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Calculation and Comparison of a Turbofan Engine Performance Parameters with Various Definitions

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***Abstract*—In this paper, some performance parameters of a selected turbofan engine (JT9D) are analyzed. The engine is a high bypass turbofan engine which powers a wide-body aircraft and it produces 206 kN thrust force (thrust/weight ratio is 5.4). The objective parameters for the engine include calculation of power, specific fuel consumption, specific thrust, engine propulsive, thermal and overall efficiencies according to the various definitions given in the literature. Furthermore, in the case study, wasted energy from the exhaust is calculated at the maximum power setting (i.e. take off phase) for the engine.

***Keywords*—Turbofan, power, efficiency, trust.

I. INTRODUCTION

WORLWIDE passenger traffic will show nearly 5.1% growth, cargo traffic will show nearly 5.6% growth in recent years, and 2–5% of the world energy consumption belongs to aviation industries [1]-[5].

Effects of energy consumption in aviation sector give rise to potential environmental hazards. Therefore, energy consumption plays a crucial role to achieve sustainable development; balancing economic and social development with environmental protection. The importance of energy efficiency is also linked to the environmental problems such as global warming and atmospheric pollution [6], [7].

Energy intensity can be related to 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 into propulsive 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 the propulsion power in terms of payload carried per unit range. Energy intensity (E_I) is a suitable parameter when comparing efficiency and environmental impact. It consists of two components-energy use, and load factor, as shown in (1) [8].

$$E_I = \frac{E_U}{L_f} = \frac{MJ}{RPK} = \frac{MJ}{ASK} / \frac{RPK}{ASK} \tag{1}$$

where MJ is in megajoules of kerosene fuel energy, RPK is the revenue passenger-kilometers, ASK is the available seat-kilometers, and L_f is the 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 an important role in the energy intensity of an aircraft. Energy efficiency in commercial aircrafts is improved by approximately 1.5% annually with the introduction of bypass turbofan engines. However, as the bypass ratio increased, engine diameter also increases, leading to an increase in momentum drag. Other way towards the propulsion system improvement is to increase the turbine inlet temperature, which is limited by materials and cooling technology. Between the introductions of B707 and B777, commercial aircrafts have been constructed exclusively of aluminum and they are currently about 90% metallic by weight. So, improvements of structural efficiency are less evident [8].

The first law of thermodynamics is widely used in energy systems analysis. Many researchers suggest that the thermodynamic performance is best evaluated by using exergy analysis. The second law involves the reversibility or irreversibility of processes and is a very important aspect in the exergy method of energy systems analysis. In this regard, exergy analysis appears to be a significant tool for the determination of locations, types and true magnitudes of waste energy and losses to design more efficient energy systems and to distinguish the quality of energy [9].

Turbofan engines are air breathing jet engines with fan(s) located in front of compressors. In addition to the jet engines, turbofan engines have another turbine for rotating fans. This configuration is named as two-spool engine. Spool is used for defining the shafts that connect fan and its turbine, and compressor and its turbine [10].

Turbofan engines similarly work as a jet engine but they have two flows. These flows are named as cold flow and hot flow. Cold flow goes from fan to nozzle without mixing with fuel, and hot flow mixed with fuel at combustion chamber goes from compressor to turbine and nozzle. This part, that contains compressor, combustion chamber, turbine and nozzle, is called core of engine. There is a difference between those two flows. This is named by-pass ratio. By-pass ratio is shown with β symbol [10].

There are two types of turbofan engines. One is high-bypass, and the other one is low-by-pass. More jet power is used in low by-pass engines, while more fan power is used in high by-pass engines. The low by-pass engines are used in military aircraft because of their power to weight ratios, while the high by-pass engines are used in commercial aircrafts because of their low fuel consumption [12]. Both are shown in Fig. 2.

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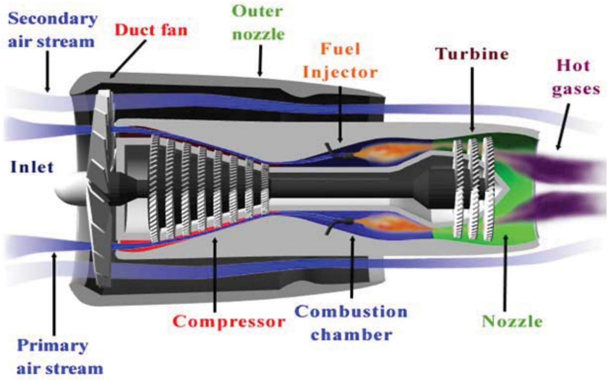

Fig. 1 Turbofan engine [11]

