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SUSTAINABLE ASSESSMENT OF TURBOFAN ENGINE INTEGRATED WITH ORGANIC RANKINE CYCLE THROUGH EXERGETIC APPROACH

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ABSTRACT

The growth in civil aviation industry causes an unavoidable increase in greenhouse gas emission and the need to achieve a system with good performance and also sustainable. One of the proposed solutions is to use energy and exergy analysis to calculate the performance and sustainability index of an engine. In this paper, an Organic Rankine Cycle (ORC) is connected to a two-spools turbofan engine with mixed exhaust flow in order to extract the waste heat from the engine's exhaust. The objective is to perform sustainable analysis based on exergy and to assess the impact of recovering waste heat using ORC to overall index of sustainability. The parameters used for ORC system are provided by Engineering Equation Solver (EES) and this data is then used to determine the exergetic sustainability index of the turbofan engine integrated with ORC system. The turbofan engine data is taken from the simulation results by using GasTurb13 software. In order to assess the sustainability of the whole system, the overall exergy efficiency, waste exergy ratio, exergy destruction factor, environmental effect factor and the exergetic sustainability index are determined. The results obtained for these parameters are 63%, 86%, 17%, 1.37 and 0.73 respectively. Finally the result is compared to the actual turbofan engine without ORC system in order to evaluate the impact of integrating the ORC to the engine and the conclusion found is that a turbofan engine with ORC system results in a higher sustainability index compared to the one without the ORC.

Keywords: exergy; GasTurb 13; organic Rankine cycle; sustainability, waste heat

1.0 INTRODUCTION

Energy resources and their utilization were intimately related to sustainable energy development. For the societies to attain sustainable development, much effort must be devoted not only in discovering sustainable energy resources, but also in increasing the energy efficiencies of processes utilizing these resources. For aircraft, the exhaust emissions effect air quality water quality, climate, energy, and noise [1]. Therefore, energy consumption plays a very important role to achieve sustainable development, balancing economic and social development with environmental protection.

Various efforts had already been taken for the development of analysis plans for energy conversion systems considering more efficient utilization of fossil fuels. In this regard, exergy analysis appears to be a significant tool for determining locations, types and true magnitudes of waste energy and losses to design more efficient energy systems. The exergy sustainability for the turbofan engine are exergy efficiency, waste exergy ratio, exergy destruction ratio, and environmental effect factor and exergetic sustainability index [2 - 4].

Actual jet cycles are not ideal due to thermodynamic losses. The gases in the jet cycle are expanded in the gas turbine to the pressure that allows generation of the power needed by the compressor, generator, hydraulic pump, and other work-consuming devices. Efforts to increase power and reduce noise and fuel consumption have led to improvements in turbojet and turbofan engines [2]. Hence, by incorporating ORC technology with proven reactor requirement, it will offers high reliability while minimizing the need for the component development [5].

A study done by Etele and Rosen for a turbojet engine with afterburner for various altitudes and air speeds shows that at sea level, the highest exergy efficiency is observed within the compressor at 96.7 %, followed by the nozzle at 93.7% and turbine at approximately 92.3%. This trend is similar for the exergy efficiency calculated at 11,000 m of altitude [6]. However, this study did not look at the sustainability aspect of the system.

A more recent study done by Aydin et al. in 2015 for a turbofan engine developed in conjunction with exergetic analysis and sustainable development, shows that the values of exergy efficiency, waste exergy ratio, exergy destruction factor, recoverable exergy rate, environmental effect factor and exergetic sustainability index are found to be 0.315, 0.685, 0.408, 0, 2.174, and 0.460, respectively [7]. Even though the sustainability index of this type of engine looks promising, it is quite wasted that there are no energy being recovered from the exhaust system.

To summarize, the rapid growth of civil aviation industry causes an unavoidably increase in aviation greenhouse gas emissions. Therefore, the aviation industry has started to construct remarkably complex aircrafts, demanding more data acquisition to estimate the overall performance of the system. Different methods have been proposed since the very beginning of this industry to study the flight performance. However, it is agreed that a common basis must be applied. Therefore, the objective of this study is to perform sustainable analysis based on exergy to access the environmental effects caused by the engine, and to assess the impact of recovering waste heat from turbofan engine using ORC, to overall index of sustainability.

2.0 METHODOLOGY

Since its manufacturing began in 1970s, CF6-80 turbofan engines have been used in many different aircraft, including the Airbus such as A320, A370 and latest A350, and Boeing such as B747 and B767. The CF6-80 turbofan engine provides relatively high by-pass ratios, by order of 4.5 and was designed especially for wide body aircraft [8].

