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BYPASS RATE IMPACT ON TURBOFAN PARAMETERS USING ENERGY AND EXERGY ANALYSIS

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ABSTRACT
One of the important parameters in turbofans is the bypass rates. In this paper, the rate of bypass in turbofans and also the accurate modeling of turbofans according to energy and exergy analysis is studied. Also physical and chemical exergy in cycle according to the changes in the outlet temperature of the combustion chambers and inlet Mach number is considered in modeling procedure. The results show that the high-pressure compressor has a high recovery rate. Also the combustion chamber has the highest rate of exergy loss which is 29% of the total cycle exergy loss. The second law efficiency of the turbofan was calculated to be 44%. The results also showed that with increasing Mach number at inlet, exergy efficiency almost remains constant and overall efficiency of the cycle depends on bypass rate ratio but generally shows a relative decrease.

KEYWORDS: Turbofan, exergy, Bypass rate.

INTRODUCTION

Charles Svoboda provided a large database of the so far known turbofan engines for the bypass ratio above number two. Basic parameters such as weight, length and diameter of the fan, motor length, thrust force in the horizontal position and inlet air mass flow, bypass ratio, fuel consumption of the airplane takeoff were all studied based on the engine thrust force [1].

Bethel proposed a simple design for fuel consumption performance and thrust force of the biaxial turbofan [2].

Mattias Henriksson et al [3] were trying to increase the axial force based on the axial force calculation for turbofan engine and air bypass. This model was simulated based on a thermodynamic semi-transition which the reported results suggests accurate measurements.

In the case of the optimization the work of Homaifar and et al [4] can be pointed out which applied genetic algorithms to optimize the turbofan cycle.

In this paper using genetic algorithms, turbofan engine systems has been optimized. In this work two criteria for evaluation were selected. These criteria are defined based on the overall efficiency increase and axial momentum flux increase and optimized by using four key parameters such as Mach number, compressor pressure ratio, fan pressure ratio and

round ratio. The results were acceptable comparing with previous studies that.

In 2010, Cesare Tona et al [5] studied exergy and thermo-economic of a turbofan to reduce costs and obtaining an algorithm to find optimal performance during a flight. The purpose of this paper is to present an exergy based analysis.

In a more accurate study conducted by Wenjuan and et al in 2012 [6] on the turbofans, the analysis of the thermodynamic performance of the engine with a pulse blast in the duct heater were performed which can be considered as a reference for the other hybrid propulsion production systems.

Recently H.Z. Hassan [7] studied local exergy loss in a turbofan. They benefited exergy analysis as a powerful tool in the design and operation of these systems to study CF6-50 turbofan and discussing entropy production in each component. Bejan [8] considered the need for exergy analysis and thermodynamic optimization in aircraft development. One of very important factors in increasing turbofan thrust force is bypass ratio is which in this paper, according to the first and second thermodynamic law and by considering the sensitivity analysis conducted on this item, it has been tried to study performance of this parameter on important turbofan characteristics

such as: total exergy loss, exergy efficiency, overall efficiency, SFC and thrust force. In this study, by sensitivity analysis and with a holistic view provided by first and second thermodynamic law, this parameter was assessed. In this work we tried to obtain an accurate model using the least assumptions.

MODELING
Modeling is done based on the figure (schematic of the turbofan cycle) on the turbofan according to the following conditions.

Air and gas mixture of combustion modeling
Air is considered to be a mixture of gases with specific composition as expressed in table 1.

Table1. Inlet air parameters and composition [9,10]

Component	Molar fraction (%)	Molecular mass (kJ/kmol)	Chemical Exergy (kJ/kg)
N_2	77.48	28.013	25.71
O_2	20.59	31.999	124.062
CO_2	0.03	44.010	457.72
H_2O	1.90	18.015	650.55

Each of these compounds has specific enthalpy and entropy which can be determined from the following equations and ultimately the mixture of gases are determined from the following equation [9]:

$$h_{\chi,j} = \frac{10^3}{M_{\chi,j}} \left[a + b \times \left(\frac{T}{1000}\right)^2 - c \times \left(\frac{T}{1000}\right)^{-1} + \frac{d}{3}\left(\frac{T}{1000}\right)^3 \right] \quad (1)$$

$$s_{\chi,j} = \frac{10^3}{M_{\chi,j}} \left[a' + b \times \ln(T)^2 - c \times \left(\frac{T}{1000}\right)^{-1} + \frac{d}{3}\left(\frac{T}{1000}\right)^3 - \bar{R}\ln\left(\frac{P_i}{P_{ref}}\right) \right] \quad (2)$$

