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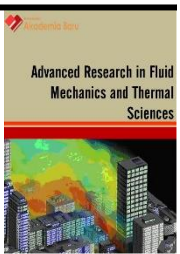

Modelling and Thermal Analysis of Organic Rankine Cycle with Superheater and Preheater

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Syamimi Saadon[1,*],Nur Athirah Mohd Nasir[1]

[1] Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

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ABSTRACT

Escalating fuel prices and carbon dioxide emission are causing new interest in methods the waste heat rejected to the environment and at the same time that can minimize the usage of fuel. One viable means is the conversion of exhaust engine waste heat to a more useful form of energy. The aim of this study is to model and investigate the thermal performance of an Organic Rankine Cycle (ORC) system which is used as waste heat recovery of exhaust gas from a turbofan engine. A simulation study has been done on the ORC in two different types of system configurations in order to predict which design will give a better thermal performance. Parameters such as net power output and the ORC system efficiency are used to represent and compare the thermal performance of both of the designs. The simulation is done by using MATLAB and REFPROP. The selection of the best configurations is based on the thermal efficiency of the system. It is found that the ORC system with superheater gives a better thermal efficiency that the one with preheater. The results also show that thrust specific fuel consumption (TSFC) of the turbofan engine reach a lower value by using ORC with superheater instead of with preheater. Hence implementation of ORC system for waste heat recovery to an aircraft engine can bring a great potential to the aviation industry.

1. Introduction

Growing consumption of primary fossil fuels and massive discharge of pollutants are some of the results caused by the world's growing population, and eventually the enlarging energy demand. It is therefore the main concerns that the developing world must face nowadays are the energy shortfall and the environmental destruction. Since 1973, the world energy consumption has been crucially increased and the world energy demands are growing up to 89% starting from 2006 till this year [1]. This affects significantly those industries which waste a huge amount of energy. And for these valid reasons the awareness of the use of the low-grade heat sources has captivated researchers around the world in recent years. To manage this matter, appropriate regulations should be established to further utilize the fossil energy and minimize the misuse energy in a more effective way. Particularly,

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[*] *Corresponding author.*
E-mail address: mimisaadon@upm.edu.my (Syamimi Saadon)

there is extra effort in the aviation field to reach a higher quality of propulsion system, as the fuel cost is increasing and the future law is becoming more severe. It was recorded that the waste fuel energy from exhaust engine is over 30-40% and only a small fraction of this energy which is roughly 12-25% were converted to useful work [2]. Apart from creating a downturn in fossil fuels market, waste heat recovery will also lead to reduction in greenhouse gases and hence making it the idea of a better future environment more promising.

There are a lot of discussions and researches emerge trying to prove that this waste heat recovery is a practical resource of energy due to its large quantity [3]. An example of steam-based waste heat recovery system applied to several industries is Heat Recovery Steam Generators (HRSGs). However, it is not recommended for a smaller gas turbine engine due to problems of weight as well as supply of water [4]. Hence an Organic Rankine Cycle (ORC) system is a solution for power production from low to medium temperature heat sources in the range of 80 to 350 °C. This technology allows for exploitation of low-grade heat that otherwise would be wasted. ORC can also be an ideal solution when the size of the application is too small for a steam power plant. By converting thermal energy to electricity at low temperature the ORC provides crucial green technology to improve energy efficiency of new and existing applications. In a Rankine cycle, the system applies the heat to rise up the temperature and pressure of an organic fluid. Thus, the name organic Rankine cycle comes from its use of an organic fluid which has a characteristic of a liquid-vapor phase change at a lower temperature than the phase change in water-steam.

ORC is suitable for a wide range of applications including low enthalpy geothermal sources, heat recovery from industrial process, power generation, biomass plants, gas compression stations and concentrated solar power. In power plant applications and marine diesel engine, there have been several researches concerning the thermal analysis and design optimization of an ORC using waste heat source [5, 6, 7] and recently a study had also been demonstrated experimentally [8]. An example of study of the performance or ORC using in biomass application was done by H. Ismail *et al.,* [9]. The study focused on selection of organic fluid as ORC's working fluid in producing a 3 MWe output. They concluded that ORC needs bigger feed pump than steam plant. Even so, to integrate the system to an aircraft engine, few factors must be taken into consideration. Principally, the aim of the system for a power plant is to recuperate a great amount of energy from the exhaust engine to supply electricity. However, in an aircraft engine the fundamental point is not to produce power, but to produce thrust and to reduce a considerable amount of fuel consumption. Bronicki *et al.,* [4] also come up with the basis reasons for an ORC to be integrated to an aircraft gas turbine engine sized which marks about 16% of the gas turbine performance's improvement.

