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Exergo-economic cost accounting for PW4000 turbofan engine and its components

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Abstract. You The several series of PW4000 high bypass turbofan engine have used so far in many aircrafts. These commercial engines have played a crucial role on passenger and freight transportations. Namely, these engines are closely related to the environment impacts and security of energy supply. In this article, exergoeconomic analysis which is useful tool to investigate existing potential for improvement of the a system efficiency were carried out. The assesment, design and optimization of energy consuming systems are performed by means of these analyses. Therefore, thermo-economic costs were assigned to existing exergetic values of PW400 engine. Also exergo-economic performance parameters were evaluated. Finally, exergo-economic deputy parameters were examined to understand relations with exergo-economic parameters. Based on the results of exergo-economics analysis, for Fan and exhaust, specific thrust costs are estimated 5.7051 \$/hkN and 68.45\$/hkN respectively. Also exergo-economics factor of PW4000 is found 7.958 % , while relative cost difference is determined at highest rate with 24.458 % for combustion chamber . With examination relations between economic variables and exergo-economic performance parameters, the change between 0.6 and 1.2 \$/kg in the fuel price leads to increase the exhaust and fan specific thrust costs with 82.4701 \$/hkN and 5.4332 \$/hkN respectively. It is expected that conclusions of this study are helpful to notify exergo-economic impact of PW4000 engine Also, it may be benchmarking for similar gas turbine engines.

1 System description

The number of PW4000-94 produced has reached over 2500 since used in service in 1987. Nearly 2300 PW4000s were still in service in 2015. In this study PW4000 shown in Fig. 1 investigated has fan pressure ratio with 1.8 value, by-pass ratio with 5.1 value and total pressure ratio with 32 value during take-off. It produces about thrust at value of 260 kN at take-off [1]. The mass flow value of inlet air is 774 kg/s while, of this, 129 kg/s passes through the core engine, the remaining air is exhausted from fan exit. Air-fuel ratio is obtained as about 48.679.

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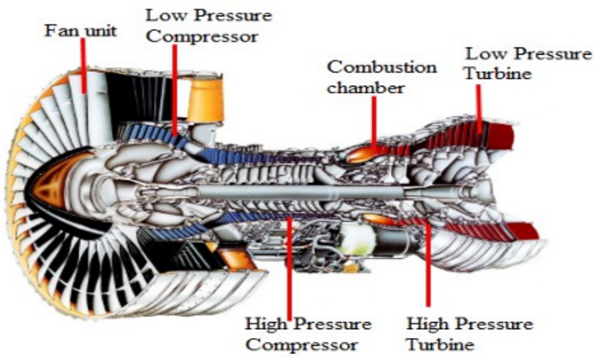


Figure 1. Illustration of PW4000 turbofan engine components [1]

2 Exergo-economic analysis of PW4000 engine

The exergoeconomic analysis arises out of combination of economic principles with second law of thermodynamics [2]. Both analyses together give more certain knowledge about system dealt with. The foundation of exergoeconomics analysis is that monetary costs associate with thermodynamic inefficiencies resulted from interactions emerged between system and its surroundings [3]. Namely, exergoeconomic methodology is employed to determine the costs of incoming and leaving streams, and exergy destructions within the system components [2]. The goal of this method is to optimize exergo-economic values for minimizing the exergy cost. Thus, the whole system has higher cost effectiveness. Exergo-economic behavior of the system can be evaluated for cost balance. Main equations related cost balance of an engine may be established as given below [4]:

$$\dot{C}_q + \int_i \dot{C}_k + \dot{Z}_k^T = \int_e \dot{C}_k + \dot{C}_w \tag{1}$$

$$\dot{C}_q = c\dot{E}_{q,k} \tag{2}$$

$$\dot{C}_k = c\dot{E}_{x,k} \tag{3}$$

$$\dot{C}_w = c\dot{W}_k \tag{4}$$

$$\dot{Z}_k^T = \dot{Z}_k^{CIC} + \dot{Z}_k^{OM} \tag{5}$$

Where $\dot{C}_q, \dot{C}_k$ and $\dot{C}_w$ represent the levelized exergy cost rate of heat transfer, entering or leaving stream and work done respectively. $\dot{E}_x, \dot{E}_q$ and $\dot{W}$ are the exergy of stream, heat transfer and power at inlet and outlet of the kth component. $\dot{Z}$ represents the levelised cost values for non exergetic with the units of \$h-1. where T denotes total of capital investment cost (CIC) and operating & maintenance cost (OM) for the kth component.