$$h_\chi = \sum_{i=1}^N X_{\chi,j} h_{\chi,j} \quad (3)$$

$$s_\chi = \sum_{i=1}^N X_{\chi,j} s_{\chi,j} \quad (4)$$

The same procedure is applied in order to calculate gas molecular mass and specific heat capacity [9, 10]:

$$Cp_{\chi,j} = A + B \times T + C \times T^2 + D \times T^3 \quad (5)$$

$$Cp_\chi = \sum_{i=1}^N X_{\chi,j} Cp_{\chi,j} \quad (6)$$

$$M_\chi = \sum_{i=1}^N X_{\chi,j} M_{\chi,j} \quad (7)$$

Then, using the universal gas constant (R) and calculating the molar mass of the gas by equation (8) to the C_v is calculated. In this model, the following equations are used to calculate γ_χ parameter.

$$R_\chi = \frac{\bar{R}}{M_\chi} \quad (8)$$

$$Cv_\chi = Cp_\chi - R_\chi \quad (9)$$

$$\gamma_\chi = \frac{Cp_\chi}{Cv_\chi} \quad (10)$$

In each in order to increase the calculation accuracy, these relationships are used to determine the properties. In thsee equations index j represents the type of component (χ). For example, $h_{air, N2}$ is characterize with $\chi = air$ and $j = N_2$.

The expressed relations are also used for mixed combustion gases which in this case, only the composition fraction has been changed. These fractions are obtained by solving the combustion and energy equation in the combustion chamber. With regard to the mentioned details, the following functions can be used to express the properties of the turbofan cycle:

$$h_\chi(i) = f\left(X_\chi, M_\chi, h_\chi(i)\right) \quad (11)$$

$$T_\chi(i) = f\left(X_\chi, M_\chi, T_\chi(i)\right) \quad (12)$$

$$s_\chi(i) = f\left(X_\chi, M_\chi, T_\chi(i), P_\chi(i)\right) \quad (13)$$

where i represents each point of the cycle.

The fuel with $C_xH_yN_zO_k$ composition has been considered.

The fuel API is calculated from the following equation. By understanding the relationship between x and y coefficients in accordance with Table 2, other coefficient can be determined. Based on the equations described in reference [11] the calorific value of the fuel (kJ / kg) is calculated. The amount of fuel heat capacity can be determined as well with the following equation which is used in the fuel combustion equation [11].

$$API = \frac{141.5}{d_r\left(\frac{at\,289K}{289K}\right)} - 131.5 \quad (14)$$

$$M_{fuel} = \frac{11280}{(\text{API Gravity})^{1.1}} \quad (15)$$

To calculate LHV of liquid fuels, first, higher heating value of the fuel should be calculated:

$$HHV = 14500 \times C + 62000 \times \left(H_2 - \frac{O_2}{8}\right) + 4000 \times S \quad (16)$$

For calculating lower heating value, Equation 17 was used in terms of Btu/lb:

$$LHV = HHV - 9720 \times H_2 - 1110W \quad (17)$$

Where W is percent of fuel humidity and C, H_2, O_2 and S are weight percent of carbon, hydrogen, oxygen and sulfur in the fuel, respectively [11].

$$Cp_{fuel} = \frac{0.76 + 0.00335 T_{fuel}}{d_r^{0.5}} \qquad (18)$$

Where T_{fuel} is temperature of input fuel.

Table 2. Relationship between carbon and hydrogen in different fuels [10]

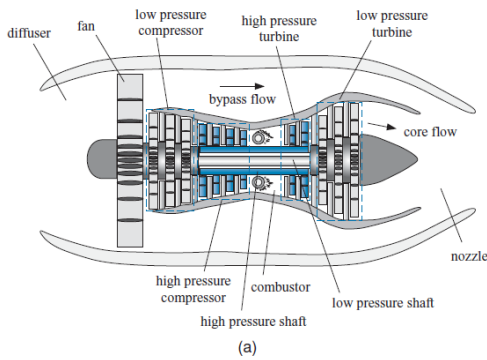| Fuel (phase)	Formula
Gasoline(l)	$C_nH_{1.87n}$
Light diesel (l)	$C_nH_{1.8n}$
Heavy diesel (l)	$C_nH_{1.7n}$