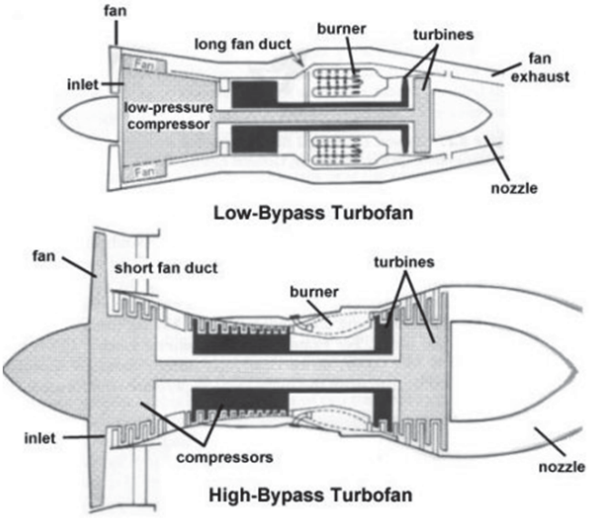

Fig. 2 Low by-pass and high by-pass engines [13]

JT9D, shown in Fig. 3, is a high-bypass turbofan engine that is powered Boeing 747, 767, Airbus A300, A310, and McDonnell Douglas DC-10 aircrafts [14].

JT9D is a high bypass turbofan engine which powers the wide-body aircraft. The engine weight is 3905 kg and it produces 206 kN thrust force (thrust/weight ratio is 5.4). The engine consists of 1-stage fan, 14-stage compressor (3-stage LP compressor and 11-stage HP compressor), and annular combustion chamber. The JT9D was, however, chosen to power the Boeing 747. Further, the Boeing 747 is one of the most easily recognized commercial aircraft and it is a 400-plus passenger aircraft and is powered by four engines. It was the first wide body, or dual-aisle, and the largest commercial aircraft developed to date and for decades after, seating from 400 to 497 passengers [15]. The 747 also revolutionized airline transport by dramatically reducing the cost per seat mile and therefore the cost of long-haul air transportation. Moreover, the JT9D was the first high-bypass turbofan engine used in a civilian transport aircraft [16]. By the way, it is worth noting that, until now, the high bypass turbofans are currently used to thrust large civil aircrafts when high capacity and flight economy are of primary importance.

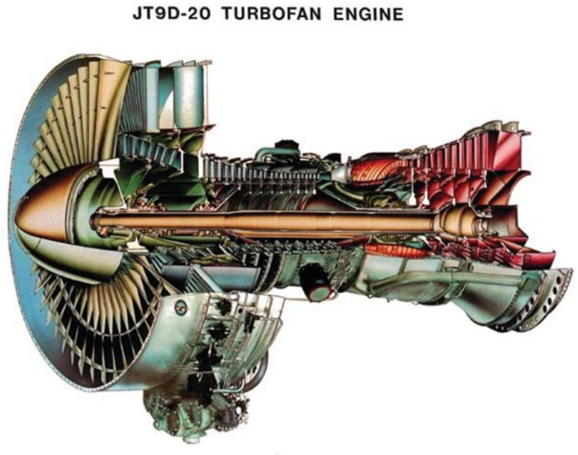

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Fig. 3 JT9D engine [17]

II. Methodology of Analysis

Thrust is the force for propelling an aircraft in different flight regimes. Thrust, drag, lift, and weight represent the forces that govern the aircraft motion. An aircraft engine must identify the different requirements for all flight phases such as takeoff, climb, cruise and maneuvering, descending, and landing.

During the cruise, the four forces are in equilibrium in pairs-thrust and drag as well as lift and weight. Thrust force is used in braking the aircraft via thrust-reversing mechanism during landing. The optimum match point between an engine and a configuration of an aircraft is mutually dependent on the available engine propulsive performance, flight mission profile, and constraints [18], [19].

Thrust force of an aero-engine can be derived from the basic conservation laws of mass and momentum in their integral forms; the momentum and continuity equations. Consider a schematic diagram for an engine with a pod installation as shown in Fig. 4. Control volume passes through the engine exhaust at (2) and extends far upstream at (1). In Fig. 3, the two sides of the control volume are parallel to the flight velocity u. The surface areas at stations (1) and (2) are equal and are denoted by A. The exhaust area for gases leaving the engine has an area Ae at (2), while stream tube of air entering the engine is Ai at (1). The velocity and pressure over station (1) are u (which is also flight velocity) and Pa (ambient pressure at same altitude), respectively. Over the station (2), velocity and pressure are same at station (1) except over the exhaust area Ae where the values are to be ue and Pe. The flow is steady within the control volume, and external flow is reversible [19].