However, researches on design and performance analysis of an ORC waste heat recovery system integrated to aircraft engine and their possible advantages are still very few. Only one assessment study so far done by Perullo *et al.,* [10]. They examined the feasibility and the benefits of an ORC heat recovery system to be used for inflight aircraft power generation. In this study, they utilize the Environmental Design Space (EDS) as the simulation tool [11, 12]. The method applies a refine boiler situated inside the nozzle walls of an aircraft engine to extract heat from the engine exhaust. The organic fluid chosen to evaluate the system was R245fa because of its highest cycle energy performance across multiple operating pressure compare to other three possible fluids.

Nevertheless, because of limited time and resources, they decided to make several modelling assumptions. The researchers decided to use a fixed heat transfer coefficient to search for the off-design conditions and they estimated a pressure loss only in the turbine and although the engine fluid flow progress during the engine running, they assumed a fixed core exhaust flow of 30% that links to the evaporator. Consequently, about 0.9% fuel burn savings is possible but it depends on the whole engine system weight. However, their aim is not to analyze the thermal performance, in terms of how the heat transfer being produced, and the overall performance of the system; hence, a very brief presentation of the model was provided. A preliminary study by Saadon *et al.,* [13] intended to better understand the thermal characteristics by evaluating the net power output of the ORC and the system overall efficiency. However, their results are still open to ambiguity and the study on the impact of the ORC system to the aircraft was not performed. Moreover, they only considered one type of configuration in designing the heat exchanger for the ORC system. Therefore, our study tries to fill in this gap by performing: (i) two different types of configurations of the ORC system; (ii) the thermal analysis of the system cycle; (iii) the evaluation of the total Thrust Specific Fuel Consumption (TSFC) and the fuel burn.

2. Methodology

2.1 Organic Rankine Cycle (ORC) System with Superheater and Preheater

There are two scenarios of ORC system that will be simulated in this study which are named Scenario A and Scenario B. The first schematic diagram of ORC which will be implemented in Scenario A is described in Figure 1. The first diagram consists of ORC system with a superheater which contains an evaporator along with a superheater, a turbine, a condenser and a working fluid pump, all together integrated to a turbofan engine between exit of the low-pressure turbine (LPT) and the exhaust nozzle. Here, the working fluid is the organic fluid.

