An analytical study on the performance of the organic Rankine cycle for turbofan engine exhaust heat recovery

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Abstract. Due to energy shortage and global warming, issues of energy saving have become more important. To increase the energy efficiency and reduce the fuel consumption, waste heat recovery is a significant method for energy saving. The organic Rankine cycle (ORC) has great potential to recover the waste heat from the core jet exhaust of a turbofan engine and use it to produce power. Preliminary study of the design concept and thermodynamic performance of this ORC system would assist researchers to predict the benefits of using the ORC system to extract the exhaust heat engine. In addition, a mathematical model of the heat transfer of this ORC system is studied and developed. The results show that with the increment of exhaust heat temperature, the mass flow rate of the working fluid, net power output and the system thermal efficiency will also increase. Consequently, total consumption of jet fuel could be significantly saved as well.

1. Introduction
Due to the world’s growing population, the requirement for energy is increasing very fast, resulting in a higher primary fossil fuels consumption and enormous emission of waste. According to the research done by Saleh et al. [1], the consumption of the worldwide energy had gone up over 40% these past decades. This results in a significant environmental and also economical complications. The misused energy of the fuel from exhaust engine is over 30-40% and only a small fraction of the energy, which is roughly 12-25%, are converted to useful work [2]. Therefore, in recent years, studies linked to waste heat recovery have pinched a greater awareness. Specifically, there is motivating force in the aviation industry to achieve a better propulsion system performance, principally due to the fuel cost issues and stricter future laws. Besides causing a drop in fossil fuels market, waste heat recovery will also cause a drop in greenhouse gases and thus making it easier to supply the future with a better environment.

There is a lot of debates proving that this waste heat recovery energy as a practical resource of a growing attention due to its large quantity [3]. Heat Recovery Steam Generators (HRSGs) is one type of steam-based recuperative system that have been used on various applications but are not generally fit to be applied in smaller gas turbines engine due to problems of weight as well as supply of water [4]. However, organic Rankine cycle (ORC) has become one of the favourable waste heat recovery energy technologies due to its small size and its undoubtedly great benefit for integration in the power
production systems in the next few years. A Rankine cycle is a heat engine thermodynamic cycle that can convert the heat into mechanical work. The heat is supplied externally to a closed loop. An organic Rankine cycle is named for its use of organic fluid with liquid-vapor phase change occurring at a lower temperature than the phase change in water-steam, thus allowing Rankine cycle heat recovery from lower temperature. The low temperature heat is converted into useful work that can itself be converted into electricity. The researchers also provide the reasons behind the use of an ORC with an aircraft gas turbine engine sized and indicates an improvement of performance in the neighbourhood of 16% [4]. In a Rankine cycle, the system makes use of the heat to lift up the temperature and pressure of organic fluid. ORC technology has already been widely exploited in various low-grade waste thermal energy applications such as biomass energy, solar energy, geothermal energy and also waste heat energy [5]. In power plant applications and marine diesel engine, there have been several researches concerning the thermodynamic analysis and optimization method of an ORC using waste heat source [6, 7, 8] and the study has also been proven experimentally recently [9]. Nonetheless, several factors must be taken into consideration when assessing the idea on an aircraft engine. Firstly, the objective of the system for a power plant is to draw out as much as possible energy from the exhaust engine to produce electricity. However, in a jet engine, the main point is not to supply power but to produce thrust and to reduce as much as possible the fuel consumption.

As part of the normal operation of a jet engine, some chambers inside it contain air at very high pressure. Most of this air goes through the combustion chamber and exits at the nozzle to provide thrust. A small amount is bled off by an inlet or duct, and channelled by pipes and used to pressurize the cabin by supplying air to the environmental control system. Additionally, bleed air is also been used to keep critical parts of the aircraft ice-free. Bleed air is essentially loss of engine thrust as some air is taken out of it, thus this air cannot be used to provide thrust. This has led to current technologies shift in the development of the bleed-less aircraft (or low bleed use) such as engine driven electric compressor. However, there is a trade off as electric functions need higher electricity generation from engine.

