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# A Comparison Study For the Performance of the Mixed and Unmixed Flow Two Spool Turbofan Engines at Variable Parameters

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*Abstract*— **The following paper is to investigate the influence of some operational and design parameters on the performance of a turbofan engine with two spools and for mixed and unmixed flow. Because there are many influential variables on the performance, here a computer program with VISUAL BASIC has been developed to carry out this study. The input variables taken in consideration are the flight speed, compressor pressure ratio, fan pressure ratio, the altitude and the combustion temperature. The output obtained at these variables, which are the thrust specific fuel consumption, specific thrust, propulsive efficiency and thermal efficiency are depicted and discussed for the two types of flow.**

**The results show that there is a great influence of these variables on the performance parameters.**

*Index Terms:* **turbofan engine, two spool, flight speed, thrust, efficiency.**

## I. INTRODUCTION

The turbofan engine, a modern variation of the basic gas turbine engine, has gained popularity in most new jet-powered aircrafts, including military and civilian types. Basically, the turbofan is a turbojet engine with an addition of a fan. The fan causes more air to bypass the engine core and exit at higher speeds, resulting in greater thrust, lower specific fuel consumption and reduced noise level. Usually, the fan and low-pressure compressor are connected on the same shaft to a low pressure turbine. A turbofan with this type of arrangement is called a two-spool turbofan engine [1].

The conception of the turbofan engine as an extension of the turbojet was originally meant as a means to increase the propulsive efficiency of the turbojet by reducing the mean exit stream velocity thus increasing the fuel efficiency . Another issue the turbojet engine faces is the issue of excess heat from the combustion process. The turbofan engine mitigates this issue by incorporating a bypass stream . This stream passes over the core of the engine and cools its components with air from the inlet. This bypass stream is then exhausted through a separate nozzle. Figure. 1 illustrates the configuration of the conventional commercial two-spool turbofan engine [2].

Modern Turbofan engines can deliver high thrust without the high fuel consumption as compared to a turbojet engine. By trading the energy in the high velocity exhaust stream for power to drive a fan, the turbofan engine can process large amounts of air which yields a higher thrust per amount of fuel used. The amount of fuel used per thrust is called thrust specific fuel consumption (TSFC). A numerically lower value of TSFC is indicative that the engine uses less fuel to produce a given amount of thrust [3].

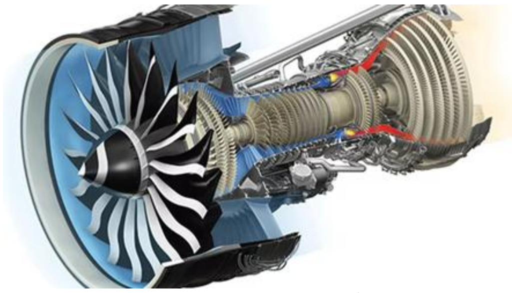

Figure 1. Two Spool Unmixed Turbofan Engine [4].

Thus in general turbofan engines have a better performance, greater fuel economy than turbojet at low power setting, low speed, and low altitudes [5].

Turbofan engines can be classified into many categories and many types according to design and operation and the following diagram in Figure. 2 shows these types [6].

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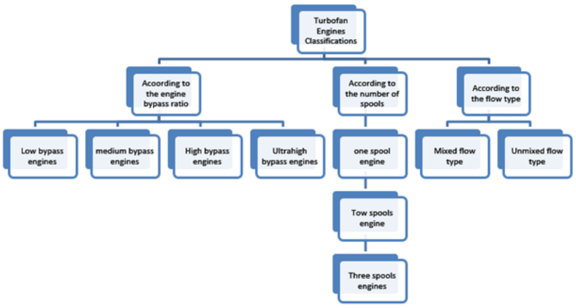


Figure 2. Classification of turbofan engines

According to the bypass ratio , in general, two types of engines are used, one is high and the other is low, Figures. 3 and 4. The low bypass engines are used in military aircrafts because of their power to weight ratios, while the high bypass engines are used in commercial aircrafts because of their low fuel consumption [7].

