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Advanced Exergy Analysis on the Turbofan Engine

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***Abstract*—Studies on energy utilization underscore the paramount importance of energy, as evidenced by numerous researchers. This research encompasses both conventional and advanced exergy analyses. Advanced exergy analysis aims to ascertain the extent of energy loss in each component, influenced by irreversibility, and to account for component interactions within the system. Furthermore, advanced exergy analysis seeks to enhance the operational efficiency of each engine component. The findings reveal that the combustion chamber exhibits the highest level of energy loss, amounting to 32.817 MW. This energy loss primarily stems from irreversibility triggered by chemical reactions leading to heat transfer. Overall, the study results indicate that the exergy influx from external sources surpasses that generated internally in each component system.**

***Index Terms*—Advanced Exergy, Destruction, Energy, Turbofan**

I. INTRODUCTION

Over the past few decades, energy has been recognized as one of the most vital aspects, a fact supported by the many studies that have been conducted in the field of energy source utilization. One approach that has been taken in this context is exergy analysis [1]. While the first rule of thermodynamics defines energy as a major source of inspiration for turbofan engines, it does not explicitly take energy sources into utilization; hence, energy remains unaccounted for [2]. Consequently, the significance of the second law of thermodynamics sometimes referred to as exergy analysis, arises since it categorizes energy quality, determines the course of the process, and takes time into account [3]. Exergy analysis allows the evaluation of energy quality, entropy production (which reflects the degree of irreversibility), as well as the ability to perform work. Exergy gives an idea of the amount of work a system can do in the context of its environment, given the reversible nature of processes. Unlike energy, exergy does not obey the law of conservation but is destroyed when its energy quality is degraded due to irreversibility in the processes. The idea that a process has the power to destroy an entity serves as a very helpful foundation for the design, analysis, and optimization of energy systems [4]. Conventional exergy analysis is unable to precisely estimate the energy losses arising from the interaction between components. However, knowledge of the interactions between components is essential to produce accurate analyses and optimal designs. To achieve this, it is necessary to use advanced exergy analyses that can calculate energy losses caused by interactions between components in greater detail [5].

Chemical reactions, heat transmission through finite temperature changes, mixing of materials at distinct forms or conditions, uncontrolled expansion, and friction are examples of real processes that are immutable [6]. Conventional exergy analysis determines which system components experience the greatest exergy destruction and clarifies the underlying mechanisms that lead to it. By reducing the amount of energy lost within these parts, There is room to increase the system's efficiency. However, given the technological constraints, certain energy losses and destruction may be inevitable, as indicated by distinguishing between unavoidable and avoidable energy destruction. Additionally, some energy losses may stem from exogenous factors elsewhere in the energy conversion system under examination [7].

This study aims to analyze the exergy of aircraft turbofan engines, both conventionally and through advanced approaches. The traditional method of calculating exergy requires several characteristics that are subsequently tabulated, including fuel exergy value, product exergy, destruction exergy, exergy efficiency, exergy improvement potential, and the ratio of exergy loss to total exergy destroyed. Advanced energy computations, on the other hand, take into account the value of energy loss, whether it be avoidable, unavoidable, endogenous, or exogenous; they also include avoidable, endogenous, and unavoidable exogenous energy loss, as well as unavoidable exogenous energy loss and unavoidable exogenous energy destruction. The table also includes the outcomes of advanced exergy computations.

A. Conventional Exergy

Exergy analysis based on the second law of thermodynamics indicates that the spent exergy, which correlates with the growth in entropy, can be used to quantify the irreversibility of a process. The assessment of exergy loss involves calculating the increase in entropy [8]. Moreover, the concept of exergy aids in determining the optimal theoretical performance of cycles, machines, and units in the field of thermodynamics. Exergy is known as the energy that can be used to do a job, with the maximum job being affected by the surrounding environment to reach equilibrium [9]. The standard environmental temperature used is = 298 K, = 1 atm, where to perform exergy analysis on thermal systems and mass flow exergy must be considered. Four categories can be used to separate the exergy of mass flow: potential exergy, chemical exergy, kinetic exergy, and physical exergy [10].