An ORC waste heat recovery system basically recuperates waste heat out of the core turbofan’s engine exhaust system and exploits it to generate electrical power to operate the aircraft environmental control system or other systems. It is a recovery system that searches to expand the performance of the overall engine. The waste heat in this application is used to produce electricity in order to operate the external air compressors to supply flow to the aircraft environmental control system. Therefore, less electricity generation is needed from the aircraft engine, hence less fuel consumption. This reduces the engine bleed air and consequently provides higher thrust for the aircraft engine.

Unfortunately, there was not a lot of studies concerning thermodynamic analysis of an ORC waste heat recovery system in an aircraft and their potential benefits, except for one by C A Perullo et al. [10]. They examined the possibility as well as the advantages of an ORC recuperative system in order to be applied to in-flight aircraft power generation. They also assumed a good ORC system design and some explanations are given to sum up the complete ORC system. In this study, the researchers used the Environmental Design Space (EDS) as the investigation tool to examine the possible advantages of an ORC system integrated to an aircraft engine [11, 12]. The technique applies an improved boiler located inside the nozzle walls of an existing aircraft engine to withdraw heat out of engine exhaust. An organic fluid named R245fa was used as the working fluid in order to examine the system because it appeared to have the highest cycle energy performance throughout various functioning pressures compared to the other three potential working fluids. However, they decided to make several modeling assumptions due to the interest of time and resources. First, in order to estimate off-design conditions, the researchers decided to work with fixed heat transfer coefficients. Secondly, it was assumed that there is no pressure losses other than across the turbine. Though the core engine fluid flow evolves in respect to the engine running status and throttle situation, they supposed a fixed core exhaust flow with a percentage of 30% that connects with the evaporator. Furthermore, before the expansion process in the nozzle, the heat is withdrawn out of the engine exhaust circulation. As a result, fuel burn savings of about 2.3% is possible depending on the real ORC-jet engine system weight. The purpose of their
study is not to evaluate the design procedure in terms of the detailed heat transfer involved and the thermodynamic performance of an ORC system, hence a very short explanation of the model was given. The aim of this study is to carry out the detailed design process of the ORC system through analytical study of their thermodynamic behavior and to investigate the total fuel consumption and the system performance.

2. Analysis of thermodynamic and heat transfer

Figure 1 shows the schematic diagram of a basic ORC system integrated with the engine core of an aircraft. Composition of an ORC system normally consists of an evaporator, a turbine, a condenser, a working fluid pump and a regenerator to preheat the working fluid before entering the evaporator in order to increase thermal efficiency of the system. Basically the system is integrated to the jet engine in the middle of the low pressure turbine exit duct and the core nozzle. Figure 1 below illustrates the connection between the Brayton cycle and the ORC cycle, which is located at the evaporator. The system begins to operate at the outlet of the cold side of the regenerator (station 1) with a specific heat transfer from the exhaust jet engine and a specific evaporator outlet temperature. An inlet temperature of the working fluid to evaporator, $T_{EV,WF, In}(t)$ is guessed and the system is analysed once through.

The ORC system diagram is shown in Figure 2, of which the thermal process can be described as follows. The evaporator used in this study is a shell-tube heat exchanger. It is the most common type of heat exchanger in many industrial applications and is suited for higher-pressure applications. The heat exchanger of this type consists of a shell with several tubes inside it. One fluid flows inside the tubes while the other flows outside the tubes within the shell to transfer heat between the two fluids. Heat is then transferred from one fluid to the other through the tube walls.

