum \dot{m}_{in}s_{in} - \sum \frac{\dot{Q}_k}{T_k}\tag{8}$$

Also, it is usually more convenient to find $\dot{S}_{gen}$ first and then to evaluate the exergy destroyed or the irreversibility rate $\dot{I}$ directly from the following equation, which is called Gouy–Stodola relation (Szargut et al., 1988):

$$\dot{I} = \dot{E}x_{dest} = T_0\dot{S}_{gen}\tag{9}$$

Assuming air to be a perfect gas, the specific physical exergy of air is calculated by the following relation (Kotas, 1995)

$$ex_{air,per} = C_{p,a}\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right) + R_a T_0 \ln\frac{P}{P_0}\tag{10}$$

Numerous ways of formulating exergy (or second-law) efficiency for various energy systems are given in detail elsewhere (Cornelissen, 1997). 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.

$$\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}}\tag{11}$$

Assumptions

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.

Airflow

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.

Combustion balances and emissions

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. Combustion balance equation is calculated by Eq.(12),

$$C_{12}H_{23}+369\begin{pmatrix}0.7748N_2\\+0.2059O_2\\+0.0003CO_2\\+0.019H_2O\end{pmatrix}\Rightarrow\begin{pmatrix}12.11CO_2\\+18.51H_2O\\+58.22O_2\\+285.9N_2\end{pmatrix} \quad (12)$$

The mass of combustion gases are obtained as 3.43 kg/s for CO_2, 2.14 kg/s for H_2O, 11.98 kg/s for O_2 and 51.46 kg/s for N_2 after combustor chamber.

Specific heat capacities of air and combustion gas

The cold air specific heat capacity is calculated by Eq. (2) as follow

$$c_{P,air}(T)=1.04841-0.000383719T+\frac{9.45378T^2}{10^7}-\frac{5.49031T^3}{10^{10}}+\frac{7.92981T^4}{10^{14}} \quad (13)$$

The specific heat capacity of the combustion gases after combustion chamber for JT8D is calculated from the composition of Eq (1) of each emissions' mass percentage as follow.

$$c_{P,gas}(T)=0.9886+\frac{2.043T}{10^5}+\frac{1.551T^2}{10^7}-\frac{6.717T^3}{10^{11}} \quad (14)$$

Where the unit of temperature is K. For hot gases, R value is calculated as 0.2901 kJ/kg.

EXERGY ANALYSIS

The exergy analysis of JT8D gas turbine engine's Fan, HPC, combustor, HPT and LPT will be performed. The exergy parameters of JT8D for two investigated operating conditions will be calculated by Eqs. (13-19)

i. Fan;

$$\sum\dot{E}x_{in,fan}-\sum\dot{E}x_{out,fan}=\sum\dot{E}x_{dest,fan} \quad (15a)$$

$$\sum\dot{E}x_{in,fan}-\sum\dot{E}x_{out,fan}=\dot{W}_{fan}+\dot{E}x_2-(\dot{E}x_{13}+\dot{E}x_{25}) \quad (15b)$$

$$\dot{W}_{fan}=\frac{\dot{m}_{fan}(\overline{h}_{13}-\overline{h}_2)+\dot{m}_A(\overline{h}_{25}-\overline{h}_2)}{M_A} \quad (15c)$$

$$\eta_{ex,fan}=\frac{\dot{E}x_{13}+\dot{E}x_{25}-\dot{E}x_2}{\dot{W}_{fan}} \quad (15d)$$

ii. High Pressure Compressor;

$$\sum\dot{E}x_{in,HPC}-\sum\dot{E}x_{out,HPC}=\sum\dot{E}x_{dest,HPC} \quad (16a)$$

$$\sum\dot{E}x_{in,HPC}-\sum\dot{E}x_{out,HPC}=\dot{W}_{HPC}+\dot{E}x_{25}-\dot{E}x_3 \quad (16b)$$

$$\dot{W}_{HPC}=\frac{\dot{m}_{HPC}(\overline{h}_3-\overline{h}_{25})}{M_A} \quad (16c)$$