The "Fuel - Product" idea is frequently used in traditional analytical computations to estimate the exergy of specific components. According to this theory, the energy used in the kth component to produce the product exergy is represented by the fuel exergy. On the other hand, indicates the intended result obtained from the kth component [11].

B. Advanced Exergy

While damage and irreversibility can be determined through the exergy analysis, the cause and source cannot be determined using conventional analysis. Exergy damage should be considered in advanced assessments

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based on the outcomes of standard exergy analysis to achieve a more complicated impact. With this approach, entropy production and exergy degradation at specific segments can be classified. The impairment experienced by a device is not only affected by its performance but also by its interaction with other related components or segments [12]. However, destruction based on the segment itself can be avoided compared to other interacting segments. Furthermore, the impairment of one segment can impact the impairment of every other segment within the system [13]. Through advanced exergy analysis, the identification of inefficiencies and the development of more efficient systems are facilitated by distinguishing between endogenous and exogenous components of exergy destruction. This helps in pinpointing the sources of inefficiency [12].

Advanced exergy analysis introduces a fresh perspective on assessing cycle thermodynamics, recognizing that the exergy degradation of a component is influenced not only by its irreversibility but also by that of other components within the cycle. This method allows for a comprehensive understanding of how inefficiencies in one component affect those in others, as well as the mechanism of exergy destruction. Consequently, it offers insights into the root causes of inefficiencies, facilitates effective enhancements, and directs attention toward the pertinent components [14]. Employing this method, the exergy degradation of the kth component is divided into two distinct categories: endogenous, arising from within the component, and exogenous, originating from external influences. Moreover, exergy can be categorized into avoidable exergy destruction and unavoidable exergy destruction, considering not only its origin but also the potential for remediation [6].

This research aims to investigate the exergy of an open-cycle gas turbine system within an aircraft's turbofan propulsion system. The irreversibility of a gas turbine system is considered to be the determining factor for all its performance aspects [12]. Conventional exergy analyses on the CFM56-7B turbofan engine have been carried out as well as the comparison between manual calculations and simulation results using Cycle Tempo software [2]. For this reason, the exergy study of the turbofan system will be complemented by an advanced exergy analysis.

II. Experimental And Procedures

The objective of this investigation is to ascertain the exergy value associated with each segment of the CFM56-7B turbofan engine utilizing the advanced exergy analysis technique. The energetic data used is data from turbofan engine performance tests in 2020. The exergy computation will entail assessing the exergy values of the high-pressure compressor (HPC), combustion chamber (CC), and high-pressure turbine (HPT), as well as evaluating the exergy destruction and efficiency values of each component. The parameters utilized are detailed in Table 1, with the fuel composition specified as kerosene (JETA-1) or in the chemical compound element C12H23. The results are presented in the form of tables and graphs to facilitate the reading of the results and can make it easier to identify engine parts that require performance improvement by further evaluation. A schematic of the CFM56-7B turbofan engine is shown in Fig. 1.