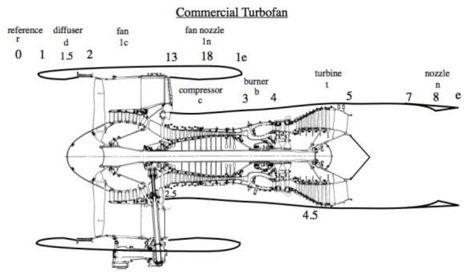


Figure 3. High bypass ratio turbofan engine [8].

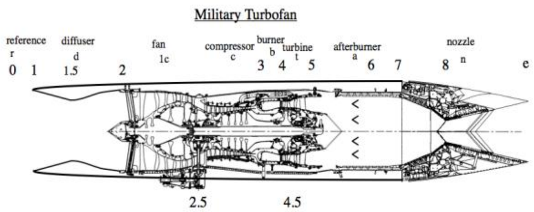


Figure 4. Low bypass ratio turbofan engine with after burner [8].

## II. PERFORMANCE ANALYSIS OF THE FORWARD FAN TWO SPOOL TURBOFAN ENGINE

In the unmixed flow the cold air stream that passes through the fan enters a duct, then passes through its own nozzle, while the hot stream continues its way through the core which is exactly the same as in turbojet engine. While in the mixed flow turbofan engines the cold compressed air leaving the fan is not directly exhausted as previously described but flows in a long duct surrounding the engine core and then mixes with the hot gases leaving the low pressure turbine (LPT). Thus the cold air is heated while the hot gases are cooled. Only one mixed exhaust is found. In the two spool engine two coaxial shafts are used in which the fan and the low pressure compressor (LPC) are driven by the low pressure turbine (LPT), while the high pressure compressor (HPC) is driven by the high pressure turbine (HPT) .

*Analysis Assumptions*

To study the performance of these two types at variable operational and design parameters a computer program has been developed, using visual basic language to obtain the results at the variable input parameters, such as flight Mach number, altitude, compressor pressure ratio, fan pressure ratio and combustion temperature, and according to the nominations given in Figures 3 and 4, with the following assumptions:

1- The flow process through the engine is considered calorically perfect, thus the specific heat ratios are constant $C_{Pd}$=$C_{Pc}$=$C_{Pf}$= 1.005 kJ/kg.K, $\gamma_C = 1.4$, $C_{Pt} = C_{Pn} = 1.2kJ/kg$K , , $\gamma_h = 1.33$.
2- Isentropic efficiencies for the components are specified and considered constant.
3- The properties of air, such as pressure and temperature are variable according to the altitude, and determined from the standard atmosphere relationships.
4- Combustion process is considered adiabatic with a heat added process only without chemical reaction.

### A. *Performance Parameters*

Parametric cycle analysis desires to determine how the engine performance varies with changes in the flight conditions (e.g., Mach number), design limits (e.g., main burner exit temperature), component performance (e.g., turbine efficiency), and design choices (e.g., compressor pressure ratio) [4].

In general the most engine performance parameters are identified as a function of by-pass ratio ( $\beta$ ), which is defined as the ratio of the air flow passing through the fan tips and the duct to the air flow passing through the gas generator (core ) engine [9] , thus:

$$\beta = \frac{\dot{m}_{cold}}{\dot{m}_{hot}} \qquad (1)$$

These parameters include propulsive efficiency , thermal efficiency, overall efficiency and thrust specific fuel consumption. In addition of that the take-off thrust and the aircraft range are very important parameters too. Military aircraft are powered by engines that fulfil their mission requirements. For this reason, the take-off thrust and manoeuvrability are the critical issues, with some sacrifice of fuel consumption in some types such as fighters and interceptors. For civil transports, specific fuel consumption and the aircraft range are the critical design issues. In both types, several efficiencies related to the conversion of heat generated by fuel burning into thrust force are important[1].