According to J Sun and W Li [8], there are three types of modelling approaches that can be applied to envisage the performance of the evaporator, which include distributed modelling, zone modelling and single node lump modelling methods. The single node lump modelling concept is normally not suitable when the phase change occurs since the method assumes that the temperature difference inside the “lump” is negligible, thus implies that constant specific heat inside is unchanged too. Meanwhile, for the second method which is zone modelling, the evaporator is divided into three zones: super-heat, two-phase and sub-cool. Subsequently, in each zone, the single node lump modelling can be applied.
However, a robust iterative algorithm is demanded in order to achieve the value of the heat transfer surface area of each zone [8]. The third choice of modelling method is distributed modelling, which considers the evaporator as small segments from the inlet of the flow to the outlet. Accordingly, the single node lump modelling, for example NTU-ε (Number of Transfer Units) and LMTD (Log-Mean Temperature Difference) methods, can be applied in each segment in order to predict the heat and mass transfer. This distributed modelling method has a better precision in contrast to the first two modelling with a robust approach. In this analytical study, the distributed modelling is applied in order to simulate the two heat exchangers, which are the condenser and the evaporator.

Figure 3 is showing three successive segments, noted i-1, i and i+1. As the precision is sufficient to suppose that heat capacity of the exhaust heat from jet engine and working fluid are roughly invariable in each discrete segment, to form the conservation equations, the single node modelling which is here, the NTU-ε method is applied. For segment i, the enthalpy increases at the working fluid side due to the heat absorbed from the exhaust heat of the jet engine.

Figure 3. Discrete segments of evaporator

\[
q_{EV,WF}(i) \cdot = m_{EV,WF} [h_{EV,WF,Out}(i) - h_{EV,WF,In}(i)]
\]  (1)

According to Equation 1, \( q_{EV,WF}(i) \) is the heat transfer rate of the evaporator, \( m_{EV,WF} \) is the mass flow rate of the working fluid through the evaporator and \( h_{EV,WF,Out}(i) \) as well as \( h_{EV,WF,In}(i) \) are the entrance and exit enthalpies of the working fluid for the segment i. In the same manner, heat transfer rate at the hot side, \( q_{EV,HF}(i) \) (exhaust heat of the jet engine) is noted as:

\[
q_{EV,HF}(i) \cdot = m_{EV,HF} C_{p, EV, HF}(i) [T_{EV,HF,In}(i) - T_{EV,HF,Out}(i)]
\]  (2)

Here, \( C_{p, EV, HF}(i) \) is the specific heat of the exhaust heat, \( m_{EV, HF} \) is the mass flow rate of the exhaust heat through the evaporator and \( T_{EV,HF,In}(i) \) as well as \( T_{EV,HF,Out}(i) \) are the entrance and exit temperatures of the exhaust heat for the segment i.

The maximum energy transferred, \( q_{EV,MAX}(i) \) along the evaporator can be defined as:

\[
q_{EV,MAX}(i) = C_{EV,MIN}(i) [T_{EV,HF,In}(i) - T_{EV,WF,In}(i)]
\]  (3)

with \( C_{EV,MIN}(i) = MIN\{m_{EV,WF} C_{p, EV, WF}(i), m_{EV, HF} C_{p, EV, HF}(i)\}\)  (4)

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\[
\text{Figure 3. Discrete segments of evaporator}
\]

\[
q_{EV,WF}(i) \cdot = m_{EV,WF} [h_{EV,WF,Out}(i) - h_{EV,WF,In}(i)]
\]  (1)

\[
q_{EV,HF}(i) \cdot = m_{EV,HF} C_{p, EV, HF}(i) [T_{EV,HF,In}(i) - T_{EV,HF,Out}(i)]
\]  (2)

\[
q_{EV,MAX}(i) = C_{EV,MIN}(i) [T_{EV,HF,In}(i) - T_{EV,WF,In}(i)]
\]  (3)

with \( C_{EV,MIN}(i) = MIN\{m_{EV,WF} C_{p, EV, WF}(i), m_{EV, HF} C_{p, EV, HF}(i)\}\)  (4)
Meanwhile, the effectiveness \( \varepsilon_{EV}(i) \) can be written as:

\[
\varepsilon_{EV}(i) = \left\{ 2 \times \left[ \left[ 1 + C_{r, EV}(i) \right] + \left( 1 + C_{2, EV}(i) \right)^{0.5} \right] \times \frac{1 + \exp \left( -NTU_{EV}(i) \times \left( 1 + C_{r, EV}(i) \right)^{0.5} \right)}{1 - \exp \left( -NTU_{EV}(i) \times \left( 1 + C_{2, EV}(i) \right)^{0.5} \right)} \right\}^{-1}
\]