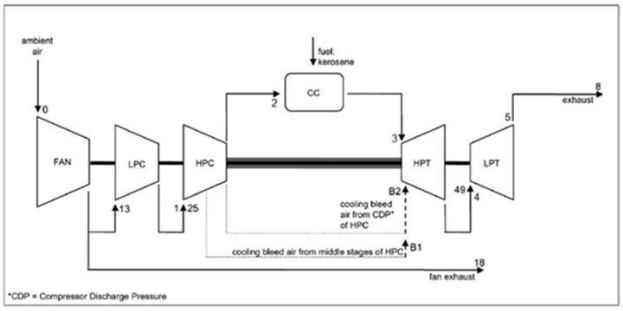


Fig. 1. Schematic of CFM56-7B turbofan engine

Table 1. Performance data of CFM56-7B turbofan engine

Data Sampling	Values	Unit
Temperature Ambient (T_0)	298	K
Atmospheric Pressure (P_0)	101,325	kPa
Temperature at Compressor Inlet (T_1)	385,9	K
Pressure at the Compressor Inlet (P_1)	216,540	kPa
Temperature at Compressor Outlet (T_2)	832,4	K
Pressure at the Compressor Outlet (P_2)	2683,49	kPa
Temperature at Turbine Inlet (T_3)	1553	K
Pressure at the Turbine Inlet (P_3)	2545,35	kPa
Temperature at Turbine Outlet (T_4)	1121,9	K
Pressure at the Turbine Outlet (P_4)	529,433	kPa
Low Heating Value (LHV)	43219,4	kJ/Kg
Air Flow Rate	39,57	Kg/s
Fuel Flow Rate	1,29	Kg/s

Calculation of turbofan exergy performance begins with an analysis of the compressor. If the compression process takes place isentropically where pressure and heat do not change, then the equation used to determine the value of compressor work can be calculated using Equation 1.

$$W_{comp} = \dot{m}_g \times (h_2 - h_1) \quad (1)$$

Where W_{comp} = compressor work (MW), $\dot{m}_g$ = air flow rate (Kg/s), h_2 = enthalpy of compressor outlet (kJ/Kg), h_1 = enthalpy of inlet compressor (kJ/Kg). Meanwhile, to calculate the work of the turbine, Equation 2 is used.

$$W_{GT} = \left(\dot{m}_g \times \dot{m}_F\right) \times (h_2 - h_1) \quad (2)$$

where W_{GT} = turbine work (MW), $\dot{m}_F$ = fuel flow rate (Kg/s), h_2 = enthalpy outlet turbine (kJ/Kg), h_1 = enthalpy inlet turbine (kJ/Kg).

The total system exergy for material flow is divided into four parts, i.e. kinetic exergy $\dot{E}_{ke}$, potential exergy $\dot{E}_{po}$, physical exergy $\dot{E}_{ph}$ and chemical exergy $\dot{E}_{ch}$ as shown in Equation 3. Kinetic exergy and potential exergy in this system can be ignored [11][15][16].

$$\dot{E}x = \dot{E}_{po} + \dot{E}_{ke} + \dot{E}_{ph} + \dot{E}_{ch} \quad (3)$$

Physical exergy is the exergy determined by changes in pressure and temperature in the flow [2][17] and can be calculated based on Equation 4.

$$\dot{E}_{ph} = \dot{m}_g \left[(h_k - h_0) - T_0 \left(S_k - S_0 - R \ln \frac{P_k}{P_0}\right)\right] \quad (4)$$

with $\dot{E}_{ph}$ = physical exergy (MW), h_k = enthalpy of the kth component (kJ/Kg), h_0 = enthalpy at ambient temperature (kg/s), T_0 = ambient temperature (K), S_k = entropy on the kth component (kJ/Kg.K), S_0 = entropy at ambient temperature (kJ/Kg.K), R = gas constant of 0.287 (kJ/Kg.K), Pk = pressure on the kth component (kPa), P_0 = pressure at ambient temperature (kPa).

Before determining the chemical exergy value, first calculate the specific exergy ratio value of hydrocarbon fuel and its specific exergy value. The specific exergy ratio value of hydrocarbon fuels can be determined using Equation 5.

$$\gamma_F = 1{,}0033 + 0{,}0169\frac{a}{b} - \frac{0{,}0698}{a} \quad (5)$$

Meanwhile, to find the specific exergy value, Equation 6 can be used.

$$e_{CH} = \gamma_F \times LHV \quad (6)$$

with e_{CH} = value of specific exergy (kJ/kg), γ_F = hydrocarbon fuel specific exergy ratio value, LHV = low heating value (kJ/kg).

Chemical exergy is exergy determined by changes in chemical compounds. Chemical exergy is used to calculate exergy in fuel [2] as in Equation 7.

$$\dot{E}_{ch} = \dot{m}_{fuel} \times e_{ch} \quad (7)$$

where $\dot{E}_{ch}$ = chemical exergy (MW), $\dot{m}_{fuel}$ = fuel flow rate (Kg/s), e_{ch} = specific exergy (kJ/Kg).