- **Propulsive Efficiency :** Propulsive efficiency is the conversion of the kinetic energy of air when it passes through the engine into a propulsive power. It is influenced by the amount of the energy wasted in the propelling nozzle(s) and denoted by $(\eta_p)$ [5]. It is defined as

$$\eta_p = \frac{Thrust\ Power}{Thrust\ Power + Power\ Wasted\ in\ the\ Exhaust}$$

In the case of mixed flow the thrust power is given by

$$Thrust\ Power = Flight\ Speed\ \times Thrust\ Force$$

Where thrust force ($T$) is

$$T = \dot{m}_a[(1 + f + \beta)u_e - (1 + \beta)u_\infty] + A_e(P_e - P_a) \quad (2)$$

Where $f$ is the fuel to air ratio, $u_e$ is the exhaust velocity and $u_\infty$ is the flight speed. While the power wasted ($W$) in the exhaust is

$$W = 0.5\dot{m}_a(1 + f)(u_e - u_\infty)^2 \quad (3)$$

Then the propulsive efficiency is given by

$$\eta_p = \frac{u_\infty T}{u_\infty T + W} \quad (4)$$

In the case of unmixed flow the air coming into the engine is split into two streams, first through the fan and is cold and the second through the core where it exits hot. Thus we get two thrust forces , cold thrust ($T_c$) and hot thrust ($T_h$), where given by

$$T_c = \dot{m}_c[u_{ec} - u_\infty] + A_{ec}(P_{ec} - P_a) \quad (5)$$

$$T_h = \dot{m}_h[(1 + f)u_{eh} - u] + A_{eh}(P_{eh} - P_a) \quad (6)$$

Also we get two power wasted terms, one is cold (Wc) and the second is hot (Wh), and given by

$$W_c = 0.5\dot{m}_c(u_{ec} - u_\infty)^2 \quad (7)$$

$$W_h = 0.5\dot{m}_h(u_{eh} - u_\infty)^2 \quad (8)$$

Then the propulsive efficiency for the unmixed flow turbine engine becomes

$$\eta_p = \frac{u_\infty(T_c + T_h)}{u_\infty(T_c + T_h) + W_c + W_h} \quad (9)$$

- **Thermal Efficiency :** The ability of an engine to convert the thermal energy inherent in the fuel (which is unleashed in a chemical reaction) to a net kinetic energy gain of the working medium is called the engine thermal efficiency, $\eta_{th}$ [10].

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

For mixed flow the following expression is employed:

$$\eta_{th} = \frac{u_\infty T + W}{\dot{m}_{fuel}Q_R} \quad (10)$$

Where $\dot{m}_{fuel}$ is the fuel mass flow rate and $Q_R$ is the heating value of fuel.

While for unmixed flow the thermal efficiency is given by

$$\eta_{th} = \frac{u_\infty(T_c + T_h) + W_c + W_h}{\dot{m}_{fuel}Q_R} \quad (11)$$

- **Overall Efficiency:** The product of the propulsive and thermal efficiencies is called the overall efficiency, thus

$$\eta_0 = \eta_p \times \eta_{th} \quad (12)$$

- **Thrust Specific** Fuel Consumption (TSFC): This performance parameter of the engine has a direct influence on the costs of aircraft trip and flight economics, and it is the amount of fuel consumed to generate unit thrust force [4].

For mixed flow

$$TSFC = \frac{\dot{m}_{fuel}}{T} \quad (13)$$

For unmixed flow

$$TSFC = \frac{\dot{m}_{fuel}}{T_c + T_h} \quad (14)$$

TSFC can be used to “rank” the engine fuel efficiency and aide in the engine selection processes as an aircraft power plant. A large part of the cost of operating an airline is fuel; hence the desire for operators looking to turn a profit flying cargo or passengers to minimize this cost. Fuel usage is one of the largest factors in the cost of operating a commercial aircraft. The cost of fuel is based on a variety of economic, political and some technical factors. However, the amount of fuel consumed to power the commercial aircraft can be diagnosed from solely a technical basis [3].

## III. RESULTS AND DISCUSSION

To carry out the comparison study of the performance of the mixed and unmixed flow turbofan engines the following variables have been taken in consideration: altitude of the aircraft (H), Flight Mach number ($M_f$) for subsonic flow only up to 0.95, compressor pressure ratio ($\pi_c$), and fan pressure ratio ($\pi_f$). According to these variables the performance parameters that have been determined are the thrust specific fuel consumption (TSFC), the propulsive efficiency ($\eta_p$), and the thermal efficiency ($\eta_{th}$), and for both cases mixed and unmixed flow. The first group of diagrams are given only for the unmixed flow turbofan engine to find the influence of the operational and design variables on the performance parameters because for both cases we find similar trends of the curves, but with deferent values. These differences have been shown in the second group of diagrams.