$$\eta_{ex,HPC}=\frac{\dot{E}x_3-\dot{E}x_{2.5}}{\dot{W}_{HPC}} \quad (16d)$$

iii. *Combustor (CC);*

$$\sum \dot{E}x_{in,CC} - \sum \dot{E}x_{out,CC} = \sum \dot{E}x_{dest,CC} \quad (17a)$$

$$\sum \dot{E}x_{in,CC} - \sum \dot{E}x_{out,CC} = \dot{E}x_3 + \dot{E}x_{3,fuel} - \dot{E}x_4 \quad (17b)$$

$$\eta_{ex,CC} = \frac{\dot{E}x_4}{\dot{E}x_3 + \dot{E}x_{3,fuel}} \quad (17c)$$

iv. High Pressure Turbine (HPT):

$$\sum \dot{E}x_{in,HPT} - \sum \dot{E}x_{out,HPT} = \sum \dot{E}x_{dest,HPT} \quad (18a)$$

$$\sum \dot{E}x_{in,HPT} - \sum \dot{E}x_{out,HPT} = \dot{E}x_4 - (\dot{W}_{HPT} + \dot{E}x_{45}) \quad (18b)$$

$$\eta_{ex,HPT} = \frac{\dot{W}_{HPT}}{\dot{E}x_4 - \dot{E}x_{45}} \quad (18c)$$

v. Low Pressure Turbine (LPT):

$$\sum \dot{E}x_{in,LPT} - \sum \dot{E}x_{out,LPT} = \sum \dot{E}x_{dest,LPT} \quad (19a)$$

$$\sum \dot{E}x_{in,LPT} - \sum \dot{E}x_{out,LPT} = \dot{E}x_{45} - (\dot{W}_{LPT} + \dot{E}x_5) \quad (19b)$$

$$\eta_{ex,LPT} = \frac{\dot{W}_{LPT}}{\dot{E}x_{45} - \dot{E}x_5} \quad (19c)$$

JT8D thermodynamic parameters are listed in Tables 1 and 2.

Table 1. JT8D Turbofan engine thermodynamic data for takeoff thrust running.

Station No	Location	Mass flow (kg s-1)	Temperature (K)	Pressure (kPa)	Exergy flow (MW)
0	Air	677.2	288.15	101.35	0
2	FAN inlet	677.2	288.15	101.35	0
1.3	FAN bypass outlet	565.3	327.6	155.8	21.51
2.5	FAN core outlet	111.9	372	221.3	8,39
2.5	HPC inlet	111.9	372	221.3	8,39
3	HPC outlet	111.9	744.2	2178.7	50.55
3	Combustor inlet	111.9	744.2	2178.7	50.55
3	Fuel	2,110	288.15	2000	94.37
4	Combustor outlet	114,2	1350	2082.2	1103
4	HPT inlet	114.2	1350	2082.2	110.3
4.5	HPT outlet	114.2	985	535	59.43
4.5	LPT inlet	114.2	985	535	59.43
5	LPT outlet	114.2	727.6	144.1	24.51

Source: (Farokhi, 2009)

Table 2. Exergy values of the JT8D turbofan engine and its component for takeoff thrust running.

Component	Inlet exergy (MW)	Outlet exergy (MW)	Exergy dest. (MW)	Exergy Efficiency (%)
FAN	32.43	29.90	2.53	0.922
HPC	56.66	50.55	6.11	0.873
Combustor	144.92	110.30	34.62	0.761
HPT	110.30	108.18	2.12	0.958
LPT	59.43	57.26	2.17	0.938
JT8D	94.37	27.92		0.296

RESULTS AND CONCLUSIONS

In this paper, first the exergy analysis of JT8D high bypass turbofan engine at takeoff thrust power has been carried out. In this analysis main exergetic parameters are energy and exergy flows, exergy destruction and exergy efficiency. Now, it is necessary to definite the phases of flight for an aircraft. The phase of flight definitions given in Table 3 consist of broad operational phases. Most of them have sub-phases. 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. Concerning the classification of flight phases as an engine power, it is difficult to see many examples in the literature.

Table 2. Standard definitions the phases of a flight.