3 Exergy assessment of PW4000 engine

The effiencieny in the energy use is very significant because all of the energy cannot be converted into useful work. Application of existing techonologies and several optimisation techniques together could provide benefit to reduce energy consumption [5]. The rise in energy efficiency means both the protection of environment from harmful emissions and economic saving for aviation sector. In fact, the limited resources lead to find out methods of sustainable development. For thermal systems, exergy evaluation is a foundation of economics, environmental and sustainability analyses, and thanks to results obtained, optimization of systems could performed on more factual base. Even only if applications of aircraft gas turbine engines are considered, the significance of an exergetic approach could be easily comprehended. Several exergy components exist in nature. The most used of them are physical and chemical exergies. Kinetic exergy is used only where velocity is high.

The meaning of physical exergy is the useful work provided from interaction between system and its surrounding, whereas chemical exergy could be defined as theorical work provided due to chemical composition difference between a system and its reference environment. Chemical exergy emerges only in combustion situations. If the first and the second laws of thermodynamics is applied on thermal systems, exergetic balance equality is easily established for related components. Physical exergy flow as called thermo-mechanical exergy divided into two components as thermal and pressure exergy. When ideal gas relations and constant specific heat capacity are accepted, this terms could be determined as follows respectively [6]:

$$E^{th} = \dot{m}c_p[(T_k - T_{amb}) - T_{amb}ln\frac{T_k}{T_{amb}}] \quad (6)$$

$$E^{pres} = \dot{m}RTln\frac{P_k}{P_{amb}} \quad (7)$$

In this study, when calculating thrust cost rate, exergies of Fan exit and exhaust is calculated with aid of kinetic exergy. The kinetic exergy of air and combustion gases is accounted for as follows [7]:

$$E^{pres} = \dot{m}RTln\frac{P_k}{P_{amb}} \quad (8)$$

Considering fossil fuels which is formulated as C_aH_b, their chemical exergy is defined as:

$$E^{ch} = \dot{m}_f \times LHV \times \left(1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a}\right) \quad (9)$$

Whereas, chemical exergy of air constituents is found by [8]:

$$ex_{ch} = \sum_k x_k ex_k^{ch} + RT_0 \sum_k x_k lnx_k \quad (10)$$

In this context, exergy balance equilibrium for any control volume could be established as:

$$E^{ch} + \sum(E_o^{th} - E_i^{th}) + \sum(E_o^{pres} - E_i^{pres}) + \mathrm{T}_{amb}\sum(S_o - S_i) + \dot{Q} + \dot{W} = 0 \quad (11)$$

Exergy destruction required during efficiency calculations could be determined with aid of entropy production occured in components.

$$E_{xd} = T_{amb}\sum(S_o - S_i) \quad (12)$$

As for exergy efficiency, in literature various methods exist for this term. For in any component, this parameter could be defined by [8]:

$$\eta_{ex,k} = \frac{Ex_{pr}}{Ex_f} \tag{13}$$

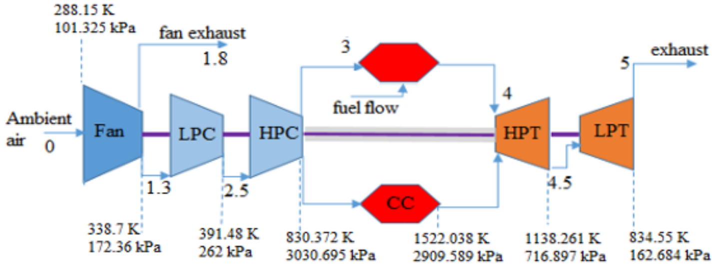
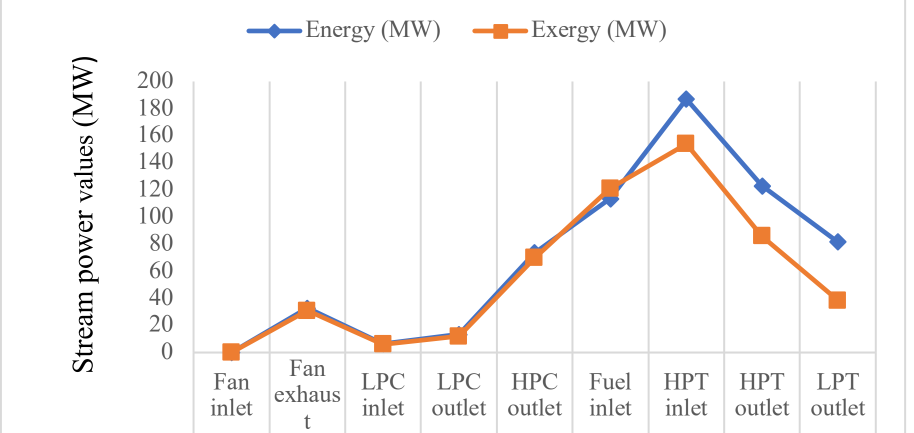


Figure 2. Cross-section drawing of PW4000 with thermodynamic informations

According to thermodynamics values given Figure 2, exergy analysis of PW4000 engine was carried out in advance [9,10].



	Fan inlet	Fan exhaust	LPC inlet	LPC outlet	HPC outlet	Fuel inlet	HPT inlet	HPT outlet	LPT outlet
Energy (MW)	0	32,76	6,552	13,51	73,58	113,42	187	122,86	81,58
Exergy (MW)	0	30,94	6,18	12,1	69,83	121,12	153,86	85,85	38,33

Figure 3. Energetic and exergetic values of PW4000 engine for each station

4 Results and discussion

In this article, exergoeconomic analysis of high bypass PW4000 turbofan engine was carried out with aid of energy and exergy analysis performed in advance. The linear equation system solution and the relations between exergo-economic variables and economic performance parameters was provided developing code in the Matlab environment.

In Figure 4 cost rates is associated with the exergy destruction for each component. Thanks to two different methods, this parameter provide us opportunity to evaluate costs of these inefficiencies from different point views.

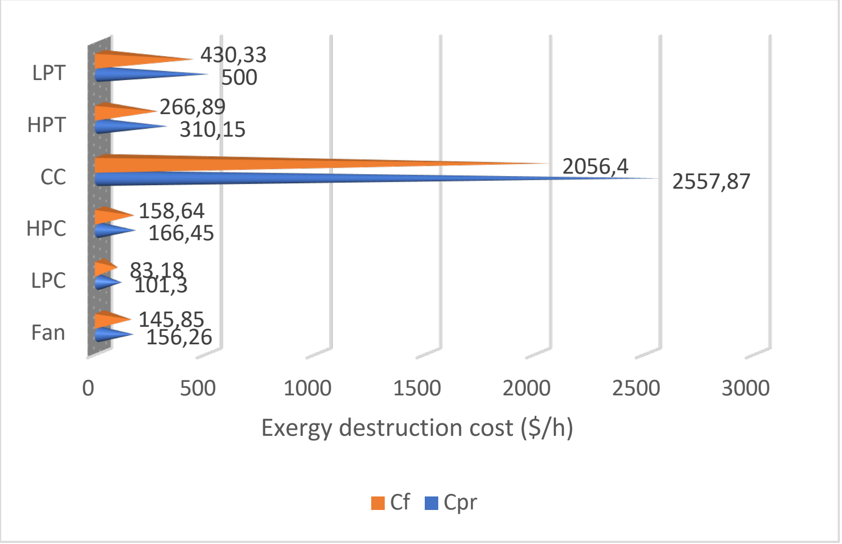


Figure 4. Exergy destruction cost rates of PW4000 engine components

Exergo-economic factor can display whether improvements to be performed is worth. This parameter is affected by two component. The first one is the exergetic costs resulted from inefficiencies. If this factor enjoys relatively low values, it should be known that exergetic costs outweigh. On the contrary, in high values of this factor, non-exergetic costs are dominant factor. According to Fig. 5, CC unit enjoys the lowest exergo-economic factor with 1.0801 %, while LPC unit has the highest ratio with 27.206 %. Fan, HPC and HPT stay modest values with 17.57 %,20.206 and 13.444 % respectively. Finally, LPT has second the lowest value with 6.738 %