(a)
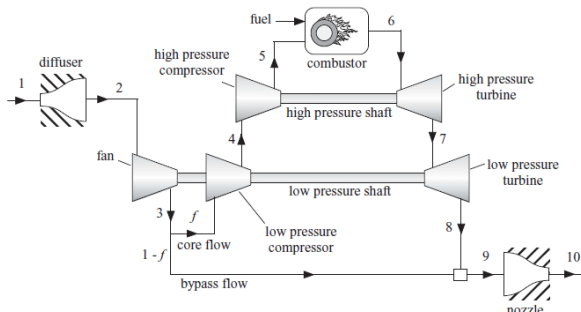
Figure 1: Schematic of the turbofan cycle modeling [12]

Turbofan cycle components modeling

- cycle pressure calculation

The first step to solve the problem is to calculate the individual pressure in cycles. By knowing this parameter under the polytropic process assumption the efficiency of the components other parameters are calculated. According to the figure 1 (cycle scheme) inlet air to diffuser is in accordance with the atmospheric pressure which varies with altitude from the sea level. Then, according to the diffuser equation the pressure at point 2 can be obtained [12].

$$P_{atm} = \frac{(760 \times (1\text{-}226 \times 10^{-7} \times H)^{5.25})}{735} \qquad (19)$$

$$P(1) = P_{atm} \qquad (20)$$

$$P(2) = P(1) + k_p \frac{\rho_{air} V_1^2}{2} \qquad (21)$$

Pressure at points (2), (3), (4) and (5) is determined

in accordance with the pressure ratio of each component and before entrance pressure. Here for the fan, compressor LP, HP the pressure of the mentioned point can be calculated [12]:

$$P(3) = r_{fan} P(2) \qquad (22)$$

$$P(4) = r_{LPC} P(3) \qquad (23)$$

$$P(5) = r_{HPC} P(4) \qquad (24)$$

An overall pressure drop can be considered for combustion chamber, according to three basic dropes, which includes the inlet diffuser pressure drop, hot pressure drop of the combustion and liners pressure drop [11], which can be calculated using following equation:

$$P(6) = (1 - \Delta P_{loss}) P(5) \qquad (25)$$

Also according to the mentioned specified pressure ratios for the before components, after pressures for high pressure and low pressure turbines can be determined and ultimately outlet nozzle pressure will be considered equal to the atmospheric pressure.

- The calculation of the enthalpy, entropy and temperature of the cycle

In following equation considering the diffuser, the enthalpy of point 2 can be calculated and the air temperature can be obtained using its molar mass, composition and determined enthalpy by using the (11) relations. Using temperature and pressure, entropy can be calculated at this stage [12]:

$$V_1 = M \times C_{air} \qquad (26)$$

$$C_{air} = \sqrt{\gamma_{air} R_{air} T_{air}(1)} \qquad (27)$$

$$h_{air}(2) = h_{air}(1) + \frac{V_1^2}{2} \qquad (28)$$

$$T_{air}(2) = f\left(X_{air}, M_{air}, h_{air}(2)\right) \qquad (29)$$

$$s_{air}(2) = f\left(X_{air}, M_{air}, T_{air}(2), P_{air}(2)\right) \qquad (30)$$

The procedure of the fan, LP and HP compressors modeling are almost similar with the only differences in the pressure ratio changes and isentropic efficiency. The important point is the temperature change in each stage which by using a trial and error method the exact value of the outlet temperature can be determined.

Based on the isentropic efficiency and polytropic process assumption the (31) equation is derived which indicate the outlet temperature of each component.

$$T_\chi(i) = T_\chi(i-1)\left(1 + \frac{1}{\eta_k}\left(r_k^{\frac{\gamma_\chi - 1}{\gamma_\chi}} - 1\right)\right) \quad (31)$$

where $\chi = air$ and k represents each component. For fan i =3, compressor i = 4 and HP compressor i = 5. The fans and compressors work (kJ/kg)is calculated using the following:

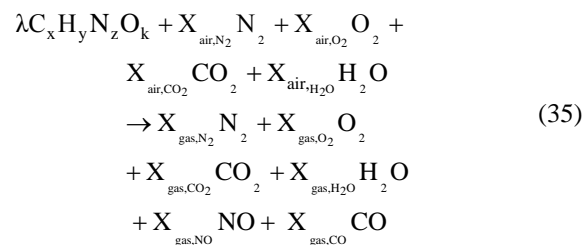$$W_k = h_\chi(i-1) - h_\chi(i) \quad (32)$$