(5)

where \( C_{r, EV}(i) = \frac{C_{EV, MIN}(i)}{C_{EV, MAX}(i)} \)

(6)

\[
C_{EV, MAX}(i) = \text{MAX} \left\{ m_{EV, WF} C_{p, EV, WF}(i), m_{EV, HF} C_{p, EV, HF}(i) \right\}
\]

(7)

The rate of heat transfer in the evaporator \( NTU_{EV}(i) \) is calculated and defined as:

\[
NTU_{EV}(i) = \frac{U(i)A_{EV}(i)}{C_{EV, MIN}(i)}
\]

(8)

The total heat transfer rates of the segments \( Q_{EV} \),

\[
Q_{EV} = \sum_{i=1}^{N_{EV}} q_{EV}(i)
\]

(9)

where \( N_{EV} \) is the total of evaporator segments.

The pump power consumption in process 5 to 6 is defined by:

\[
W_{pump} = \frac{m_{WF} C_{p, WF}}{\eta_{pump}} \left( \Pi^{\gamma-1} - 1 \right)
\]

(10)

where \( \Pi = \frac{P_2}{P_1} \), \( \eta_{pump} \) is the efficiency of the pump and \( \gamma \) is the specific heat ratio of the working fluid.

When the working fluid exits the pump as a high pressure saturated or superheat fluid and flows through the turbine, the power is produced and exits from the turbine as low pressure superheat fluid. Then the turbine power output is obtained from:

\[
W_{exp} = m_{WF} C_{p, WF} \eta_{exp} T_{exp, in} \left( 1 - \Pi^{1-\gamma} \right)
\]

(11)

where \( T_{exp, in} \) the turbine inlet temperature and \( \eta_{exp} \) is the efficiency of the turbine.
The net power output of the ORC system is:

\[ W_{\text{net}} = W_{\text{exp}} - W_{\text{pump}} \]  \hspace{1cm} (12)

The thermal efficiency of the ORC system is defined as:

\[ \eta_{\text{net}} = \frac{W_{\text{exp}} - W_{\text{pump}}}{Q_{EV}} \]  \hspace{1cm} (13)

Consequently, the total of conventional fuel (kerosene) that could be saved is:

\[ m_{\text{fuel}} = \frac{Q_{EV}}{HV_{\text{fuel}}} \]  \hspace{1cm} (14)

where \( HV_{\text{fuel}} \) is the heating value of kerosene, \( HV_{\text{fuel}} = 43\,000\,\text{kJ/kg} \).

3. Results and discussions

This section walks through the potential benefits of ORC system, which is integrated to a CFM56-7B turbofan engine on an aircraft size of 737-800. The working fluid chosen is R245fa. Design parameters are listed in Table 1 below based on the study done by other researchers [10]. The specific heat of the working fluid R245fa is assumed to be 1.36 kJ/kg.K in the range of the design temperature value whereas the one for kerosene is 2.01 kJ/kg.K. A calculation is run according to the equations defined in Section 2.

| Property                      | Unit | Value     |
|-------------------------------|------|-----------|
| Mass flow rate of R245fa      | kg/s | 1 – 5.4   |
| Mass flow rate of hot gas     | kg/s | 0.1 – 4.4 |
| Exhaust heat temperature      | K    | 700 - 1140|
| Inlet temperature of R245fa   | K    | 100 - 540 |
| Inlet temperature of turbine  | K    | 100 - 500 |
| Turbine inlet pressure        | MPa  | 1.2       |
| Turbine outlet pressure       | MPa  | 0.053     |
| Pump inlet pressure           | MPa  | 0.045     |
| Pump outlet pressure          | MPa  | 1.36      |
| Turbine efficiency            | -    | 0.776     |
| Pump efficiency               | -    | 0.577     |