Destruction exergy is the exergy lost or damaged due to irreversibility in the process. Destruction exergy is calculated as the difference between fuel exergy and product exergy in kth components [18]. The value of the exergy of destruction is calculated using Equation 8 [1].

$$\dot{E}_D = \dot{E}_{F.k} - \dot{E}_{Pr.k} \quad (8)$$

where $\dot{E}_D$ is the destruction exergy (MW), $\dot{E}_{F.k}$ the fuel exergy (MW), $\dot{E}_{Pr.k}$ the product exergy (MW).

Exergy efficiency can be calculated by comparing product exergy ($\dot{E}_{Pr}$) and fuel exergy ($\dot{E}_F$). To calculate the exergy efficiency, Equation 9 can be used [12]

$$\psi = \frac{\dot{E}_P}{\dot{E}_F} \times 100\% \quad (9)$$

were ψ = exergy efficiency (%), $\dot{E}_P$ = product exergy (MW), $\dot{E}_F$ = fuel exergy (MW).

The exergy improvement potential relates to the amount by which the efficiency of a system or process can be improved. In terms of exergy, the maximum value of exergy that can be extracted from a system is when the system reaches equilibrium with its environment. The exergy improvement potential is calculated using Equation 10 [12].

$$\dot{E}xI\dot{P}_k = (1 - \psi_k)\dot{E}_{D.k} \quad (10)$$

where $\dot{E}xI\dot{P}_k$ = exergetic improvement potential (MW), ψ_k = kth exergy efficiency (%), $\dot{E}_{D.k}$ = kth exergy destruction (MW).

The ratio of total exergy loss and exergy destruction is a term used in thermodynamics to measure the efficiency and irreversibility of a process or can be called the ratio of exergy loss to total exergy input. The ratio of total exergy loss and exergy destruction is calculated using Equation 11 [1]

$$Y_k = \frac{\dot{E}_{D.k}}{\dot{E}_{F.k}} \quad (11)$$

where Y_k = ratio of exergy loss, $\dot{E}_{D.k}$ = kth exergy destruction (MW), $\dot{E}_{F.k}$ = kth fuel exergy (MW).

While the fuel exergy with the total exergy destruction is calculated using Equation 12.

$$Y^*{}_k = \frac{\dot{E}_{D.k}}{\dot{E}_{D.tot}} \quad (12)$$

where $Y^*{}_k$ = exergy of fuel with the total exergy destruction, $\dot{E}_{D.k}$ = kth exergy destruction (MW), $\dot{E}_{D.tot}$ = total exergy destruction (MW).

Endogenous exergy destruction is calculated when the kth component operates under real conditions, while all other system components operate under their ideal conditions [19]. According to the definition of endogenous and exogenous exergy destruction, the exergy destruction of the kth component can be formulated using Equations 13 and 14.

$$\dot{E}^{EN}_{D.k} = \dot{E}^{RL}_{Pr,k} \times \left(\frac{\dot{E}_D}{\dot{E}_{Pr}}\right)^{EN}_k \quad (13)$$

$$\dot{E}_{D.k} = \dot{E}^{Ex}_{D,k} + \dot{E}^{EN}_{D,n} \quad (14)$$

Unavoidable endogenous exergy destruction is established when the kth component operates under inescapable real-world conditions, while all other components in the system operate under ideal conditions [19]. Despite technological advancements, the unavoidable aspect of the segment remains unchanged [1]. Unavoidable endogenous exergy destruction is calculated when the kth component operates under inevitable real-world conditions, while all other components in the system operate under ideal conditions [20]. Although technology has changed, the unavoidable part of the segment cannot be eliminated [1]. Equation 15 is utilized to compute the unavoidable portion of exergy within the kth segment.

$$\dot{E}^{UN}_{D.k} = \dot{E}^{RL}_{Pr.k} \times \left(\frac{\dot{E}_D}{\dot{E}_{Pr}}\right)^{UN}_k \quad (15)$$

The avoidable exergy loss at the kth section is obtained by subtracting the unavoidable component from the exergy loss rate at that section. This part can be changed with the help of regeneration techniques [1]. Technological limitations restrict the unavoidable exergy destruction. It is calculated by taking the most favorable operating conditions by considering each component separately. These conditions show the absolute minimum exergy destruction when the product does not change at all. This condition is caused by very low-temperature differences and very small thermal and mechanical exergy losses in the components being analyzed. However, the assumptions to simulate unavoidable conditions depend on the scope of the data to be analyzed. Therefore, the assumptions are free to some extent [4].