Combustion chamber modeling can be done in two ways: one based on the combustion chamber outlet temperature (being specified) and the other by determining inlet fuel flow rate. The first method is used in this modeling. As a result, by considering the combustion chamber as a volume control and 2% heat loss for this component [11],the ratio of the fuel to air can be calculated (λ) [9]:

$$h(5) + \lambda h_{fuel} = (1+\lambda)h(6) + 0.02 LHV \quad (33)$$

$$\lambda = \frac{n_{fuel}}{n_{air}} = \left(\frac{\dfrac{\dot{m}_{fuel}}{M_{fuel}}}{\dfrac{\dot{m}_{air}}{M_{air}}}\right) \quad (34)$$

In this equation air-fuel ratio also affect determining the composition from the combustion.

Consequently, by considering the combustion relation as following and by balancing the elements, composition fraction can be related to the air to fuel ratio [9]:

$$\begin{aligned}
\lambda C_x H_y N_z O_k &+ X_{air,N_2} N_2 + X_{air,O_2} O_2 + \\
&X_{air,CO_2} CO_2 + X_{air,H_2O} H_2O \\
&\rightarrow X_{gas,N_2} N_2 + X_{gas,O_2} O_2 \\
&+ X_{gas,CO_2} CO_2 + X_{gas,H_2O} H_2O \\
&+ X_{gas,NO} NO + X_{gas,CO} CO
\end{aligned} \quad (35)$$

By integrating the energy equations with combustion and element balance equations a new equation in terms of (λ) can be obtained. By solving this equation and determining this parameter, fuel flow can be calculated with regard to the definition of the mentioned (relationship).

$$\begin{aligned}
\lambda &= \frac{X_{air.O_2}\Delta h_{air.O_2} + X_{air.N_2}\Delta h_{air.N_2} + X_{air.CO_2}\Delta h_{air.CO_2} + X_{air.H_2O}\Delta h_{air.H_2O}}{h_{fuel} + x h_{air.O_2,T(6)} + {yh_{air.O_2,T(6)}}/{4} - x h_{air.CO_2,T(6)} - {yh_{H_2O,T(6)}}/{2}} \\
&= \frac{\dot{m}_{fuel}}{\dot{m}_{air}} \times \frac{M_{air}}{M_{fuel}}
\end{aligned}$$

$$(36)$$

Which in the above relations $\Delta h_{air,i}$ is input and output enthalpy difference. For instance, for water it can be expressed as follow:

$$\Delta h_{H_2O} = h_{air.H_2O,T(6)} - h_{air.H_2O,T(5)} \quad (37)$$

In determining the outlet temperature of the HP and LP gas turbine the following equations can be used [12]:

$$\frac{W_{GT.H}}{\dot{m}_{air}(6) + \dot{m}_{fuel}} = \frac{W_{AC,H}}{\dot{m}_{air}(4)} \quad (38)$$

$$h_{gas}(7) = h_{gas}(6) - W_{GT.H} \quad (39)$$

$$\frac{W_{GT.L}}{\dot{m}_{air}(7) + \dot{m}_{fuel}} = \frac{W_{AC,L}}{\dot{m}_{air}(4)} + \frac{W_{Fan}}{\dot{m}_{air}(2)} \quad (40)$$

$$h_{gas}(8) = h_{gas}(7) - W_{GT.H} \quad (41)$$

$$T_{gas}(i) = f\left(X_{gas}, M_{gas}, h_{gas}(i)\right) \quad (42)$$

$$s_{gas}(i) = f\left(X_{gas}, M_{gas}, T_{gas}(i), P_{gas}(i)\right) \quad (43)$$

At the entrance of the nozzle two streams are combined. The first stream, with respect to the ratio of f fter fan goes to the LP and HP section which and composition change is combined with the second stream. The change in mass flow rate of the fan can be obtained from the following:

$$\dot{m}_{air}(9) = (\dot{m}_{air} + \dot{m}_{fuel})(1-f) + \dot{m}_{air} \times f \quad (44)$$

Finally, with regard to the continuity equation the composition of each component in the inlet of the nozzle can be obtained:

$$X_{Mix} = \frac{(\dot{m}_{air} + \dot{m}_{fuel})(1-f) \times X_{gas} + \dot{m}_{air} \times f \times X_{air}}{\dot{m}_{air} + \dot{m}_{fuel}} \quad (45)$$