Phase	Symbol	Definition	Sub-phases
Standing	STD	prior to pushback or taxi, or after arrival, at the gate or parking area, while the aircraft is stationary	engine(s) i) not operating ii) start-up iii) operating iv) shut-down
Pushback/Towing	PBT	aircraft is moving in the gate, ramp, or parking area, assisted by a tow vehicle	engine(s) i) not operating ii) start-up iii) operating iv) shut-down
Taxi	TXI	aircraft is moving on the ground under its own power prior to take-off and after landing	i) power back ii) taxi to runway iii) taxi to take-off position iv) taxi from run way
Take-off	TOF	from the application of take-off power through rotation and to an altitude of 35 feet above runway elevation	i) take-off ii) rejected take-off
Initial Climb	ICL	from the end of the take-off to the first prescribed power reduction, or until reaching 1,000 feet above runway elevation	-
En Route	ENR	from completion of Initial Climb through cruise altitude and completion of controlled descent to the Initial Approach Fix	i) climb to cruise ii) cruise iii) change of cruise level iv) descent v) holding
Maneuvering	MNVR	low altitude/aerobatic flight operations	i) aerobatics ii) low flying
Approach	APPR	From the Initial Approach Fix to the beginning of the landing flare.	i) initial approach ii) final approach iii) missed approach/go-around
Landing	LDG	from the beginning of the landing flare until aircraft exits the landing runway, comes to a stop on the runway	i) flare ii) landing roll iii) aborted landing after touchdown
Emergency descent	EMG	a controlled descent during any airborne phase in response to a perceived emergency situation	-
Uncontrolled descent	UND	a descent during any airborne phase in which the aircraft does not sustain controlled flight	-
Post-impact	PIM	any of that portion of the flight which occurs after impact with a person, object, obstacle	-

Source: (EADS, 2012)

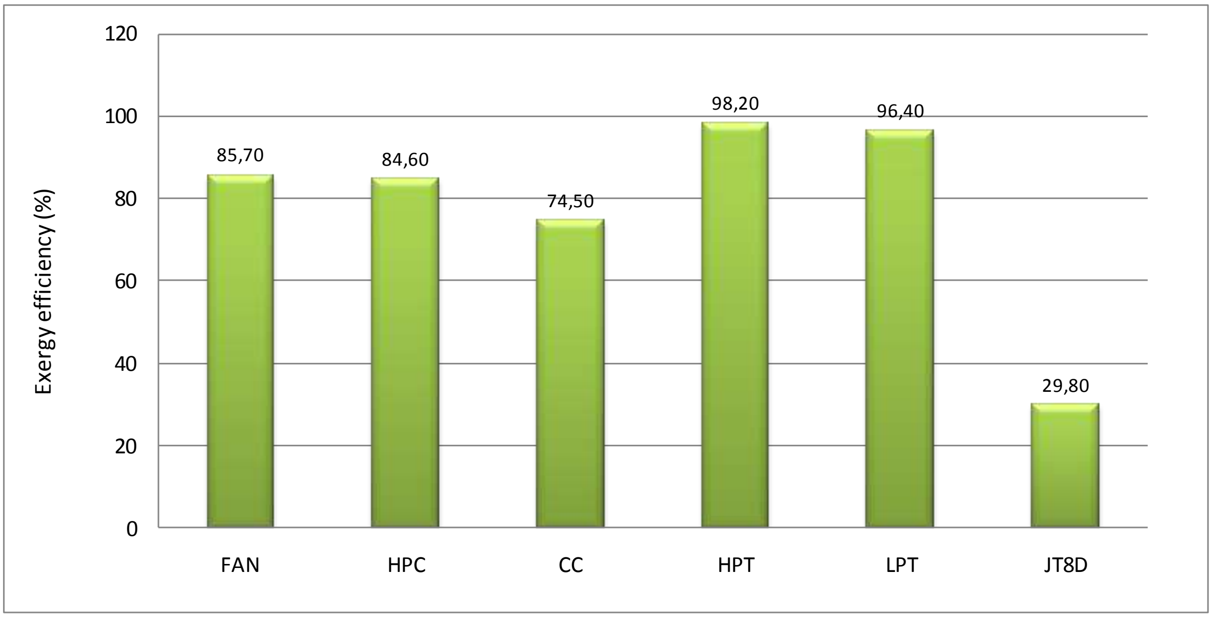


Fig.2. Exergy efficiencies (%) of JT8D turbofan engine at takeoff thrust.