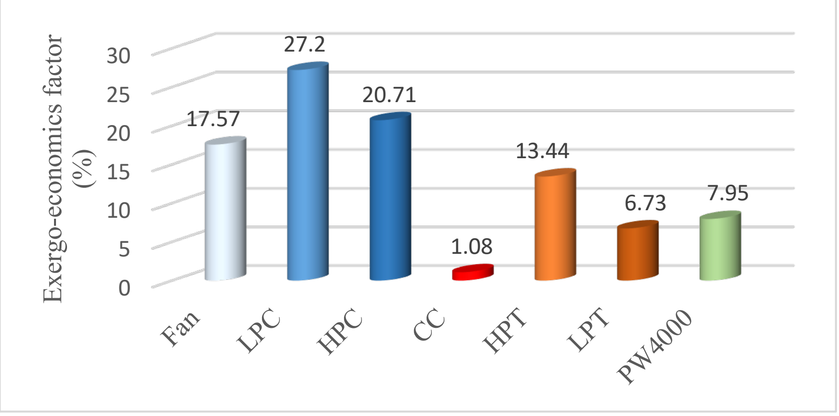


Figure 5. Exergo-economic factor values of PW4000 and its components (%)

For this engine, about three quarters of thrust is generated by Fan unit, whereas the rest amount of thrust is provided by combustion gases from exhaust. After find unit cost rate for Fan thrust with solution of linear equation system, corresponding unit cost for exhaust thrust can be calculated. Considering these calculations, cost rate for exhaust thrust is determined 4448 $/h, whereas for the Fan thrust, it is estimated as 1116 $/h. When these rates are divided to thrust values to find STC parameter, corresponding values are 68.45 $/hkN and 5.705

$/hkN respectively. Enormous difference in thrust cost rates could divert us to several initiatives such as increasing bypass ratio and fan pressure ratio to increase amount of fan thrust, but with current technology, some causes such as aerodynamic performance and sensitive balance between design variables do not allow us to achieve these attempt. As seen in Fig. 6, effect of the fuel price on specific thrust cost rate are handled. The variation in the range of 0.6 and 1.2 $/kg at the fuel price leads to rise the exhaust and fan specific thrust costs at the ratios of 110.239 % of 96.61% respectively. Corresponding rises are 82.4701 $/hkN and 5.4332 $/hkN respectively. It may be deduced that if new techniques towards increasing combustion efficiency or fuel derivations for turbofan engines are not explored, the aviation sector may not compete with the increase in fuel price.

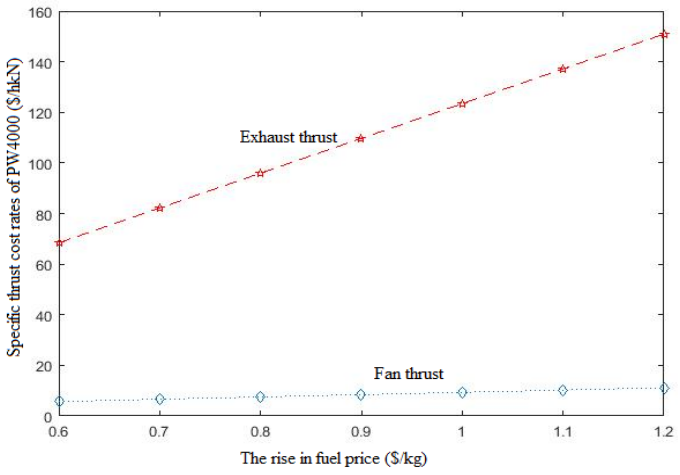


Figure 6. The variation in STC rates versus fuel price

Effect of PECs for HPC and HPT units on the fuel cost rates is displayed in Fig. 7. Although specific fuel cost ratios are not change much between 1.2 M$ and 2.4 M$, the variation in fuel cost ratios is calculated to be 80.12237 $/h and 75.03821 $/h respectively. These figures are highly crucial to consider PECs of components. Also these increases show parallelism with magnitude of exergo-economic factor which component has. Namely, HPC unit has relatively high exergo-economic factor. It is expected that it has higher rise in fuel cost rate according to variation in PEC. In Fig. 7, this situation emerged as mentioned.