Table 3. Assumed conditions for calculating advanced exergy analysis under real, unavoidable, and ideal conditions

Data Sampling	Real	Unavoidable	Ideal	Unit
Temperature Ambient (T_0)	298	298	298	K
Atmospheric Pressure (P_0)	101.325	101.325	101.325	kPa
Compressor Inlet Temperature (T_1)	385.9	385.9	473.15	K
Compressor Inlet Pressure (P_1)	216.540	216.5	300	kPa
Compressor Outlet Temperature (T_2)	832.4	832.4	873.15	K
Compressor Outlet Pressure (P_2)	2683.49	2680	2683	kPa
Turbine Inlet Temperature (T_3)	1553	1553	1918.92	K
Turbine Inlet Pressure (P_3)	2545.347	2545	2545.347	kPa
Turbine Outlet Temperature (T_4)	1121.9	1121.9	1578.15	K
Turbine Outlet Pressure (P_4)	529.433	529	529.433	kPa
Low Heating Value (LHV)	43219.4	42800	43600	kJ/Kg
Air Flow Rate	39.57	39.57	39.57	Kg/s
Fuel Flow Rate	1.29	1.29	1.29	Kg/s

The equation for calculating the avoidable exergy destruction in the kth section is Equation 16.

$$\dot{E}_{D.k}^{AV} = \dot{E}_{D.k}^{RL} - \dot{E}_{D.k}^{UN} \quad (16)$$

The input data for the advanced exergy calculations were partially obtained from the turbofan engine performance test results and are tabulated in Table 3.

Equations 17, 18, 19, and 20 are the equations to determine the exergy destruction rate ($\dot{E}_D$) for advanced exergy analysis

$$\dot{E}_{D.k}^{UNEN} = \dot{E}_{D.k}^{RL} \times \left(\frac{\dot{E}_D^{UN}}{\dot{E}_D^{RL}} \times \frac{\dot{E}_D^{EN}}{\dot{E}_D^{RL}}\right) = \frac{\dot{E}_D^{UN} \times \dot{E}_D^{EN}}{\dot{E}_D^{RL}} \quad (17)$$

$$\dot{E}_{D.k}^{UNEX} = \dot{E}_{D.k}^{RL} \times \left(\frac{\dot{E}_D^{UN}}{\dot{E}_D^{RL}} \times \frac{\dot{E}_D^{EX}}{\dot{E}_D^{RL}}\right) = \frac{\dot{E}_D^{UN} \times \dot{E}_D^{EX}}{\dot{E}_D^{RL}} \quad (18)$$

$$\dot{E}_{D.k}^{AVEN} = \dot{E}_{D.k}^{RL} \times \left(\frac{\dot{E}_D^{AV}}{\dot{E}_D^{RL}} \times \frac{\dot{E}_D^{EN}}{\dot{E}_D^{RL}}\right) = \frac{\dot{E}_D^{AV} \times \dot{E}_D^{EN}}{\dot{E}_D^{RL}} \quad (19)$$

$$\dot{E}_{D.k}^{AVEX} = \dot{E}_{D.k}^{RL} \times \left(\frac{\dot{E}_D^{AV}}{\dot{E}_D^{RL}} \times \frac{\dot{E}_D^{EX}}{\dot{E}_D^{RL}}\right) = \frac{\dot{E}_D^{AV} \times \dot{E}_D^{EX}}{\dot{E}_D^{RL}} \quad (20)$$

where $\dot{E}_{D.k}^{AVEN}$ can be reduced by upgrading the corresponding segment, while $\dot{E}_{D.k}^{AVEX}$ can be reduced through upgrading other system segments [12].