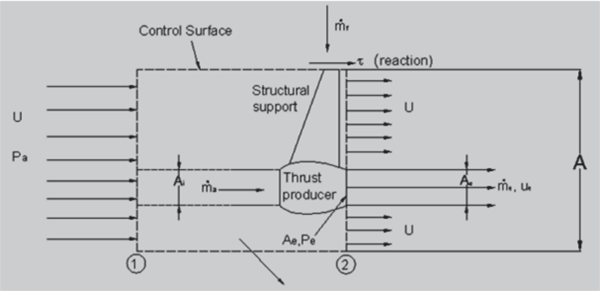

Fig. 4 A schematic diagram for a thrust producer device

The continuity equation (2) gives for the control volume [19],

$$\frac{\partial}{\partial t}\iiint\limits_{CV} \rho dv + \oiint\limits_{CS} \rho \bar{u} d\bar{A} \qquad (2)$$

According to the momentum equation [19],

$$\sum \bar{F} = \frac{\partial}{\partial t}\iiint\limits_{CV} \rho \bar{u} dv + \oiint\limits_{CS} \bar{u}(\rho \bar{u} d\bar{A}) = 0 \qquad (3)$$

From (2) and (3), net thrust force τ can be determined for an aero engine as [19]:

$$\tau = \dot{m}_a[(1+f)u_e - u] + A_e(P_e - P_a)] \qquad (4)$$

On a rate basis, the integral form of the conservation of energy may be written as [20]

$$\begin{aligned}\dot{Q} - \dot{W}_s - \dot{W}_{shear} - \dot{W}_{other} \\ = \frac{\partial}{\partial t}\int\limits_{CV} e\rho dv + \int\limits_{CS} (e+\rho v)\, \rho U.dA\end{aligned} \qquad (5)$$

where $\dot{Q}$ is the heat transfer rate, $\dot{W}_s$ is the work transfer rate at surface, $\dot{W}_{shear}$ is the work rate due shear, $\dot{W}_{other}$ is the work from all other forms (electrical, shaft etc.), $\frac{\partial}{\partial t}\int_{CV} e\rho dv$ is time rate of change of energy inside the control volume, $\int_{CS}(e + \rho v)\, \rho U.dA$ is the flux of energy across control surface, e is the specific energy [20].

It is needed to calculate some parameters for evaluating aircraft engine performance [19]. Those parameters are:

1. Propulsive efficiency
2. Thermal efficiency
3. Overall efficiency
4. Specific fuel consumption

Main core components of the JT9D turbofan engine are fan (F), low and high compressors (LPC and HPC), annular combustion chamber (CC), high pressure turbine (HPT), and low pressure turbine (LPT) shown in Fig. 4. Thrust range of the engine is 206-222 kN with bypass ratio 5 at takeoff. For the JT9D engine, however, fan and compressor pressure ratios are 14.26 and 1.64, respectively. Besides, the total airflow mass rate is 677.2 kg/s that includes 564.3 kg/s for fan air and 111.9 kg/s for core air. Air is taken into fan at ambient temperature of 288.15 K and ambient pressure of 101.35 kPa. In aero gas turbine engines, a part of compressed air is extracted to use for cooling, sealing, and thrust balancing. In this study, the cooling airflow is neglected since it does not have a meaningful effect on the results.

A. Propulsive Efficiency

Propulsive efficiency can be described as the ratio of power of the aircraft to power supplied by the engine [21]. Propulsive efficiency is shown with η_p and is defined [19]:

$$\eta_p = \frac{Thrust\ power}{Power\ imparted\ to\ engine\ airlow} \qquad (6)$$

or

$$\eta_p = \frac{Thrust\ power}{Trust\ power + power\ wated\ in\ exhaust} \qquad (7)$$

This expression is also called as first expression of propulsive efficiency. Propulsive efficiency has another expression that is called as second expression which is:

$$\eta_p = \frac{Thrust\ power}{Rate\ of\ kinetic\ enegy\ added\ to\ engine\ flow} \qquad (8)$$

Turbofan engines have two different streams that called hot stream which comes from the core of the engine and cold stream which passes through fan of the engine. The first expression of propulsive efficiency becomes:

$$\eta_p = \frac{u(T_h + T_c)}{u(T_h + T_c) + W_h + W_c} \qquad (9)$$

Here, *u* is the velocity of free stream, T_h and T_c are the trusts, and W_h and W_c are the wasted powers. *h* and *c* represent hot stream and cold stream, respectively. Those are defined as:

$$T_h = \dot{m}_h[(1+f)u_{eh}] + A_{eh}(P_{eh} - P_a) \qquad (10)$$

$$T_c = \dot{m}_c[u_{ec} - u] + A_{ec}(P_{ec} - P_a) \qquad (11)$$

$$W_h = \frac{1}{2}\dot{m}_h(1+f)(u_{eh} - u)^2 \qquad (12)$$

$$W_c = \frac{1}{2}\dot{m}_c(u_{ec} - u)^2 \qquad (13)$$

The second expression of propulsive efficiency for turbofan engines is defined as:

$$\eta_p = \frac{2uT}{\dot{m}_h[(1+f)u^2{}_{eh} + \beta u^2{}_{ec} - (1+\beta)u^2]} \qquad (14)$$