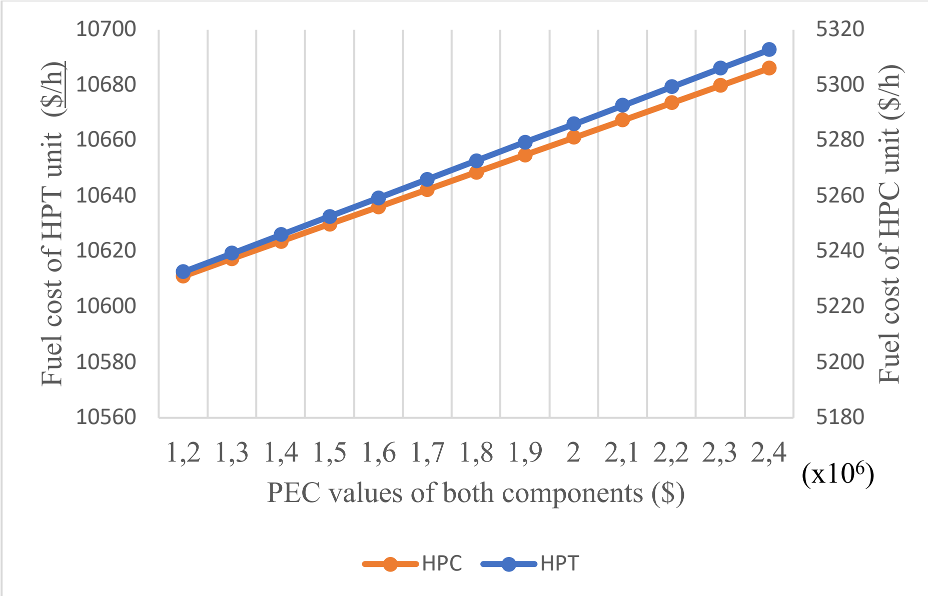


Figure 7. The change in fuel cost rates versus PEC value

5 Conclusions

The exergy analysis helps gain more point of view than the energy analysis about improvement of system. This analysis was performed in advance for PW4000 engine. If economic relations is added to this analysis, more meaningful and useful knowledge is obtained. Namely, whether the extra costs revealed from improvements could be sufficiently profitable could be determined.

• The highest value of exergy destruction cost rate as called exergoeconomic parameter belongs to CC with 2056.403 $/h according to fuel cost. Also LPC has the lowest value with 83.187 $/h.

• The relative cost ratio is important for CC unit because cost of outlet stream with 3.7507% is higher than inlet stream. Corresponding relative cost ratio is 24.386 %.

• One of the most crucial parameters among the others is exergo-economic parameter. The LPC unit is the highest magnitude with 27.206 %, while the lowest value belongs to CC unit with 1.0801 %.

• For HPC and HPT units, the variation between 1.2 M$ and 2.4 M$ in fuel cost rates versus purchased equipment cost investigated. The difference (increase) in fuel cost ratios with increasing PECs is found to be 80.12237 $/h and 75.03821$/h respectively.

• Impact of OM cost on exergo-economic factor and relative cost rate were discussed. The exergoeconomic factor of the LPC has the highest rise with 5.95 %, while the lowest variation value with 0.35 belongs to CC unit. As for relative cost rate, the variation in this parameter with the OM costs has the lowest values with 0.087 % for CC unit, while the LPC has relatively the highest value with 1.26 %.

• In the range of 3000 and 6200h, the diminish in exergoeconomic factors and relative cost rates are displayed. The highest the decrease emerges in LPC with 5.17 %, while the relatively lowest value belong to CC unit with 0.29 %.

• The magnitudes of STC parameter for exhaust and fan thrusts were determined to be 68.45 $/hkN and 5.705 $/hkN respectively.

• The variation in fuel price has a strongly effect on the exergoeconomic factor for all of components, particularly in the LPC with 16.9106%. Also effect of the fuel prices on the cost rates of the thrust could not ignore. In the range of 0.6 and 1.2 at the fuel price, the rise amount in exhaust and fan thrust costs are 82.4701 $/hkN and 5.4332 $/hkN respectively.

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