First Law Approach of a Low Bypass Turbofan Engine

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***Abstract*—The scope of this study is analyzed and discussed in detail for better understanding of energetic performance of a low bypass turbofan engine. In this regard, this study presents first law of thermodynamics of the turbofan engine for maximum thrust level. The engine has low-pressure compressor (LPC) stages, high pressure compressor (HPC) stages, a single HP turbine (HPT), and finally three LPT stages. The results show that energy flow approaches a maximum value to be 73.76 MW in the combustor outlet, while minimum energy flow is observed at fan bypass outlet with the value of 5.60 MW. Accordingly, temperature, pressure and mass flow of the engine components are also calculated from Brayton cycle equations. As a consequently, engine energetic parameters, namely specific fuel consumption and engine overall efficiency, are also calculated for the low bypass turbofan engine from this study.**

***Index Terms*—low bypass turbofan, energy, propulsion, commercial aircraft, specific fuel consumption**

I. INTRODUCTION

Air travel is continuing to experience the fastest growth among all modes of transport, averaging 5 to 6% per year. If strong growth in air travel continues, world air traffic volume may increase five-fold to as much as twenty-fold by 2050 compared to the 1990 level and account for roughly two thirds of global passenger-miles traveled [1]-[3]. Current estimates show that global air traffic volume is growing so fast that total aviation fuel consumption and subsequent aviation emissions' impacts on climate change will continue to grow despite future improvements in engine and airframe technologies and aircraft operations [2]-[4].

With a constant increase of air passengers, and the demands for technological innovation to reduce harmful emissions and noise, the impact of commercial propulsion systems becomes even more pronounced. In aviation, engine fuel consumption and aircraft impacts on the environment are two important areas of research. From an environmental perspective, using energy with high efficiency reduces pollutant emissions and harm to ecological systems. For a given output, less fuel is needed when efficiency increases and less waste is released. These benefits lead to increased life times for energy resources and greater sustainability. Turbofan engines, in particular, have led to significant improvements in noise, fuel consumption, thrust and engine size [1], [2]. The aviation industry has come to measure its technical improvement in the increasing efficiency of its engines. Historic trends in improving efficiency levels show that aircraft entering today's fleet are around 80% more fuel efficient than the increasingly high bypass ratios [5]-[7].

Energy efficiency in commercial aircrafts is improved by averaging 1.5% percent annually with the introduction of bypass turbofan engines. Other way to propulsion system improvement is to increase turbine inlet temperature [8].

The importance of energy efficiency is also linked to environmental problems, such as global warming and atmospheric pollution [9], [10].

The environmental impact of emissions can be reduced by increasing the efficiency of resource utilization [10]. Using energy with better efficiency reduces pollutant emissions. Thermodynamically concepts have been utilized in environmental sustainability, economics and engineering. Through a literature review, it is noticed that there is no work to be studied about energetic assessment for a JT8D turbofan engine in the open literatures.

In this paper, the detailed energetic analysis of JT8D low bypass turbofan engine has been performed. In this analysis, engine energetic parameters, namely specific fuel consumption, engine overall efficiency and component energy flows have been calculated at maximum thrust level. The first law of thermodynamics of JT8D has first been studied in this paper.

II. SYSTEM DESCRIPTION JT8D 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

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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 [11].

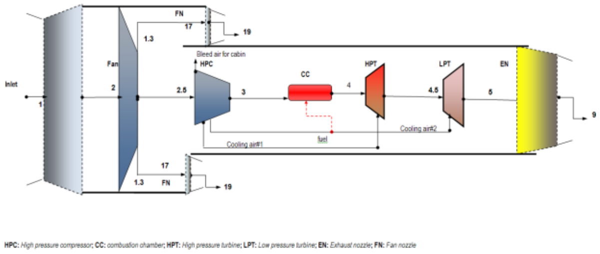


Figure 1. Main components of a low bypass turbofan engine.

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. Parametric Study 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 [12]-[14].