III. Result And Discussion

A. Results

Using the input data and performance parameters of the turbofan engine depicted in Table 1, along with calculations using Equations 1 to 12, the results of conventional exergy calculations are presented in Table 4. The values shown in Table 4 are the exergy resources released from the kth component to produce exergy products[16] with the respective values for the high-pressure compressor being 21.710 MW, the combustion chamber being 78.344 MW, and the high-pressure turbine being 45.527 MW. While the value of the desired exergy yield obtained from the kth component considered [16] with its value for the high-pressure compressor is 20.925 MW, the combustion chamber is 45.527 MW and the high-pressure turbine is 45.311 MW. The value of potential exergy improvement for the high-pressure compressor is 0.028 MW, the combustion chamber is 13.747 MW and the high-pressure turbine is 0.001 MW.

Based on the findings, the exergy destruction values at the HPC, CC, and HPT are 0.785 MW, 32.817 MW, and 0.216 MW, respectively, totaling 33.818 MW in destructive energy. Meanwhile, the exergy efficiencies at each stage are measured at 96.386%, 58.112%, and 99.525%, respectively.

Table 4. Calculation results of exergy performance in turbofan engine open system

Component	$\dot{E}_F$ (MW)	$\dot{E}_p$ (MW)	$\dot{E}_{XD}$ (MW)	ψ (%)	ExIP (MW)	Y_K	Y^*_K
HPC	21.710	20.925	0.785	96.386	0.028	3.614	2.320
CC	78.344	45.527	32.817	58.112	13.747	41.888	97.040
HPT	45.527	45.311	0.216	99.525	0.001	0.475	0.640
Total Destrusction Rate			33.818				

Table 5. Results of advanced exergy analysis

Komponen	$\dot{E}_D$	$\dot{E}_D^{UN}$	$\dot{E}_D^{AV}$	$\dot{E}_D^{EN}$	$\dot{E}_D^{EX}$	$\dot{E}_D^{AV.EX}$	$\dot{E}_D^{AV.EN}$	$\dot{E}_D^{UN.EX}$	$\dot{E}_D^{UN.EN}$
HPC	0.785	1.219	-0.434	0.263	0.522	-0.289	-0.146	0.810	0.409
CC	32.817	32.259	0.558	14.753	18.064	0.307	0.251	17.757	14.502
HPT	0.216	0.216	0	0.002	0.215	0	0	0.215	0.002

Advanced exergy analysis was conducted using Equation 13 to Equation 20 and the results are tabulated in Table 5. Table 5 shows the results of advanced exergy calculations by presenting the exergy destruction, unavoidable exergy destruction, avoidable exergy destruction, endogenous exergy destruction, exogenous exergy destruction, avoidable exogenous exergy destruction, avoidable endogenous exergy destruction, unavoidable exogenous exergy destruction dan unavoidable endogenous exergy destruction.

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B. Discussion

Table 1 shows the results of conventional exergy calculations. The highest destruction exergy is found in the combustion chamber (CC) with a value of 32.817 MW. The amount of exergy destruction in the combustion chamber (CC) is due to several reasons such as high temperatures in the combustion chamber so that there is a temperature difference between the combustion chamber and the environment which is high and then heat transfer occurs which causes large exergy losses. The combustion process in the combustion chamber tends to be incomplete. This imperfection causes irreversibility, resulting in a decrease in the temperature of the combustion products used to drive the turbine. In addition, high destruction exergy may also occur due to limited combustion capability. Although the combustion chamber design is designed to optimize combustion, some fuels may not burn completely due to various factors, such as uneven fuel distribution, limited air-fuel contact time, and non-ideal combustion conditions. Meanwhile, the destructive exergy for the high-pressure compressor (HPC) and high-pressure turbine (HPT) is low at 0.785 MW and 0.216 MW, respectively.