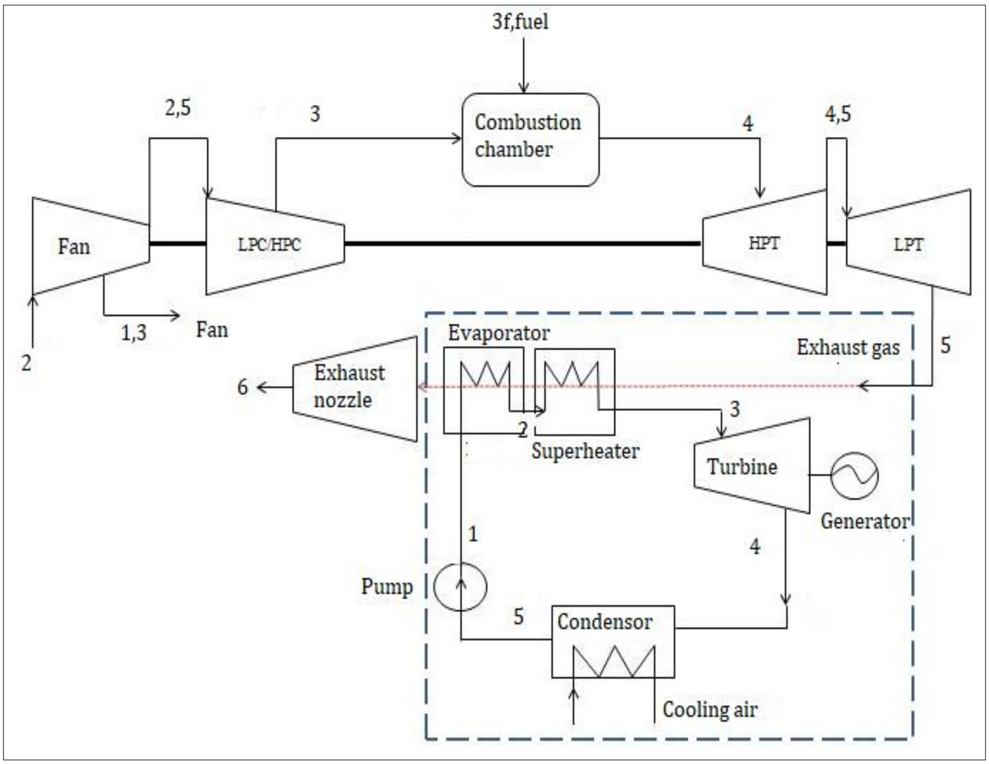

Fig. 1. Schematic diagram of the ORC system with superheater (Scenario A) applied to a turbofan engine [14]

In the second diagram for Scenario B (Figure 2), it contains of similar components except that the superheater is replaced with a preheater that is used to heat up the organic fluid before getting into the evaporator in expectation to achieve a better thermal efficiency of the system. The system starts at the outlet of the liquid side of the pump (station 1). A shell-tube heat exchanger is chosen as the evaporator as it is the most demanded in many industries and is convenient for higher-pressure applications. It consists of a shell with several tubes inside. The heat is transferred between the two fluids through the tube wall within the shell by entering one fluid inside the tubes, while the other fluid flows outside the tubes.

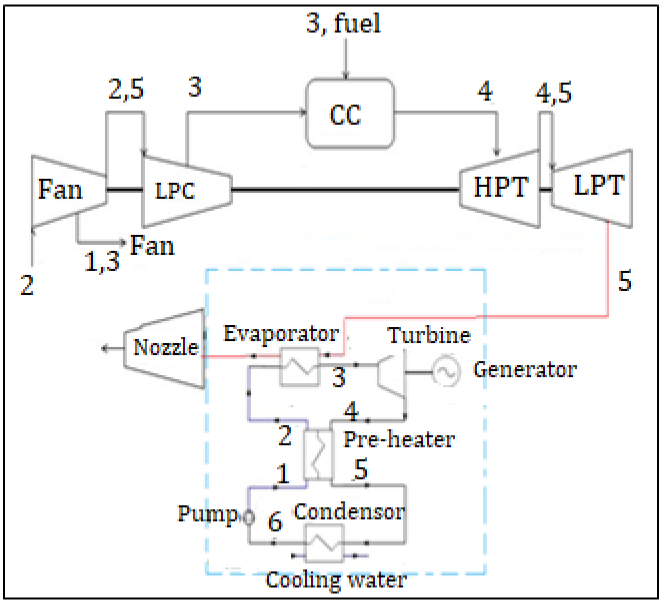

Fig. 2. Schematic diagram of the ORC system with pre-heater (Scenario B) applied to a turbofan engine

The T-s (temperature-entropy) diagram of the combined organic Rankine cycle with superheater and Brayton cycle of the turbofan engine is presented as in Figure 3 below [14]. The heat extracted from the exhaust nozzle, instead of being wasted and rejected directly to the air, is here recuperated and being ducted into the superheater and evaporator in Scenario A and into the evaporator in Scenario B. The hot gas from the waste heat will be cooled down by transferring the heat to the organic fluid in the heat exchanger. Here, the organic fluid will play the role as the cold fluid.

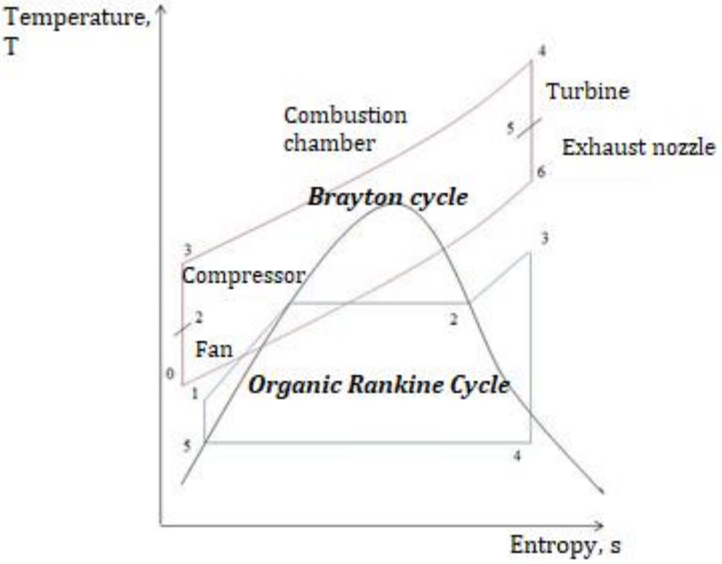

Fig. 3. Diagram of T-s for an ORC system with superheater [14]