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

$$\alpha = \frac{\text{Bypass airflow}}{\text{Primary airflow}} = \frac{\dot{m}_{fan}}{\dot{m}_{core}} = \frac{\dot{m}_{cold}}{\dot{m}_{hot}} \quad (1)$$

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

Intake (I):

The inlet conditions of the air entering the inlet are the ambient pressure and temperature (P_0 *and* T_0). The intake has an isentropic efficiency. For a flight Mach number of M_0, then the temperature ratio (τ) and pressure ratio (π) at the intake are given by the relations [15]:

$$\pi_I = \frac{P_{t2}}{P_0} = \left(1+\eta_I \frac{\gamma_c - 1}{2} M_0^2\right)^{\gamma_c/(\gamma_c-1)} \quad (2)$$

$$\tau_I = \frac{T_{t2}}{T_0} = 1+\frac{\gamma_c - 1}{2} M_0^2 \quad (3)$$

where γ_c is the specific heat ratio for core stream and η_I is the inlet isentropic efficiency.

Fan:

For a known fan pressure ratio (π_{fan}) and isentropic efficiency (η_{fan}), then the temperature and pressure at the outlet of the fan given by the following relations [15]:

$$P_{t17} = P_{t2}\left(\pi_{fan}\right) \quad (4)$$

$$T_{t17} = T_{t2}\left[1+\frac{\left(\pi_{fan}^{(\gamma_c-1)/\gamma_c} - 1\right)}{\eta_{fan}}\right] \quad (5)$$

High pressure compressor (HPC):

Similarly, both the high pressure compressor pressure ratio (π_{HPC}) and isentropic efficiency (η_{HPC}) are known. Thus, the temperature and pressure at the outlet of HPC are given by the following relations [15]:

$$P_{t3} = P_{t2.5}\left(\pi_{HPC}\right) \quad (6)$$

$$T_{t2.5} = T_{t2}\left[1+\frac{\left(\pi_{HPC}^{(\gamma_c-1)/\gamma_c} - 1\right)}{\eta_{HPC}}\right] \quad (7)$$

Combustion chamber (CC):

The temperature at the end of the combustion process is generally known. The maximum temperature in the cycle, which is frequently identified as the turbine inlet temperature occurs here. The pressure at the end of combustion depends on the pressure drop in the combustion process itself. It may be expressed as [15]:

$$P_{t4} = P_{t3} - \Delta P_{CC} \quad (8)$$

High and low pressure turbine (HPT and LPT):

HPT and LPT drive HPC and fan, respectively. The energy balance for these spools per unit air mass flow rate is given by following relations [15]:

$$\dot{W}_{HPT} = \dot{W}_{HPC} \text{ and } \dot{W}_{LPT} = \dot{W}_{fan} \quad (9)$$

Exhaust nozzle (EN):

A nozzle isentropic efficiency of (η_{EN}), the critical pressure (P_{cr}) is calculated from the relation [15]:

$$\frac{P_{t5}}{P_{cr}} = \frac{1}{\left[1-\left(1/\eta_{EN}\right)\left(\gamma_t - 1\right)/\left(\gamma_t + 1\right)\right]^{\gamma_t/(\gamma_t-1)}} \quad (10)$$

Now if the exhaust nozzle is an ideal, then $\eta_{EN} = 1$, the above equation is reduced to

$$\frac{P_{t5}}{P_{cr}} = \left[\frac{(\gamma_t + 1)}{2}\right]^{\gamma_t/(\gamma_t - 1)} \tag{11}$$

Fan nozzle (FN):

The fan nozzle is also checked to determine whether choked or unchoked. Thus, the critical pressure is calculated from the relation [15]:

$$\frac{P_{t17}}{P_{cr}} = \frac{1}{\left[1-(1/\eta_{FN})(\gamma_c - 1)/(\gamma_c + 1)\right]^{\gamma_c/(\gamma_c - 1)}} \tag{12}$$

If the fan nozzle is an ideal, then $\eta_{FN} = 1$, the above equation will be reduced to [15]:

$$\frac{P_{t5}}{P_{cr}} = \left[\frac{(\gamma_c + 1)}{2}\right]^{\gamma_c/(\gamma_c - 1)} \tag{13}$$

The thrust of the turbofan engine is obtained by momentum of the burned gases. Thrust can be expressed as follows:

$$F = \dot{m}_{fan}(V_{19} - V_0) + \dot{m}_{HPC}\left[(1+f)V_9 - V_0\right] + A_{EN}(P_9 - P_0) + A_{FN}(P_{19} - P_0) \tag{14}$$

where *f* is the fuel-air ratio, *V* is the velocity, *A* is the area.