### *A. Influence of Flight Mach Number and altitude :*

Here the study to find the performance parameters is carried out by varying the values of flight Mach number from 0.5 to 0.95 for three chosen altitudes as depicted in the following figures. Figure 5 shows the relationship between flight Mach number and thrust specific fuel consumption at the specified altitudes. Here, it is noticed that the TSFC increases with increasing Mach number at a certain altitude, also it increases with the altitude at a certain Mach number. This means that more power has to be generated to accelerate the aircraft and to rise up to higher altitudes which leads to more fuel consumption.

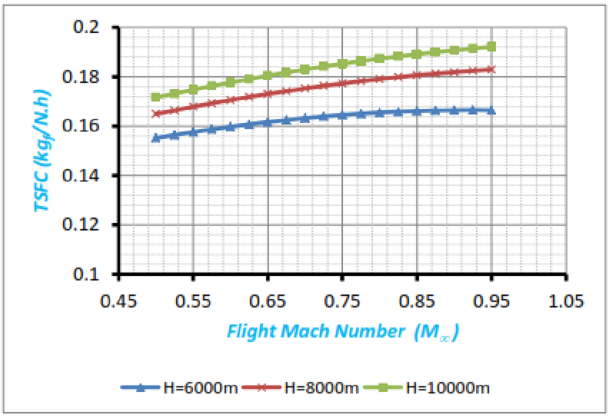


Figure 5. The relationship between flight Mach number and (TSFC).

In Figure. 6 it is shown that the propulsive efficiency is improved by increasing the flight Mach number, thus because more thrust power is generated which is directly proportional to the flight Mach number. In the other hand the wasted power is decreased which enhance the propulsive efficiency too.

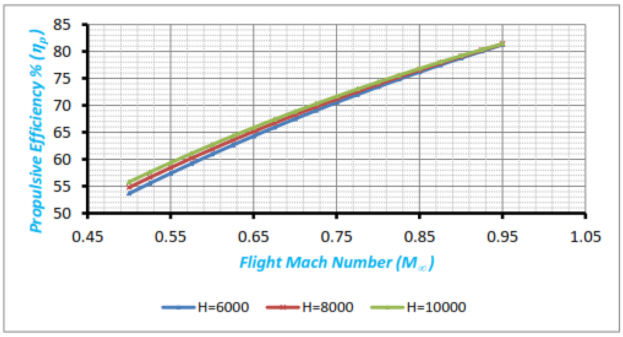


Figure 6. The relationship between flight Mach number and ($\eta_p$).

While the thermal efficiency goes down with flight Mach number as shown in Figure. 7. This is due to more consumption of fuel at higher thrust powers. But at higher altitudes the thermal efficiency get improved due to more power imparted to engine air flow.

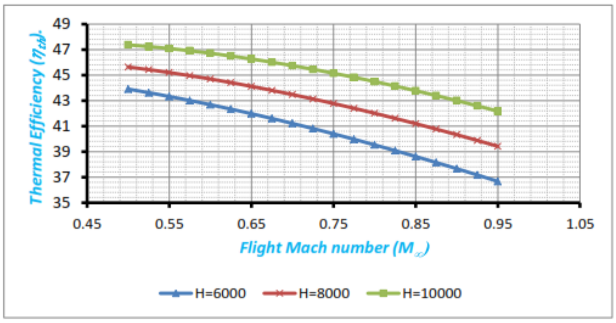


Figure 7. The relationship between flight Mach number and ($\eta_{th}$).

### *B. Influence of Compressor Pressure Ratio and altitude:*

In this case the compressor pressure ratio is taken variable from 8 up to 25, at other constant parameters such $M_f$, TC,FPR and H. Then the last constants are taken with new values and the study is repeated again to obtain the new results at these new values. Here in Figure.8 the TSFC increases with compressor pressure ratio to a certain value at lower altitude (H=6000 m ) then goes down, this may refer to more power consumed by compressor for compression which reduces the net thrust and consumes more fuel.