In this case, by using the first law of thermodynamics the temperature of points (9) can be determined and ultimately by considering nozzle efficiency (η_N) the enthalpy and velocity at point 10 can be calculated in accordance with following equations [12]:

$$V_{10}^2 = \eta_N\left(h_{Mix}(9) - h_{Mix,is}(10)\right) \quad (46)$$

$$h_{Mix,a}(10) = h_{Mix}(9) - \frac{V_{10}^2}{2} \quad (47)$$

Important parameters of the cycle are calculated as follows [12]:
The terrace force:

$$F_t = \dot{m}_{air}\left[\left(1 - \frac{\dot{m}_{fuel}}{\dot{m}_{air}}\right)V_{10} - V_1\right] \quad (48)$$

Specific energy:

$$SEC = \frac{\dot{m}_{fuel}}{F_t} \quad (49)$$

Bypass rate:

$$BPR = \frac{1-f}{f} \qquad (50)$$

Polytrophic efficiency:

$$\eta_p = \frac{2V_1F_t}{(\dot{m}_{air} + \dot{m}_{fuel})V_{10}^2 - \dot{m}_{air}V_1^2} \qquad (51)$$

Thermal efficiency:

$$\eta_{th} = \frac{(\dot{m}_{air} + \dot{m}_{fuel})V_{10}^2 - \dot{m}_{air}V_1^2}{2 \times LHV \times \dot{m}_{fuel}} \qquad (52)$$

Overall efficiency:

$$\eta_O = \eta_{th}\eta_p \qquad (53)$$

The presented data on table 3 has been used in turbofan modeling:

Table 3. Input parameters for turbofan modeling [12]

Parameter	Unit	Value
Inlet air pressure	atm	0.287
Intake air temperature	K	227
Inlet Mach number	-	0.85
Fan pressure ratio	-	1.6
fan isentropic efficiency	%	0.88
Low pressure compressor pressure ratio	-	2.5
Low pressure Isentropic efficiency	%	0.89
High pressure compressor pressure ratio	-	12
Low pressure Isentropic efficiency	%	0.89
combustion chamber outlet temperature	-	1300
Combustion chamber pressure drop	%	5
API	-	46
high pressure turbine isentropic efficiency	%	0.91
low pressure turbine isentropic efficiency	%	0.89
nozzle isentropic efficiency	%	0.93
diffuser Compressibility factor	-	0.45

Exergy analysis
This method is based on the second law of thermodynamics and the obtained strategy lead to the expression of each component energy quality.
Exergy includes different term such as physical, chemical and kinetic and potential exergy. In this modeling the potential exergy, due to the height difference is a cycles, is ignored [9].

$$\dot{E}x = \dot{E}x_{PH} + \dot{E}x_{CH} + \dot{E}x_k \qquad (54)$$

$$\dot{E}x_K = \frac{1}{2}mV^2 \qquad (55)$$

$$\dot{E}x_{ph} = \dot{m}[(h-h_\circ) - T_\circ(s-s_\circ)] \qquad (56)$$

$$\dot{E}x_{CH} = \dot{m} \times ex_{mix}^{CH} \qquad (57)$$

$$ex_{mix}^{ch} = \left[\sum_{i=1}^{N} X_i ex^{ch_i} + RT_0 \sum_{i=1}^{N} X_i lnX_i + G^E\right] \qquad (58)$$

The last term, GE; which is the excess free Gibbs energy is negligible at low pressure at a gas mixture. One can generalize the chemical exergy concept of fuel to every $C_xH_yN_zO_k$ component. The molar chemical exergy ex^{ch} c of such a component will be [9]:

$$ex_c^{ch} = (\mu_{c,0} - \mu_c^e) \qquad (59)$$

$$\mu_c^e = \alpha\mu_{co_2}^{-e} + \left(\frac{\beta}{2}\right)\mu_{H_2o}^{-e} + \left(\frac{\gamma}{2}\right)\mu_{N_2}^{-e} + (-\alpha - \frac{\beta}{4} + \frac{\delta}{2})\mu_{o_2}^{-e}$$
$$(60)$$

Where $\mu_{c,0}$ represents the chemical potential of the components at their thermo-mechanical equilibrium state with the standard ambient. For the evaluation of the fuel exergy, the above equation cannot be used. Thus, the corresponding ratio of simplified exergy is defined as the following:

$$\xi = \frac{ex_F^{ch}}{LHV_{fuel}} \qquad (61)$$

The specific chemical exergies of liquid fuels on a unit mass basis can be determined as follows [9]

$$\frac{e_{Ch}}{LHV} = \gamma_f = 1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2169\frac{S}{C}\left(1 - 2.0628\frac{H}{C}\right)$$
$$(62)$$