The exhaust heat temperature from the jet engine will vary with the aircraft engine’s performance. The variations of the working fluid mass flow rate with the exhaust heat temperature are illustrated in Figure 4. It shows that a higher exhaust engine temperature of the jet engine, the working fluid mass flow rate will also increase due to the increment in the total heat load of the ORC system. This can be justified with the increasing demands of working fluid that results in more electricity being produced due to a higher available heat resulting from a higher exhaust heat temperature.
In addition, the results show that both net power output (Figure 5) and system efficiency (Figure 6) are improved with the increment of exhaust heat temperature, which indicates that the working fluid mass flow rate and the heat source temperature play a major role in optimizing the power generation and the system's thermal performance. This is because an increase in evaporation temperature and working fluid mass flow rate would eventually simulate a better energy load. This implies an increase in the turbine power output and subsequently the overall power output. Thus the ORC heat recovery efficiency is increased too due to the relation between the heat load and the exhaust heat temperature to the engine load capacity. However, a much less mass flow rate of the working fluid is demanded at the beginning, thus a slightly decrease of system thermal efficiency at temperature around 720-740K. The reason is that, in spite of the fact that more heat are used to generate more power with growing exhaust waste heat temperature, there could be a situation where the rising electric power is counter-balanced by the working fluid pump power consumption as a means to make use of the heat. As a result, the system performance could decrease a little at a certain point.

In order to show how the ORC impacts the Brayton cycle, according to this analytical method, the overall waste heat extracted out of the exhaust heat of the jet engine in evaporator is 1244.25 kW at
exhaust heat temperature of 843 K and mass flow rate of working fluid of 2.4 kg/s of the ORC system. Suppose that the cycle is run for 300 days a year, the total extracted waste heat energy annually will be $3.225 \times 10^{10}$ kJ/year. Eventually, it could conserve the conventional fuel (kerosene) usage of $7.50 \times 10^5$ kg/year.

4. Conclusion and the way forward
Starting from a comprehensive review of the design of ORC system integrated to an aircraft’s engine and the mathematical model as well as the heat transfer process involved, this paper has presented a rigorous derivation of the net power output and the energy efficiency gained by ORC heat recovery technology from basic principles. This study also indicates the potential of reducing fuel consumption by integrating the ORC system to turbofan engine. Such results will be very useful in future to develop in details the numerical simulation of ORC system, and consequently to study the system performance with different variations of parameters and to determine the irreversibility losses through calculation of energy of each ORC component to achieve an optimized system performance and eventually higher thrust power.

References
[1] Saleh B, Koglbauer G, Wendland M and Fischer J 2007 Energy 32 1210-21
[2] Hasanuzzaman M, Rahim N A, Saidur R and Kazi S N 2011 Energy 36 233-40
[3] Ziviani D, Beyene A and Venturini M 2014 Appl. Energy 121 79-95
[4] Bronicki L Y and Schochet D N 2005 Proc. ASME Turbo Expo 79-86
[5] Tchanche B F, Lambrinos G, Frangoudakis A and Papadakis G 2011 Renew, Sustain. Energy Rev. 15 3963-79
[6] Song J, Song Y and Gu C W 2015 Energy 82 976-85
[7] Yang M H and Yeh R H 2015 Appl. Energy 149 1-12
[8] Sun J and Li W 2011 Appl. Thermal Eng. 31 2032-41
[9] Pu W, Yue C, Han D, He W, Liu X, Zhang Q and Chen Y 2016 Applied Thermal Engineering 94 221-7
[10] Perullo C A, Mavris D N and Fonseca E 2013 Proc. of ASME Turbo Expo: Turbine Technical Conf. and Exposition
[11] Kirby M and Mavris D 2008 26th Int. Cong. of the Aeronautical Sciences
[12] Schutte J, Tai J and Mavris D 2012 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conf. & Exhibit