If the exergy destruction in the combustion chamber is high, it is inversely proportional to its energy efficiency. Where the combustion chamber exergy efficiency is lower than the high-pressure compressor and high-pressure turbine. The combustion chamber exergy efficiency is 58.112%, the high-pressure compressor is 96.386% and the high-pressure turbine is 99.525%. With these results, the combustion chamber shows a less efficient value so improvement and development can be focused on this component.

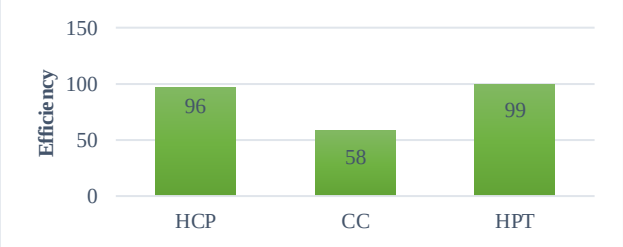


Fig. 2. Graph of turbofan engine exergy efficiency value

In the advanced exergy analysis, the exergy damage of each component calculated in the previous section can be discussed in detail to find the sources of damage and the real potential of each component to change the overall efficiency of the system. Advanced exergy analysis includes irreversible that can be divided into endogenous, exogenous, avoidable, and unavoidable to assist in observing the effects of technological limitations and component interactions on the exergy efficiency of a system for improvement. In the advanced exergy analysis, the endogenous part of the exergy destruction for the kth component is calculated by defining the real and ideal conditions on the turbofan engine data. Then, the exogenous destruction rate is obtained from the difference of the total exergy and the endogenous part (Equation 14). To calculate the unavoidable exergy rate of the destruction at the kth part by assuming the unavoidable condition. In this study, the assumption used is to use mixing at the same temperature and pressure assumed. The chemical formula of turbofan fuel is C12H23 with an assumed constant LHV of 42800 kJ/Kg. As for temperature, ambient pressure, air flow rate, and fuel flow rate, they are assumed to be constant (not assumed) to maintain operating stability as the engine is designed to operate within a certain range of air and fuel flow rates. And for the avoidable exergy destruction obtained by Equation 15. Exogenous/avoidable, endogenous/avoidable values. Exogenous/unavoidable, and endogenous/unavoidable are determined using Equations 17-20. The results of the advanced exergy analysis for each component are shown in Table 5.

In Table 5, the exogenous exergy level surpasses the endogenous exergy across the system components. Hence, it becomes imperative to enhance the performance of all components (HPC-CC-HPT) to mitigate exogenous exergy destruction. Upon examining the results of endogenous exergy, the combustion chamber component exhibits the highest value, primarily due to its inherent irreversibility. However, the level of exergy destruction that can be avoided in practice can be managed and reduced. Notably, among the three existing components listed in Table 5, the combustion chamber demonstrates the highest value of avoidable exergy at 0.558 MW. Thus, improving this component's efficiency can be accomplished by making technical adjustments, using new technologies, or swapping it out for a more effective substitute. The exogenous/avoidable exergy can be decreased by increasing the efficiency of other components, and the avoidable/endogenous fraction can be minimized by improving the efficiency of the kth component. The exogenous/unavoidable exergy removal rate is higher than the exogenous/avoidable rate in Table 5. Fig. 3 provides more information about how the exergy removal rates are divided in the high-pressure compressor, combustion chamber, and high-pressure turbine. The high-pressure turbine's inescapable exergy, as shown in Fig. 3, is 100%, meaning that no enhancements are possible. This is consistent with the study definition, which indicates that the part that cannot be enhanced because of technological limitations is referred to as inevitable energy destruction. Nonetheless, the achieved energy efficiency is almost 100%, precisely 99.525%. This implies that since the high-pressure turbine is now operating effectively, there is no need for improvement in this situation. However, as was previously said, 26% of the exergy can be regained for the high-pressure compressor, suggesting room for improvement.