After exergy calculation at each point of the cycle, exergy losses of each component is determined using the following equation [9]:

$$\dot{E}x_f = \dot{E}x_p + \dot{E}x_D + \dot{E}x_L \qquad (63)$$

In these equations, $\dot{E}x_D$ ، $\dot{E}x_L$ ، $\dot{E}x_p$ و $\dot{E}x_f$ terms represents exergy losses, losses, generation and fuel exergy respectively. Exergy efficiency will be determined by the following equation.

$$\eta_{ex} = 1 - \frac{\dot{E}x_D + \dot{E}\dot{x}_L}{\dot{E}x_f} \qquad (64)$$

RESULTS
Table 4 shows the energy and exergy analysis of the cycle with regard to the chemical and physical exergy. Based on the conducted analysis for each component, the amount of Exergy Destruction can be observed in Table 5.

Using these parameters the exergy efficiency of each component and ultimately the exergy efficiency of the cycle can be determined. As shown in Table 4, after air enters into the nozzle, its temperature has risen slightly due to the default value for that component efficiency, entropy increases.

In fan, due to the low pressure ratio, temperature and pressure has increased in a small range. In this section, a fraction of the bypassed fan air, which is included in f calculation (figure 1), is considered to be 0.2 which is subtracted from total the air flow. The subtracted amount then enters into the low pressure compressor and then high-pressure compressor and the temperature and pressure is increased in both sections.

Due to the outlet temperature of the combustion chamber which is assumed 1300 ° C, the fuel flow rate is calculated. It worth to notice that in this modeling liquid fuel API, as described in the modeling section, is equal to 46. By specifying fuel to air molar ratio, the amount and the composition of combustion gases can be determine. By changing the chemical composition, chemical exergy content has been changed and also mass flow rate is increased as fuel is injected.

According to the obtained model in the turbine sections, the combustion gas enthalpy is calculated and on this principle physical exergy can also be obtained. In combustion gases section with the air flow, separated from the LP and HP after fan, the new composition, temperature and ultimately entropy

is calculated. By nozzle modeling the temperature, chemical and physical exergy at output can also be calculated.

Table 4. Energy and exergy analysis for each point at turbofan cycle

Point	O_2	T (K)	P (atm)	m (kg/s)	Ex^{ph} (MW)	Ex^{ch} (MW)	Ex (MW)
1	0.21	227	0.29	128.1	14.32	0.252	14.57
2	0.21	262	0.35	128.1	15.65	0.252	15.90
3	0.21	304	0.56	128.1	20.54	0.252	20.79
4	0.21	405	1.41	25.62	6.53	0.050	6.59
5	0.21	819	16.9	25.62	17.73	0.050	17.78
6	0.13	1573	16.08	26.25	30.55	0.249	30.80
7	0.13	1249	1.34	26.25	16.68	0.249	16.93
8	0.13	1140	0.54	26.25	12.03	0.249	12.28
9	0.19	493	0.55	128.7	103.1	0.213	103.3
10	0.19	419	0.29	128.7	92.97	0.213	93.19

As shown in Table 5 the highest exergy loss is related to the high-pressure compressor and due to the high pressure ratio, the entropy is increased intensely. Also this component has the highest exergy loss (y_d) . The combustion chamber, due to irreversible combustion process poses very high exergy losses. On other hand the type of fuel is one of the important factors in entropy production of exergy losses which is totally depends on its heating value. Because the exhaust heat and smoke in nozzle cannot be used. Output exergy in this section is considered as exergy losses.

Table 5. Exergy analysis result for each component

	EX_D (MW)	Ex_f (MW)	Ex_L (MW)	y_d (%)	η_{ex} (%)
diffuser	1.33	15.9	0.0	2.25	0.92
Fan	0.47	21.26	0.0	0.79	0.98
LP-compressor	0.20	6.79	0.0	0.34	0.97
HP-compressor	22.76	29.34	0.0	38.5	0.22
Combustion chamber	17.26	48.07	0.0	29.2	0.64
HP-gas turbine	2.31	30.8	0.0	3.92	0.92
LP- gas turbine	4.51	16.93	0.0	7.64	0.73
nozzle	10.16	103.3	93.19	17.2	0.9
Total	59.00	272.4	93.19	1.0	0.44

Table 6 shows the results of the overall, thermal and polytropic efficiency and also the thrust force, SFC, for the cycle in design mode. The bypass is also shown in this table.