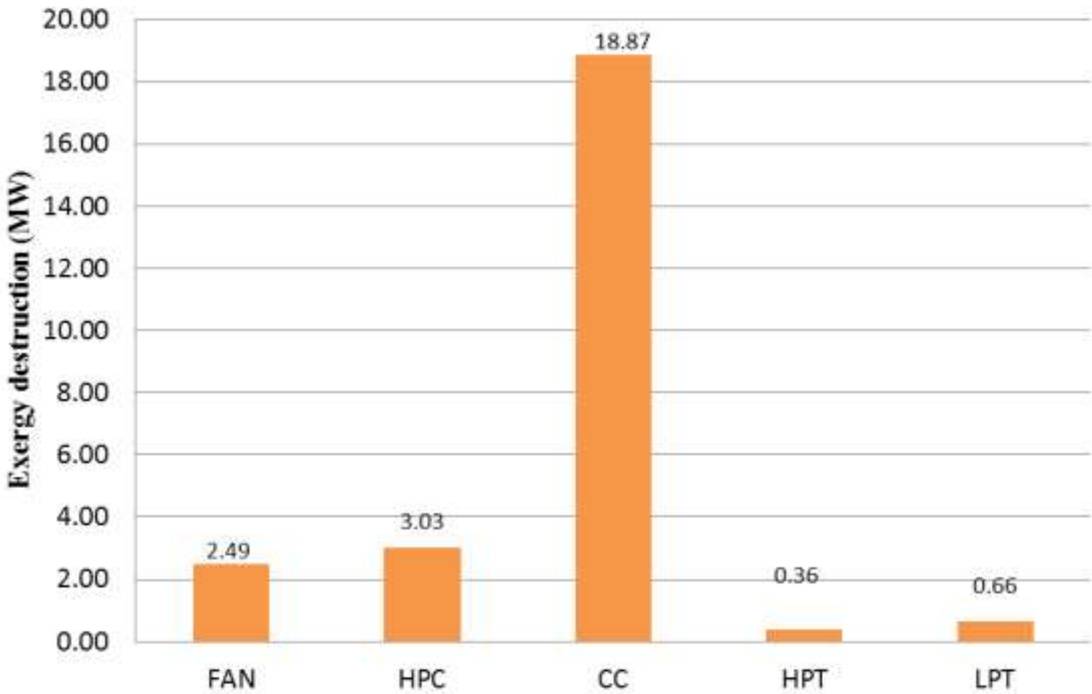


Fig.3. Exergy destruction (MW) of JT8D turbofan engine at takeoff thrust.