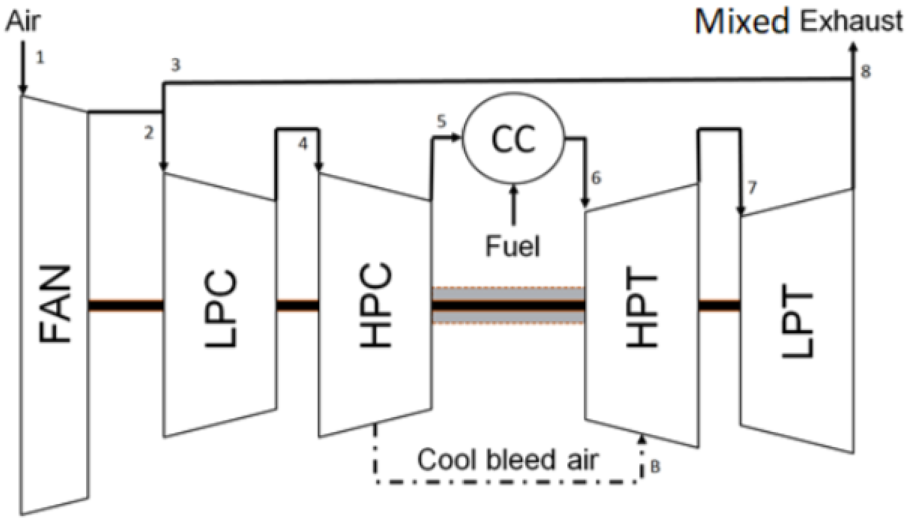

Figure 1 Schematic diagram of a two-spool mixed exhaust turbofan engine

Figure 1 shows the main component of a two-spool turbofan engine which consist of a fan, low pressure compressor (LPC), high pressure compressor (HPC), combustion chamber (CC), high pressure turbine (HPT), low pressure turbine (LPT) and mixed exhaust nozzle. Basically in the turbofan engine with mixed exhaust, the cold air after being compressed in the fan will then be compressed again with the low air coming out of the turbine. HPC release bleed air about 1% to HPT to help the HPT cool. The intake air mass for the engine is assumed to be around 679.2 kg/s, while 16.7 % of air enter the core engine via combustion process in combustion chamber. Meanwhile 82.4% of secondary air flows through the fan via bypass. The air coming out of the fan combined with the air exiting the LPT, form a mixed exhaust fluid at the exit.

In this section, the exergy analysis for each of the aircraft components and the exergetic sustainability of the whole engine with ORC are performed. Within each component, the exergy that will be considered are physical and chemical exergies except at the exhaust since high velocity occur in this part. Firstly, the exergy destruction is the rate of irreversibility of the gas turbine. In steady state cycle the exergy destruction rate is the difference of exergy input and exergy output. Denote $\dot{Ex}_{des}$as shown in Eq. (1)

$$\dot{E}x_{des,i} = \dot{E}x_{input} - \dot{E}x_{output} \tag{1}$$

where $\dot{E}x_{input}$ and $\dot{E}x_{output}$ is the exergy input and output of each component.

Subsequently, the improvement potential rate in terms of exergy is defined. This term will assist us to identify the components that required modification or improvement, as written in Eq. (2)

$$IP_i = (1 - \varepsilon_i)\left(\dot{E}x_{des,i}\right) \tag{2}$$

where ε_i is exergy efficiency of each turbofan engine's component.

Thrust power defines as

$$\dot{T} = T * V_{aircraft} \tag{3}$$

where T is the thrust of the engine and $V_{aircraft}$ is the velocity of the aircraft.

Hence, the overall exergy efficiency is

$$\varepsilon = \frac{\dot{T}}{\dot{F_{tot}}} \tag{4}$$

Waste exergy ratio = (Total waste exergy output) / (Total exergy input) (5)

Recoverable exergy = (Recoverable exergy) / (Total exergy input) (6)

In the meantime, the environmental effect factor can be defined as;

$$r_{eef} = \frac{Waste\ exergy\ ratio}{\varepsilon} \tag{7}$$

Finally, the exergetic sustainability index,

$$\Theta_{esi} = \frac{1}{r_{eef}} \tag{8}$$

In order to execute the calculation of the index of sustainability, first the thrust power must be calculated using Eq. (3) then followed by the overall exergy efficiency in Eq. (4). Once all these values are obtained, the other exergetic sustainability indicators, Eq. (5) – (8) can be computed.

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3.0 RESULTS AND DISCUSSION

In this study, the exergy destruction, exergy efficiency and improvement potential rate for each component of turbofan engine are defined and evaluated using sea level data. The parameters used for ORC system are provided by Engineering Equation Solver (EES).