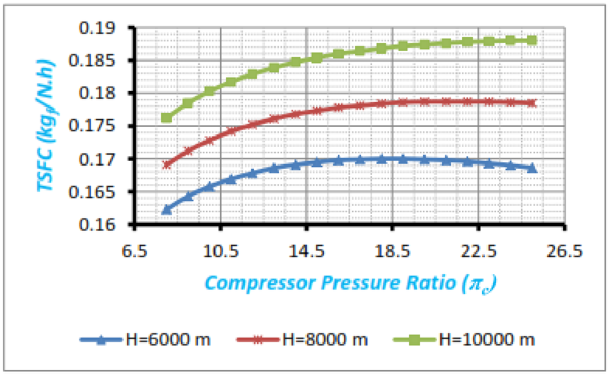


Figure 8. The relationship between compressor pressure ratio and (TSFC).

The trend of the curves in Figure. 9 is similar to that in Figure. 8 and for the same reasons, where propulsive efficiency is increased by increasing the compressor pressure ratio where more mass flow rate of air is introduced to the engine resulted in higher propulsive power.

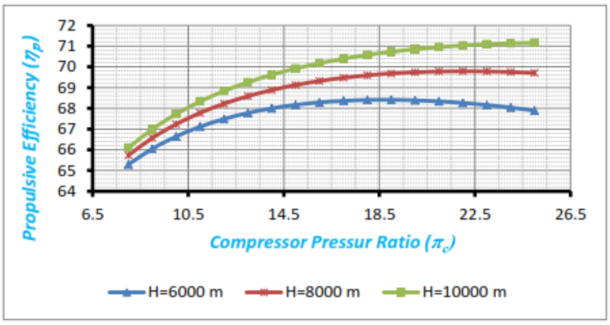


Figure 9. The relationship between compressor pressure ratio and ($\eta_p$).

While in Figure. 10 the thermal efficiency is decreased by increasing the compressor pressure ratio due to more thermal energy consumed to compensate the power needed by compressor to get more pressure ratios. Here also it is noted that this efficiency is increased by altitude to a certain ceiling at a certain compressor pressure ratio. This is why the aircrafts are flying at this altitudes during cruising.

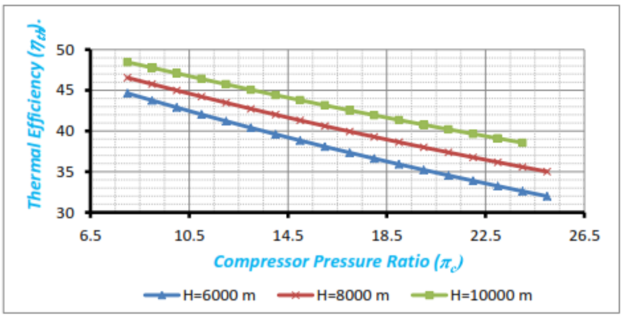


Figure 10. The relationship between compressor pressure ratio and ($\eta_{th}$).

### C. *Influence of Fan Pressure Ratio and altitude:*

The other important parameter taken in consideration for the analysis is the fan pressure ratio which is taken variable from 1.8 up to 4.0, at other constant parameters such $M_f$, $T_C$,CPR and H. Then the last constants are taken variables with new values to obtain the new results at these variables. In this case it is noted that the TSFC is goes down with increasing fan pressure ratio due to more power needed by the fan at higher ratios, as shown in Figure. 11. While the opposite is happened at higher altitudes where this parameter is increasing at a certain fan ratio, also due to more fuel consumed to impart this ratio.

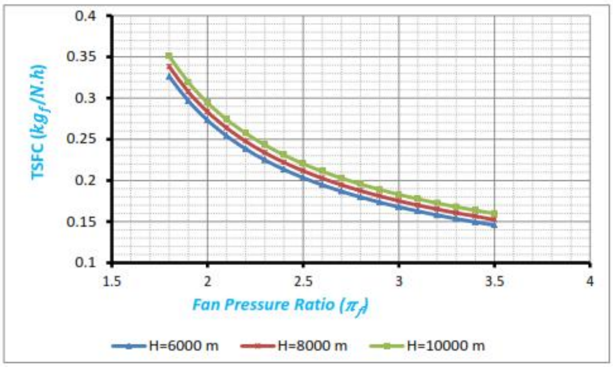


Figure 11. The relationship between fan pressure ratio and (TSFC).

Also it is shown in Figure. 12 and Figure. 13 that the propulsive efficiency and thermal efficiency have the same behavior with the fan pressure ratio, where both are decreasing with the increasing of this ratio. This is also due to more power is extracted by the fan at higher ratios and more fuel consumption.