Table 3. Cycle main parameters value

	Value
η_{th} (%)	20.84
η_{p} (%)	76.93
η_{o} (%)	16.04
SFC (kg/kN)	0.0358
F_{thrust} (kN)	17.63
BPR	4
M_{10}	1.58

By conducting the sensitivity analysis on the bypass in turbofan and changing this value, its effects can be observed on the cycle parameters. By changing the outlet temperature of the combustion chamber at different bypass ratios, it can be seen that by increasing this ratios, the exergy efficiency is decreased and as the temperature rises, the efficiency is increased. In this case, exergy efficiency is in contrast to the overall efficiency. As it can be seen in Figure 3 by decreasing temperature and increasing bypass ratio the efficiency is increased.
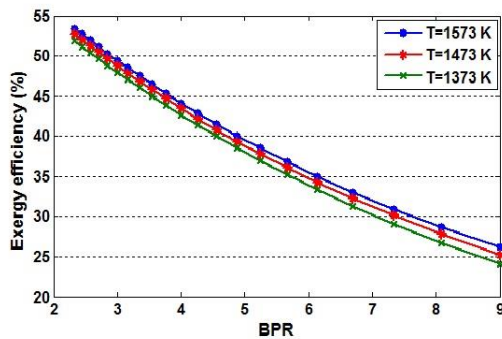
Figure 2: bypass to exergy efficiency ratio rate at different the combustion chamber outlet temperatures
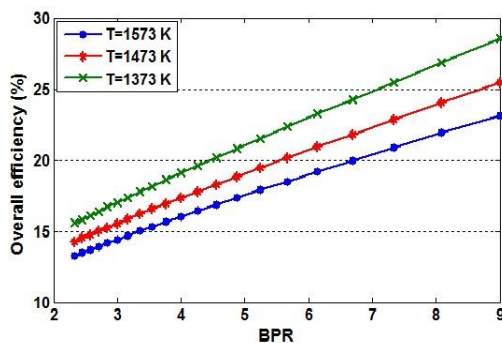
Figure 3: bypass to overall efficiency ratio rate at different the combustion chamber outlet temperatures

By increasing the combustion chamber outlet

temperature a higher terrace force can be obtained.
This phenomena is reduced at different bypass ratio which the cause of this change can be seen in Figure 5, which means the Mach number at the outlet is decreased. Due to constant inlet Mach number and also changes that occured in the ratio of fuel to air flow and outlet Mach number, it can be concluded that there are factors cause terrace force decrease.
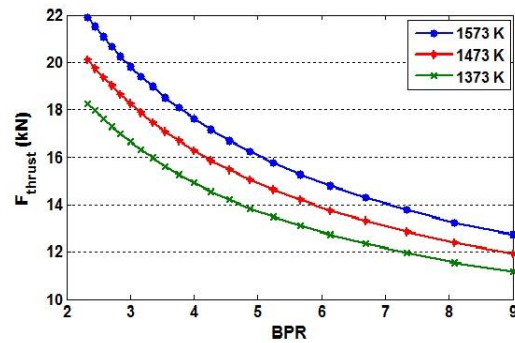

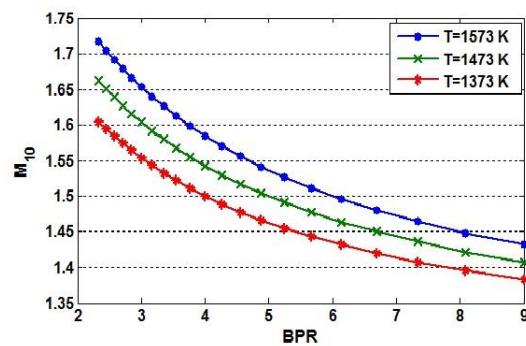*Figure 4: bypass to terrace force ratio rate at different outlet combustion chamber temperatures*

Figure 5: bypass to outlet Mach number ratio rate at different outlet combustion chamber temperatures

By comparing these two Figures it can be seen that these two parameters have a direct impact on each other and the change trend is almost the same even though the changes in the ratio of fuel to air has a little impact on change in the terrace force change trends.

With the change in the inlet Mach number, exergy efficiency is almost constant, while the overall efficiency is changed drastically and is reduced with the reduction in Mach number and bypass. (Figure 6)

It can also be observed in this figure, that by increasing bypass, th Mach number effect on the efficiency is decreased.