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

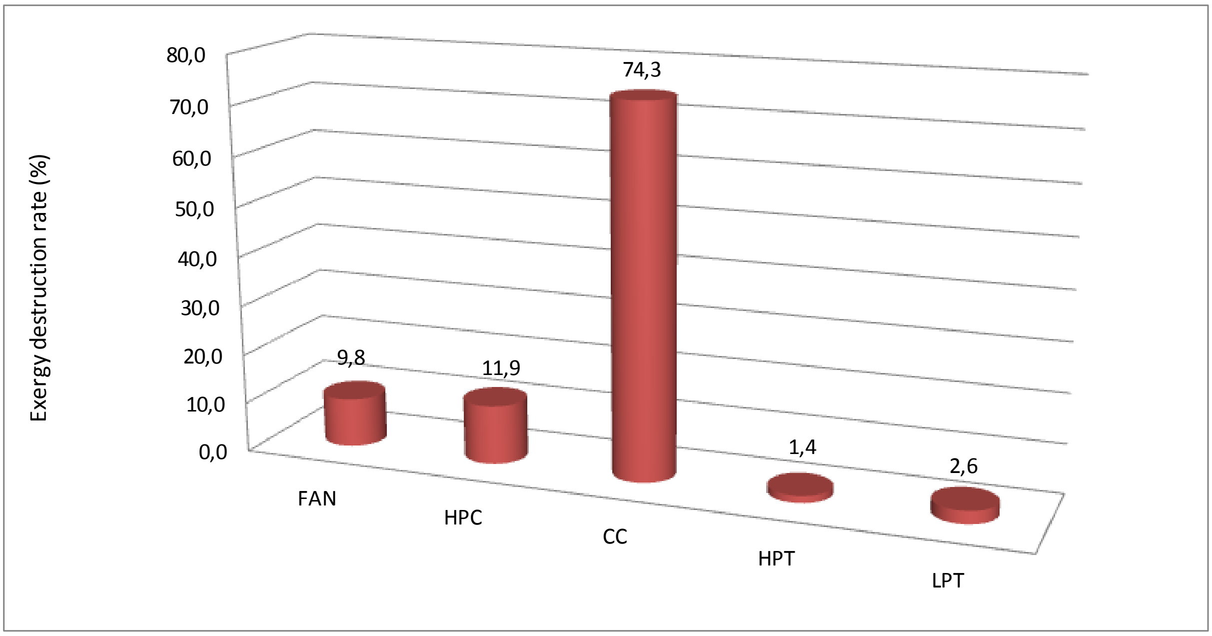


Fig.4. Exergy destruction rates (%) of JT8D turbofan engine at takeoff thrust.

Figs. 3 and 4 presents the exergy destructions and exergy destruction rates for the fan, HPC, combustor, HPT, LPT.
The exergy efficiency, one of the most 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 turboprop engine highly affected by the input-output exergetic values of the each engine component at all phases of a flight as shown in Table 2. The results in Fig.2 show that the exergy efficiency ranges from 0.745 to 0.982 in engine components. As can be seen in Fig.2, HPT and LPT are good exergy efficiencies changes between 0.964-0.982 due to higher isentropic efficiencies. For the fan and HPC exergy efficiencies are found to be 0.857 and 0.846, respectively. On the other hand, minimum exergy efficiency is observed in combustor (to be 0.745) due to internal irreversibilites in CC.
The unit with greatest exergy loss is found to be CC (to be 18.87 MW) as shown in Fig.3. The exergy destructions for the other units are found to be HPC (to be 3.03 MW), fan (to be 2.49 MW), LPT (to be 0.66 MW) and HPT (to be 0.36 MW).If so, greatest exergy destruction rate is calculated in the CC (to be 74.3%) as shown in Fig.4. It is clear from Fig.4 that HPT has minimum exergy destruction rate with value of 1.4%.

The results should provide a realistic and meaningful in the exergetic takeoff performance evaluation of low bypass turbofan engines, 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.

NOMENCLATURE

c_p	Specific heat (kJ. (kg K)$^{-1}$)
E	Energy rate (MW)
ex	Specific exergy (kJ.kg^{-1})
$\dot{E}x$	Exergy rate (MW)
f	fuel-air ratio; fuel exergy factor
h_{PR}	Fuel heating value (kJ.kg^{-1})
H	Enthalpy (kJ)
I	Irreversibility rate (kW)
ke	Kinetic energy
$\dot{m}$	Mass flow rate (kg.s^{-1})
A	Area (m^2)
M_A	Molecular weight
pe	Potential energy
P	Pressure (bar or kPa); product exergy
R	Specific gas constant (kJ. (kg. K^{-1})), diameter (m)
S	Entropy (kJ.K^{-1})

T	Temperature (K)

$\dot{W}$	Work rate (MW)

Subscripts

a	Air
ch	Chemical
dest	Destruction
f	Fuel
gen	Generated
k	kth component
LPC	Low Pressure Compressor
HPC	High Pressure Compressor
LPT	Low Pressure Turbine
HPT	High Pressure Turbine
in	Inlet
ke	Kinetic energy
LD	Loss and destruction
kn	Kinetic
out	Outlet
per	Perfect
ph	Physical
pe	Potential energy
tot	Total

A	area, m^2
c_p	specific heat, J/kg°C
h	heat transfer coefficient, W/m^2°C

Greek Letters

η	Efficiency
ρ	Air density ($kg.m^{-3}$)

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