The model for Scenario A was validated in previous articles by the authors [14] by comparing the results of net power output and system thermal efficiency with the same system on a marine diesel engine of a merchant ship [6] using R245fa as working fluid. While the Scenario B was also verified previously [15] by comparing the same parameters with the one for industrial waste heat recovery [16] using R123 at cooling water temperature of 293 K and 303 K. Regarding to these validations, the simulation studies have been proceeded with other designs of ORC system as the subject of interest of study.

3. Results and Discussion

3.1 Thermal Performance Analysis of ORC with Superheater and Preheater

This section presents the thermal performance analysis of the ORC systems in order to compare both of the systems with Superheater and Preheater. The simulation is done for both of the models by using parameters given below in Table 1, taken from a related published article [16]. The working fluid used here is R123 with specific heat of 0.9744 kJ/kg.K. The simulation is then performed with inlet temperature of the fluid at 100 K.

Table 1
Parameters of ORC system using R123 as working fluid

Description	Value
Working fluid mass flow rate	21.2 kg/s
Exhaust heat temperature	453 K
Evaporation temperature	350 K
Inlet pressure of turbine	1.21 MPa
Outlet pressure of turbine	0.55 MPa
Turbine efficiency	0.6
Pump efficiency	0.8

Figure 4 below shows the results of net power output of the ORC system, according to the inlet temperature of the waste heat recuperated from the exhaust engine. Here, we could observe that the system with preheater exhibits slightly higher net power output compare to the one with superheater. The reason behind this situation could be because in the system with preheater, the organic fluid is heated first before it enters the evaporator where it exchanges heat with the hot gas. At this level the preheater “helps” the working fluid pump to increase its temperature before entering the evaporator, thus decreasing the demand of power for the pump. Whereby in Scenario A where the superheater is used after the evaporator, the pump needs more power to heat up the organic fluid before entering the evaporator. Therefore, the net power output produced for the ORC system with superheater is a bit lower than the one with preheater.

Meanwhile in Figure 5 we could see a bit different phenomenon. The system thermal efficiency for the system with superheater is around 13.6 % while for the one with preheater is closed to 12.7 %. The ORC system with superheater exhibits higher thermal efficiency compare to the system with preheater. This could be due to the lower total heat transferred along the superheater and evaporator in Scenario A. The reason is because the “pinch temperature” which is the difference between the temperature of the hot gas from the exhaust engine and the organic fluid is lower in

Scenario A than the difference of them in Scenario B, since the hot gas is being cooled down through a superheater first before entering the evaporator.