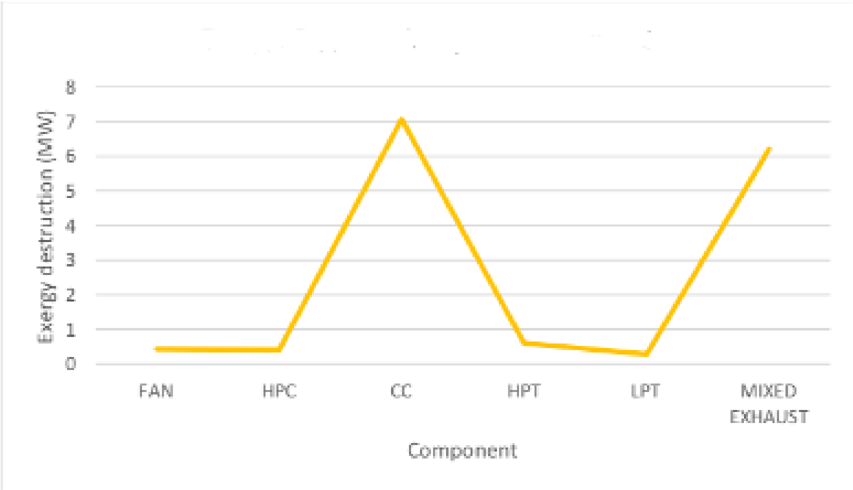

Figure 2 Exergy destruction for each component

Figure 2 depicts the results of exergy destruction. The component with the highest exergy destruction is found to be the combustion chamber with the value of 7.06 MW followed by the mixed exhaust at 6.21 MW, while the value for other components are quite low. These high values for combustion chamber and exhaust are due to the high degree of temperature of combustion occurs in the combustion chamber and high velocity of fluid exiting the exhaust nozzle. The destruction analysis pattern were similar with previous references or studies except the mixed exhaust has slightly lower exergy destruction compared to combustion chamber [9].

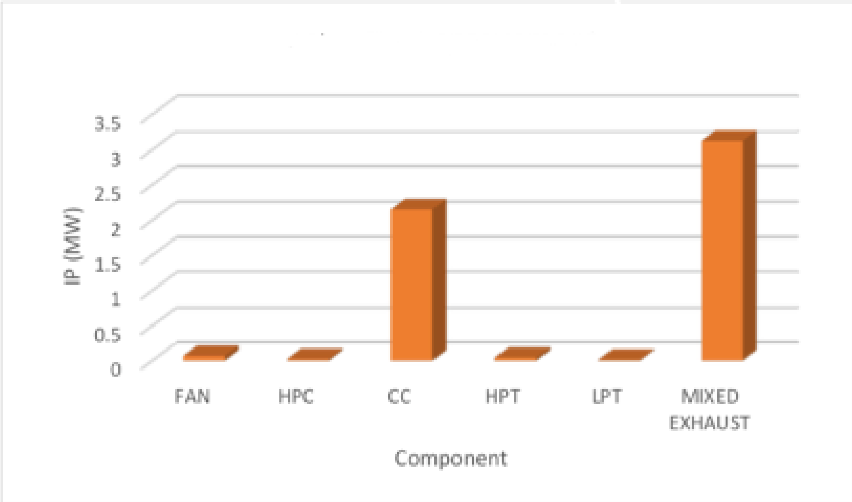

Figure 3 Potential improvement (IP) for each component

Figure 3 shows the potential improvement rate of the turbofan engine component. The highest potential improvement rate is the mixed exhaust followed by the combustion chamber. This trend is understandable by looking at the results of exergy destruction earlier. The combustion chamber has potential to be improved in the advanced technology, for example in terms of its efficiency, and by using constant volume combustion and reducing the emission. For mixed exhaust, this is where the improvement is being made, which is by connecting the ORC system to this component.

Table 1 Exergetic sustainability performance of turbofan engine

Parameters	**Value**
Exergy efficiency	0.63
Waste exergy ratio	0.87
Recoverable exergy	0.0035
Exergy destruction factor	0.17
Environmental effect factor	1.37
Sustainability index	0.73

In Table 1, the results obtained for waste exergy ratio verifies that the huge amount of exergy rate provided to the system are wasted. Meanwhile, the sustainability index for mixed exhaust engine are rather high which is 0.73. To support that, the higher the sustainability index, the better it is to be used in aerospace industry applications. On the other hand, the amount of recoverable exergy is slightly above zero with only little of emission released to be recovered in the engine. Nevertheless, this is still a slight improvement compared to an engine without ORC as the second one has a zero recoverable exergy as conventionally, all exergy are rejected to the environment [8]. Therefore, it is necessary to use the natural sources more productively or use the sustainable or renewable energy sources in order to increase sustainability of environment and engine design itself while at the same time minimizing environmental damage.