As a result, one of the parameters that has a low impact on efficiency and exergy loss is inlet Mach number. The reason is small changes in exergy loss which would cause some changes in turbofan inlet.

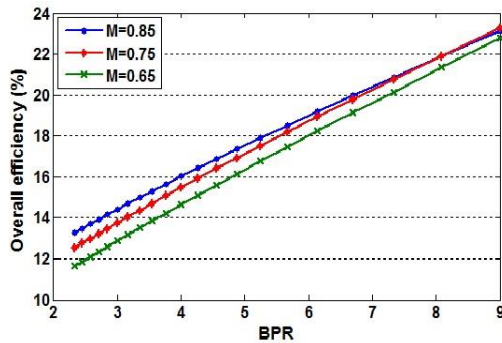Figure 7 shows total exergy losses with respect to the bypass variations.

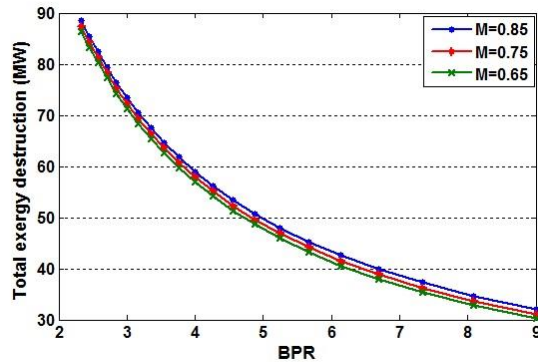*Figure 6: bypass to overall efficiency ratio at different inlet Mach numbers*

Figure 7: bypass to total exergy loss ratio at different inlet Mach numbers

Figure 8 shows the dependence of the outlet Mach number to the inlet Mach number.

By increasing the inlet Mach number, the outlet temperature in diffuser and a fan has been changed. This affects the entire cycle and after the merger of the bypass flow and main part, the enthalpy and entropy at point 9 is changed which ultimately by increasing the bypass number the terrace force, and as a result, the outlet Mach number is decreased.

By changing the type of fuel (Figure 9) it can be seen that as the fuel API is increased, Carbone and hydrogen amount in the fuel is decreased resulting in reduced fuel heating value. This will lead to a reduction in exergy efficiency (below curve in figure 8), on the other hand, it has increased the cycle overall efficiency.
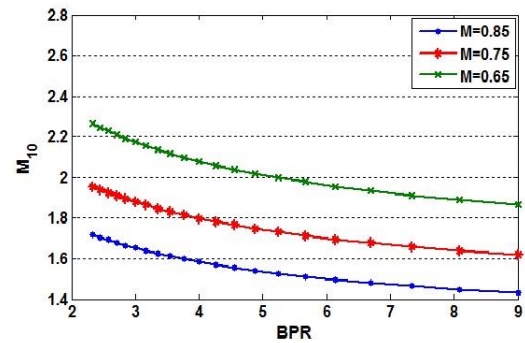

Figure 8: bypass rate exit Mach number at the inlet Mach numbers
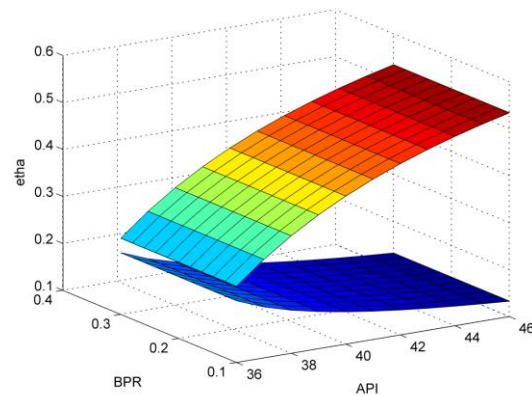

Figure 9: exergy efficiency and overall efficiency change by changing the type of fuel and turbo fan bypass rate.

CONCLUSION

The results show that:

A) In turbofan cycle, due to the high pressure ratio in HP-compressor it has maximum exergy loss which is 32% of the total losses.

B) In exergy analysis it was shown that after high-pressure compressor, combustion chamber poses the highest exergy loss.

C) Bypass rate is one of the factors that causes changes in the cycle parameters.

D) Change in types of fuel and applying fuel with higher API causes overall efficiency increase and exergy efficiency decrease.

E) Inlet Mach number increase at high bypass rates leads to a relative decrease in overall efficiency at lower Mach number.

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