B. Thermal Efficiency

Thermal efficiency is the ratio of work supplied by the engine to thermal energy supplied by the fuel [22]. Thermal efficiency is defined for turbofan engines as:

$$\eta_{th} = \frac{Power\ imparted\ to\ engine\ airflow}{Rate\ of\ energy\ supplied\ in\ the\ fuel} \tag{15}$$

Expression of thermal efficiency for turbofan engine is:

$$\eta_{th} = \frac{Tu + \frac{1}{2}\dot{m}_h(1+f)(u_{eh}-u)^2 + \frac{1}{2}\dot{m}_c(u_{ec}-u)^2}{\dot{m}_f Q_R} \tag{16}$$

If $P_a = P_e$, and f is negligible, then:

$$\eta_{th} = \frac{{u_{he}}^2 + \beta {u_{ce}}^2 - (1+\beta)u^2}{2fQ_R} \tag{17}$$

C. Overall Efficiency

Overall efficiency is the product of thermal efficiency and propulsive efficiency [19]. Expression of the overall efficiency is:

$$\eta_o = \eta_{th}\eta_p = \frac{Tu}{\dot{m}_f Q_R} \tag{18}$$

D. Specific Fuel Consumption

Specific fuel consumption or thrust specific fuel consumption is fuel flow divided by thrust [23]. It is an important parameter for evaluating the engine's running cost [19].

Unit of TSFC is kg/N.h. Specific fuel consumption expression for turbofan engines:

$$TSFC = \frac{\dot{m}_f}{T} \tag{19}$$

III. PERFORMANCE ANALYSIS, RESULTS AND CONCLUSION

Values for JT9D engine are shown in Table I.

TABLE I
ENGINE PARAMETERS

Data	Unit	Value
Thrust	kN	193.5
$\dot{m}_c$	kg/s	565.344
$\dot{m}_h$	kg/s	111.891
u_{ec}	m/s	362.712
u_{eh}	m/s	269.748
Q_R	kJ/kg	43000
f	non-dimensional	0.022

Notes about calculations:

- Flight speed is 50 m/s
- Hot and cold streams are unchoked ($P_a = P_e$)

Here, as the kerosene fuel (Jet-A1) with the chemical formula C12H23, is burned in the combustion chamber of the engine. The value of lower heating for Jet-A1 is taken to be 42,800 kJ/kg. Also, fuel mass flow is measured to be 2.11 kg/s, and hence air/fuel ratio is obtained to be 53. So, combustion balance equation can be given below:

$$\begin{aligned} C_{12}H_{23} + 305.5(0.07748N_2 + 0.2059O_2 + 0.0003CO_2 \\ + 0.019H_2O) \\ \Rightarrow (12.09CO_2 + 17.3H_2O \\ + 42.26O_2 + 236.7\,N_2) \end{aligned} \tag{20}$$

The mass rates of combustion gases are obtained as 6.89 kg/s for CO_2, 4.03 kg/s for H_2O, 17.5 kg/s for O_2 and 85.78 kg/s for N_2 after the combustor chamber.

Wasted power are calculated by using (12) and (13).

$$W_c = 13{,}650\ kW \tag{21}$$

$$W_h = 581{,}403.2\ kW \tag{22}$$

Total wasted power is calculated by summing (21) and (22):

$$W_{tot} = 595{,}053.2\ kW \tag{23}$$

To calculate hot and cold thrusts, terms of $A_{eh}(P_{eh} - P_a)$ and $A_{ec}(P_{ec} - P_a)$ are dropped because streams are unchocked. Hot and cold streams are calculated by using (10) and (11).

$$T_h = 3813.345\ N \tag{24}$$

$$T_c = 124{,}233.21\ N \tag{25}$$

Using the first expression of propulsive efficiency (9), total power is:

$$Total\ Power = 601{,}455.858\ kW \tag{26}$$

Using the second expression of propulsive (14), total power yields:

$$Total\ power = 54467.132\ kW \tag{27}$$

Propulsive efficiency is calculated by using (9) for the first expression and (14) for the second expression.

$$\eta_{p1} = 0.016 \tag{28}$$

$$\eta_{p2} = 0.036 \tag{29}$$

Thermal efficiency is calculated by using (17) because engine is unchocked.

$$\eta_{th} = 0.26 \tag{30}$$

Overall efficiency is calculated by using (18):

$$\eta_o = 9.36 * 10^{-3} \tag{31}$$

Specific fuel consumption is calculated by using (14):

$$TSFC = 0.127 kg/kN/s \tag{32}$$

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