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

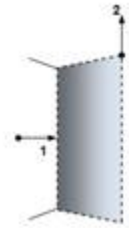
(h) Engine accessories, pumps (fuel, oil and hydraulic) are not included in the analysis.

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 following equation,

$$C_{12}H_{23} + 369\begin{pmatrix}0.7748N_2\\ +0.2059O_2\\ +0.0003CO_2\\ +0.019H_2O\end{pmatrix} \Rightarrow \begin{pmatrix}12.11CO_2\\ +18.51H_2O\\ +58.22O_2\\ +285.9N_2\end{pmatrix} \tag{19}$$

The relations given in this section are applied to the engine along with its components given in Fig. 1 and following, which includes energy definitions, is obtained for the turbofan components given below:

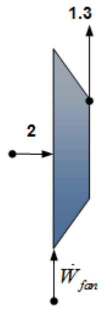
For Inlet (I):



energy balance:

$$\dot{e}_1 - \dot{e}_2 = 0 \tag{20a}$$

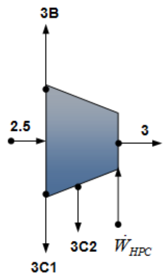
For fan:



energy balance:

$$\dot{e}_2 + \dot{w}_{fan} - \dot{e}_{1.3} = 0 \tag{20b}$$

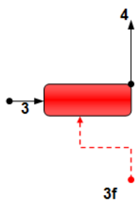
For high pressure compressor (HPC):



energy balance:

$$\dot{e}_{2.5} + \dot{w}_{HPC} - \begin{pmatrix}\dot{e}_3 +\\ \dot{e}_{3C1} +\\ \dot{e}_{3C2} +\\ \dot{e}_{3B}\end{pmatrix} = 0 \tag{20c}$$

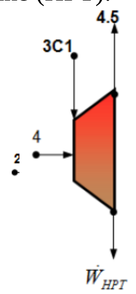
For combustion chamber (CC):



energy balance:

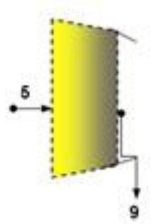
$$\dot{e}_{3f} + \dot{e}_3 - \dot{e}_4 = 0 \tag{20d}$$

For high pressure turbine (HPT):



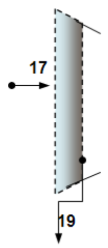
$$energy\ balance:\ \dot{e}_4 + \dot{e}_{3C1} - \begin{pmatrix} \dot{e}_{4.5} + \\ \dot{w}_{HPT} \end{pmatrix} = 0 \tag{20e}$$

For exhaust nozzle (EN):



$$energy\ balance:\ \dot{e}_5 - \dot{e}_9 = 0 \tag{20f}$$

For fan nozzle (FN):



$$energy\ balance:\ \dot{e}_{17} - \dot{e}_{19} = 0 \tag{20g}$$

Analyzing energetic performance of turbofan engine, computer program was developed in MATLAB programming language.

V. Results and Conclusions

In this paper, energetic performance of JT8D turbofan engine at takeoff thrust power have been carried out.

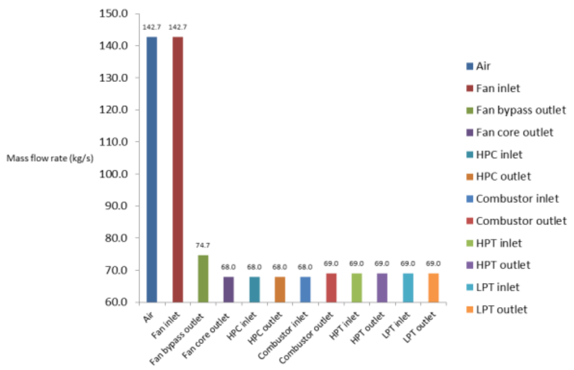


Figure 2. Mass flow rates of JT8D engine components.

Fig. 2 demonstrates the mass flow rates of inlet and outlet for the fan, HPC, combustor, HPT, LPT and JT8D turbofan engine at takeoff condition.