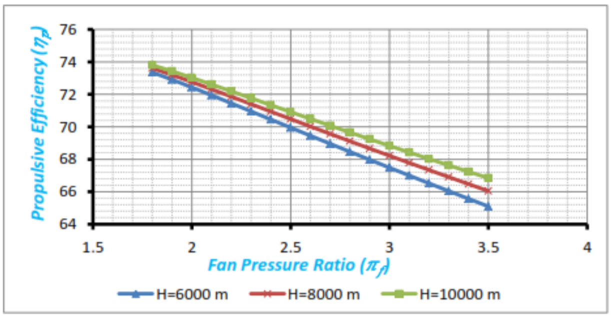


Figure 12. The relationship between fan pressure ratio and ($\eta_p$).

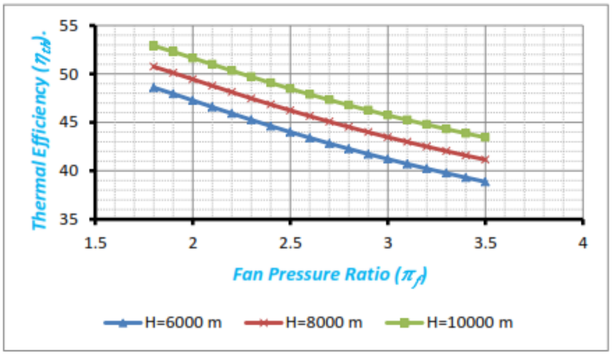


Figure 13. The relationship between the pressure ratio and ($\eta_{th}$).

### D. *Comparison of the main performance parameters for the mixed & unmixed flow:*

In the previous section the analysis is carried out for the unmixed flow turbofan engine only in which the same analysis can be carried out too for the mixed flow by the same process and can be done easily from the program designed for this purpose. So the results obtained for the comparison study for mixed and unmixed flow is taken in consideration in the following paragraphs and at the same variables which are flight speed, compressor pressure ratio, and fan pressure ratio.

- *Influence of the Flight Mach Number:*

In Figure. 14 the TSFC of unmixed flow turbofan is higher than for mixed flow at same bypass ratio and other parameters, this means that more fuel is consumed to reach to the same flight speed or propulsive power. In this case the propulsive efficiency gets lower as shown in Figure. 15. And as the flight speed increases the fuel consumption increases also for both cases as shown in Figure. 14. At the same time the propulsive efficiency increases due to increase in propulsive power which is a function of flight speed.

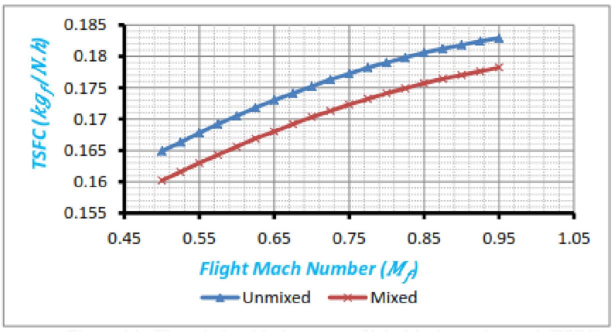


Figure 14. The relationship between flight Mach number and (TSFC).

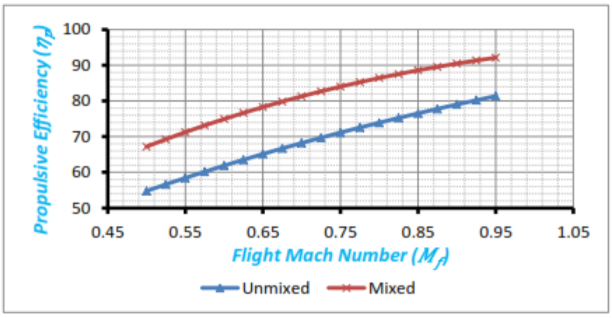


Figure 15. The relationship between flight Mach number and ($\eta_p$).

By increasing the fuel consumption to get more propulsive power the thermal energy increased which reduces the thermal efficiency as shown in Figure. 16. Here it is noticed also that the thermal efficiency for unmixed flow is higher because more thrust can be obtained from cold stream which increases the propulsive power at the same flight speed.