The comparison of exergetic sustainability performances of the two-spool turbofan engine with and without the ORC system is shown in the Figure 4 below. For the conventional turbofan engine without ORC, the exergy efficiency, waste exergy ratio, recoverable exergy, environmental effect factor and sustainability index are as follow; 0.27, 0.73, 0.39, 2.72, and 0.37. By comparing these values, to the one previously shown in Table 1, one can says that the overall performance are much better for the turbofan engine system with ORC. This exclude the result for waste exergy ratio which turns a bit higher for the system with ORC. This is might due to the engine having lower thrust which is around 10 MW only.

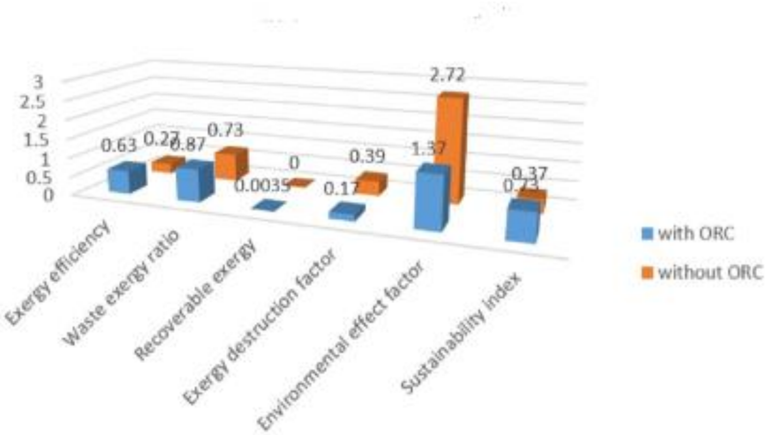

Figure 4 Graphical representation of sustainability performance

4.0 CONCLUSION

In conclusion, the result of exergetic performance for two-spool turbofan engine with ORC system showed that the mixed exhaust component has one of the highest exergy destruction and highest potential improvement. Therefore it is suggested in this study to integrate ORC to the exhaust nozzle as waste heat recovery system.

Subsequently, the results of the impact to the environment and the sustainability index prove to be successful. It shows that by integrating ORC system to the turbofan engine as waste heat recovery, the environmental damage can be minimized and therefore the whole engine system become more sustainable. Sustainability index based on exergy analysis has shown to be a crucial approach to evaluate the sustainability of a turbofan engine. The exergy method can help to identify the irreversibility of the process.

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REFERENCES

[1] Popp, D., Richard, G.N. and Jaffe, A.B. (2010). Energy, the environment, and technological change. *Handbook of the Economics of Innovation*, 2, 873-937.

[2] Balli, O., Aras, H., Aras, N. and Hepbasli, A. (2008). Exergetic and Exergo-economic Analysis of an Aircraft Jet Engine (AJE). *International Journal of Exergy*, 5(5/6), 567-581.

[3] Karakoc, T.H., Colpan, C.O., Altuntas, O. and Sohret, Y. (2019). Sustainable Aviation. *Springer International Publishing: Berlin, Germany*, ISBN 9783030141943.

[4] Calisir, D., Ekici, S., Midilli, A. and Karakoc, T.H. (2020). A review on environmental impacts from aviation sector in terms of life cycle assessment. *International Journal of Global Warming*, 22(2), 211-234.

[5] Salmah, M.S.I. and Saadon, S. (2019). Organic rankine cycle as waste heat recovery: a review of their potential applications. *PERINTIS eJournal*, 9(2), 21-36.

[6] Ehyaei, M.A., Anjiridezfuli, A. and Rosen, M.A. (2013). Exergetic analysis of an aircraft turbojet engine with an afterburner. *Thermal Sciences*, 17(4), 1181-1194.

[7] Aydin, H., Turan, O., and Karakoc, T.H. (2015). Exergetic Sustainability Indicators as a Tool in Commercial Aircraft: A Case Study for a Turbofan Engine. *International Journal of Green Energy*, 12(1), 28-40.

[8] Turgut, E.T., Karakoc T.H., Hepbasli A. and Rosen M.A. (2009). Exergy analysis of a turbofan aircraft engine. *International Journal of Exergy*, 6, 181-99.

[9] Saadon, S. and Mohd Redzuan, M.S. (2017). Sustainability assessment of turbofan engine with mixed exhaust through exergetic approach. *IOP Conference Series: Materials Science and Engineering*, 270, 012012.