Fig. 3 also illustrates the pressure distribution of the fan, HPC, combustor, HPT, LPT at takeoff condition.

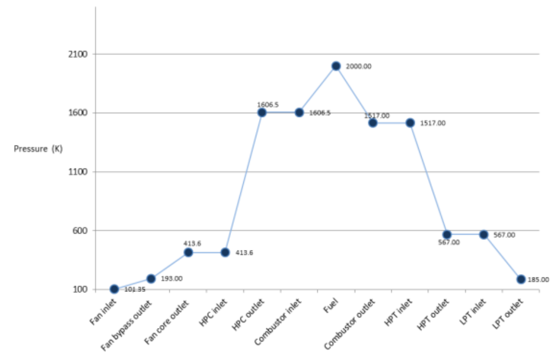


Figure 3. Pressure distribution of JT8D engine components.

Temperature values at inlet and outlet for the fan, HPC, combustor, HPT, LPT are given in Fig. 4 at takeoff condition.

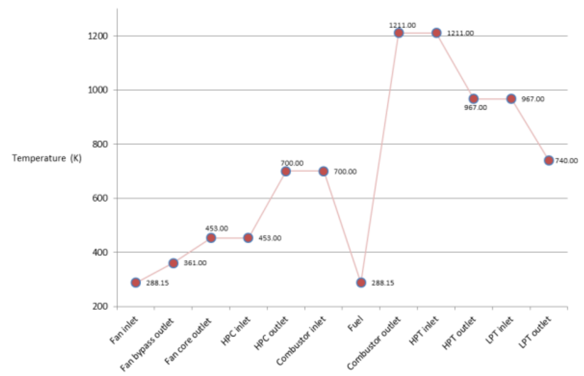


Figure 4. Temperature values of JT8D engine components.

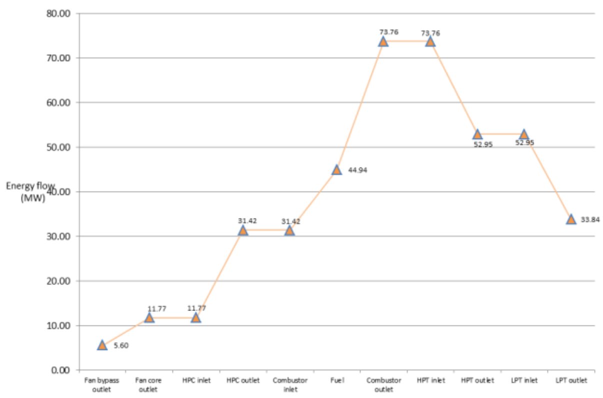


Figure 5. Product exergy factor of JT8D engine components.

Finally, Fig. 5 also shows the energy flows at the inlet and outlet for the fan, HPC, combustor, HPT, LPT at takeoff condition.

The energetic values studied in this paper, important indicators for the environment of the engine, is mainly based on the energy input and the required output. It is noticed that the specific fuel consumption and engine overall efficiency of the turbofan engine highly affected by the input-output energetic values of the each engine component at a phase of a flight. The results in Fig. 2 show that the engine total mass flow, including fan and core air flow, is 142.7 kg/s. As can be seen in Fig. 2, 1.05 kg fuel/s is added to combustor.

Air mass flow is increasing in compressor from the value of 101.35 kPa to 1606.5 kPa due to compression process as shown in Fig. 3. As an expected, combustion gases pressure is decreasing from the value of 1617 kPa to 185 kPa at the LPT outlet due to expansion process.

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%.

Among the turbofan engine components, CC exit has maximum temperature value (to be 1211 K) due to combustion reaction with air and fuel as shown in Fig. 4.

Finally, in the last figure, maximum energy flow is calculated in HPT inlet due to fuel energy with the value of 73.76 MW. On the other hand, energy flow is observed at LPT exit (to be 33.84 MW) due to expansion process.

At the end of the calculations, specific fuel consumption and overall efficiency are found to be 16.9 g/ kN.s and 8.3%, respectively.

The results should provide a realistic and meaningful in the thermodynamics first law evaluation of JT8D low bypass turbofan engine, which may be useful in the analysis of similar propulsion systems. A first law of thermodynamics can help improve the environmental performance of the low bypass engine, and consequently should be considered in future assessments.

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