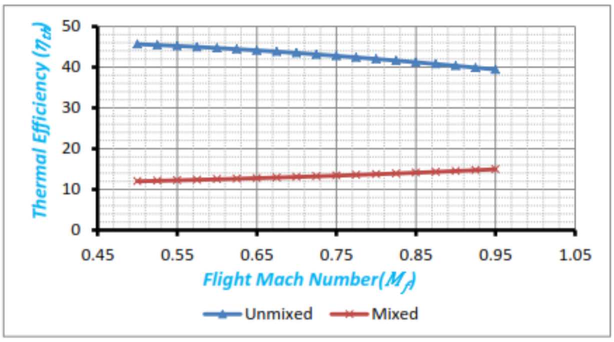


Figure 16. The relationship between flight Mach number and ($\eta_{th}$).

- *Influence of Compressor Pressure Ratio:*

The compressor pressure ratio has great influence on the performance of the jet engines, where it is noticed that by increasing this ratio the TSFC increases for both mixed and unmixed turbofans, but it is higher for unmixed flow as shown in Figure. 17. This is due to the influence of the specific thrust which is lower for unmixed flow for the same fuel mass flow rate. In the other hand the propulsive efficiency becomes less for the unmixed flow as shown in Figure. 18.

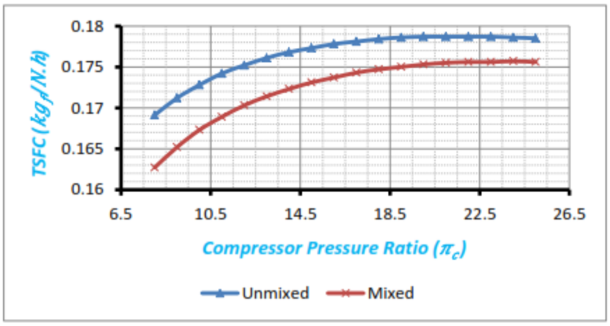


Figure 17. The relationship between compressor pressure ratio and (TSFC).

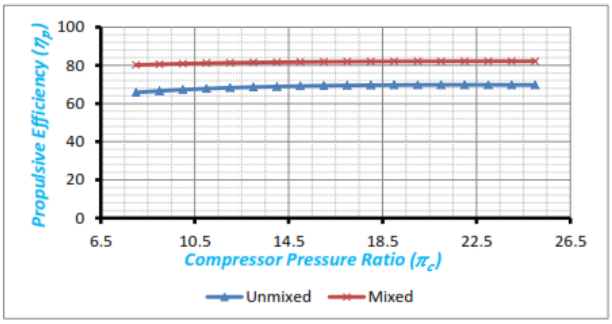


Figure 18. The relationship between fan pressure ratio and ($\eta_{pf}$).

But the thermal efficiency is higher for unmixed flow than mixed flow, while it drops with compressor pressure ratio as shown in Figure. 19 and almost stay constant for mixed flow turbofan, this is due to that both the propulsive power and the thermal energy in mixed flow increasing with the same ratio by increasing the compressor pressure ratio.

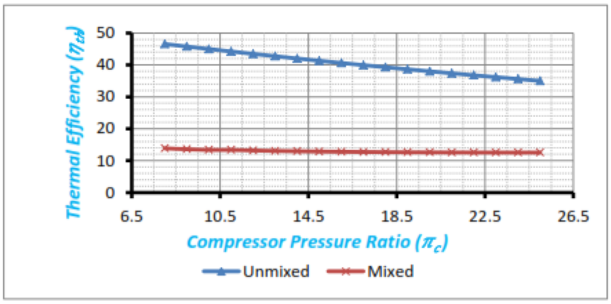


Figure 19. The relationship between compressor pressure ratio and ($\eta_{th}$).

- *Influence of the Fan Pressure Ratio:*

The other important parameter taken in consideration for analysis is the fan pressure ratio, which is taken variable from 1.8 up to 4.0, at other constant parameters such flight Mach number , combustion temperature, compressor pressure ratio and altitude.