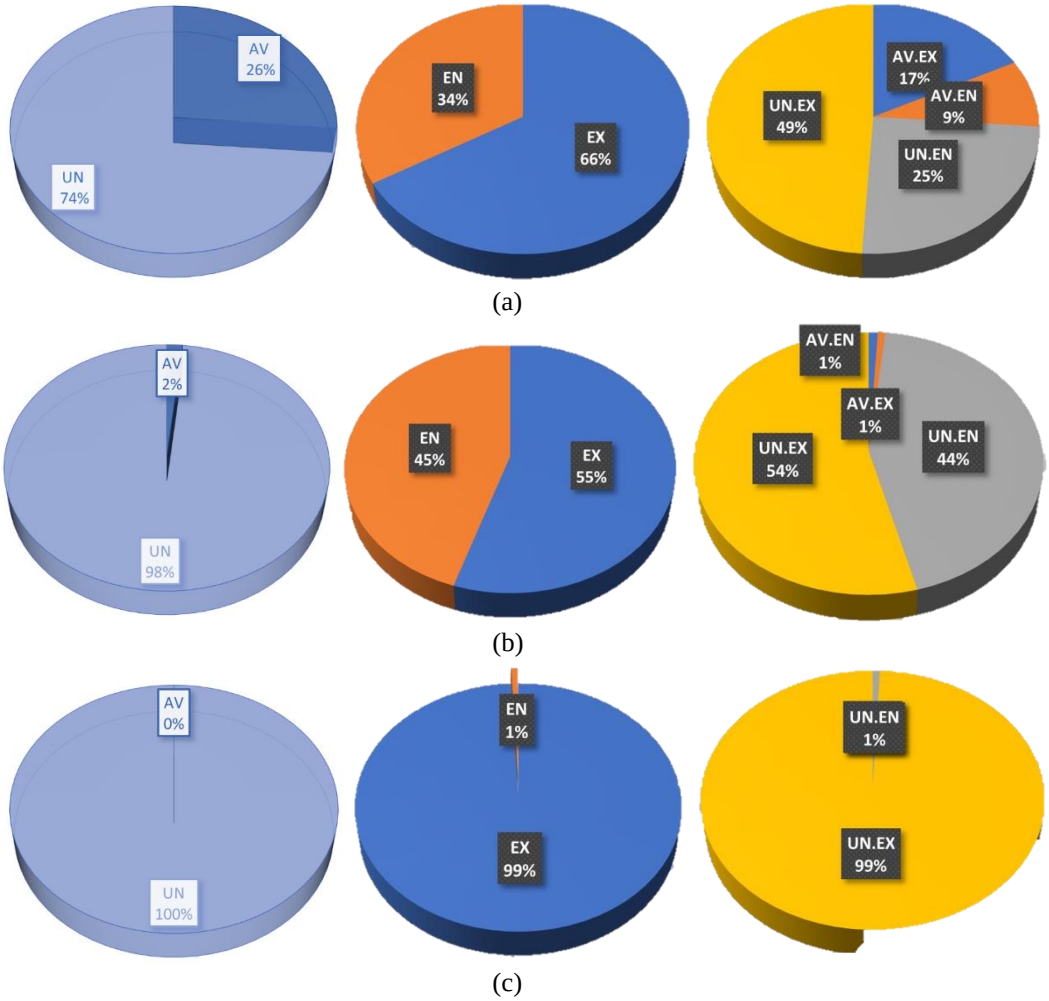


Fig. 3. Distribution of component exergy destruction levels: (a) high-pressure compressor, (b) combustion chamber, (c) high-pressure turbine

IV. Conclusion

Advanced exergy can identify exergy losses in more detail than conventional exergy analysis. Advanced exergy analysis is useful in identifying the main sources of exergy losses in turbofan engines. In this case, the highest exergy losses occur in the combustion chamber. Exogenous exergy destruction is higher than endogenous, this is due to the difference in actual conditions and the environment, the occurrence of excess heat dissipation, and the temperature difference between the system and the environment. In this study, the highest exergy occurred in exogenous/ unavoidable. 49%, 54%, and 99% of the annihilation in the high-pressure compressor, combustion chamber, and high-pressure turbine, respectively.

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