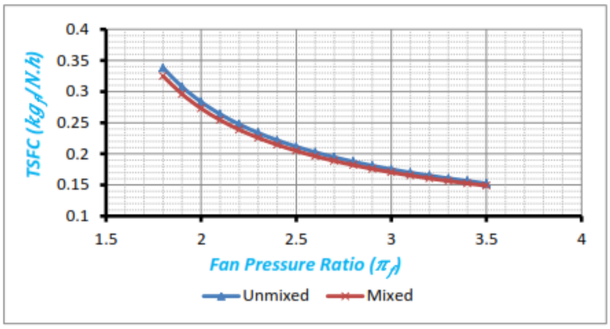


Figure 20. The relationship between fan pressure ratio and (TSFC).

With respect to the influence of this variable on TSFC there is no much difference between mixed and unmixed flow as shown in Fig. 20, but in both cases the TSFC is going down with increasing this parameter. This because by increasing the fan pressure ratio more thrust can be obtained from the cold stream which increases the thrust and reduces the fuel rate. In the same time this increase in fan pressure ratio can reduce the propulsive efficiency but not too much as shown in Figure. 21. Here also in this figure we notice that the propulsive efficiency is higher for mixed flow at certain value of fan pressure ratio due to less power wasted in this case.

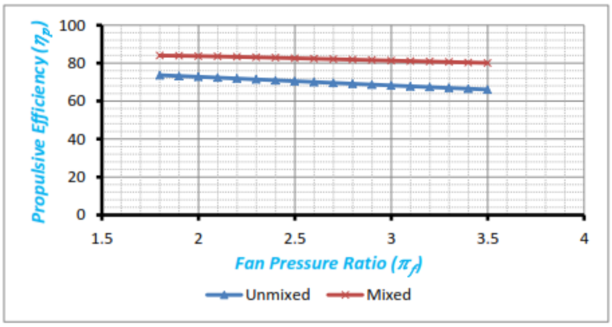


Figure 21. The relationship between fan pressure ratio and ($\eta_{pf}$).

What is interested in this analysis is the difference between the influence of fan pressure ratio in the thermal efficiency where in mixed flow it is increased while in unmixed it is decreased as shown in Figure. 22. This is due to more power wasted in unmixed flow by increasing fan pressure ratio compared with mixed flow, although more thrust is generated by cold and hot streams.

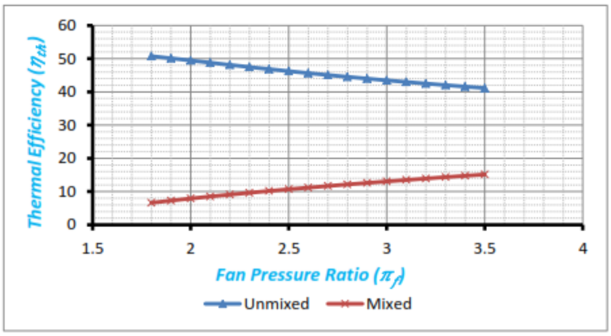


Figure 22. The relationship between fan pressure ratio and ($\eta_{th}$).

# IV. CONCLUSION

This study is carried out to study the influence of some operational and design parameters, such as flight Mach number, altitude of flight, compressor pressure ratio and fan pressure ratio, on the performance of the turbofan engine and for both cases mixed and unmixed flow. Here the researchers can conclude the following :

- By increasing the flight Mach number it is shown that the TSFC and the propulsive efficiency have increased while the thermal efficiency has decreased, in the other hand these three parameters have increased with the altitude.
- The compressor pressure ratio and the fan pressure ratio have shown influence on the performance parameters, where TSFC and propulsive efficiency increased while thermal efficiency decreased by increasing this ratio. But all these parameters decreased by increasing the fan pressure ratio.
- The comparison between mixed and unmixed flow show that the TSFC and the thermal efficiency are higher for unmixed flow at variable flight Mach number, compressor pressure ratio and fan pressure ratio, while the propulsive efficiency is lower at these variables.

# V.RECOMMENDATIONS

For future studies we recommend the following :

- This study is carried out by considering air with constant specific heat, so it is recommended to do it at variable specific heats with temperature at the components of the engine.
- Elaborate this study to include single and three spool turbofan engines, for more comparison.
- Perform the study at variable isentropic efficiencies for the whole components of the engine.
- Taking in consideration the chemical reaction process in the combustion chamber at variable fuel to air mixing ratios.

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