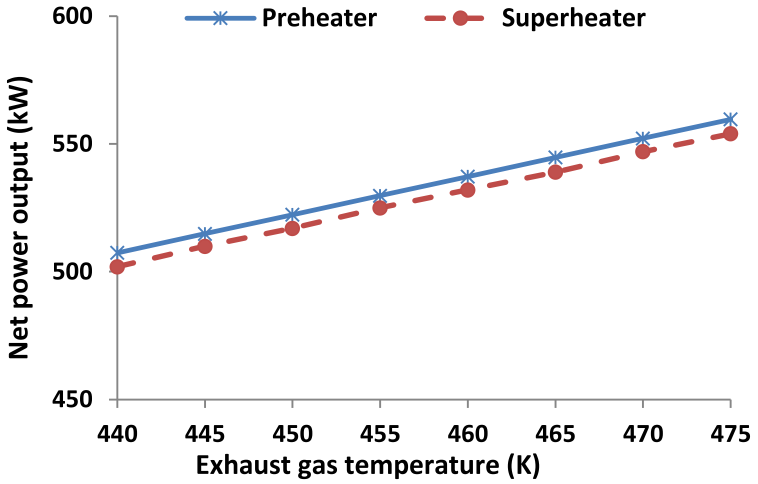

Fig. 4. Graph of net power output to the exhaust gas temperature

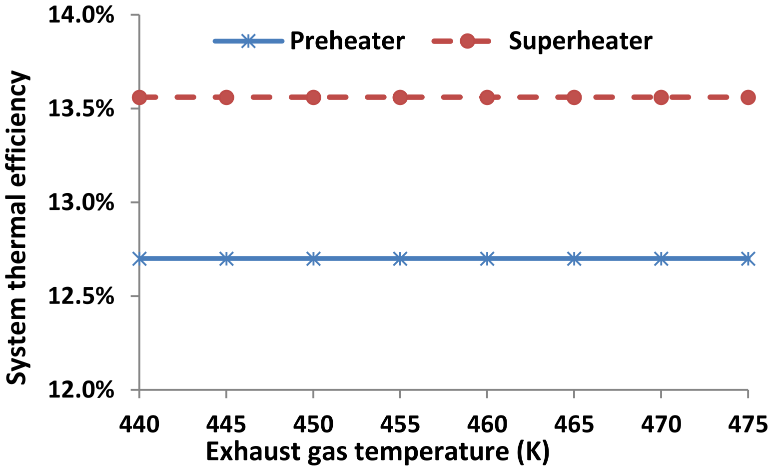

Fig. 5. Graph of system thermal efficiency to the exhaust gas temperature

3.2 Simulation of ORC Applied to a Turbofan Engine

This part presents the advantages of ORC system integrated to a CFM56-7B27 turbofan engine on an aircraft size of 737-800. The working fluid chosen is the R245fa. The specific heat of R245fa in the range of the design temperature value is 1.36 kJ/kg.K. Design parameters are listed in Table 2 below [10]. In order to solve this system, the heat transfer flowing out from the exhaust engine is varied until it matches the heat transfer calculated using the heat transfer coefficient and evaporator area from the detailed design. By doing this, it ensures that the evaporator exit temperature set by the thermodynamic limits of R245fa is maintained. The simulation is then executed as before and the results attained are presented in figure below.

Table 2
Design parameters of ORC system connected to a turbofan engine

Description	Value
Working fluid mass flow rate	3.84 kg/s
Exhaust heat temperature	843 K
Inlet temperature of working fluid	282 K
Outlet temperature of R245fa	393 K
Turbine inlet temperature	392 K
Turbine inlet pressure	1.21 MPa
Turbine outlet pressure	0.55 MPa
Turbine efficiency	0.87
Pump efficiency	0.7
Heat transfer area for evaporator	23.72 m²
Heat transfer required for evaporator	1105 kW

The turbine within the ORC was connected to a simulation of an external compressor to evaluate the impact on the engine when engine bleed air was reduced. The result shown below in Figure 6 is detail common cruise conditions with Mach 0.785 at altitude of 35,000 feet.

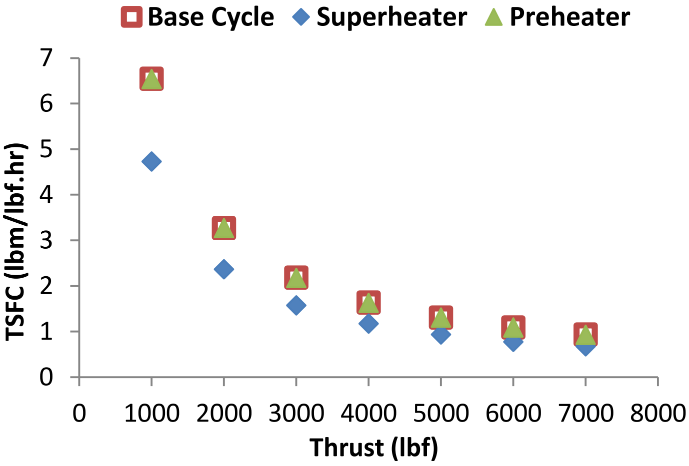

Fig. 6. ORC engine with TSFC effects

Figure 6 represents the graph of TSFC against thrust force which is compared with the base cycle without ORC for exhaust waste heat recovery [10]. The lowest TSFC of the turbofan engine is at 0.68 lbm/lbf.h and 0.91 lbm/lbf.h for Scenario A and Scenario B respectively. Thus, this confirms that the ORC system with superheater gives a better thermal performance and also better fuel consumption in terms of thrust force.

4. Conclusions

This paper presents two types of configuration of heat exchanger in order to design a better ORC system implemented in a turbofan engine. The numerical model of both configurations has been validated in previous authors' work. The results for both of the configurations provide an idea of which system is better in terms of thermal performance and how the different configurations affect the overall cycle performance.

These results are then further exploited by applying the ORC system to a turbofan's exhaust engine study the impact of both systems on the engine's thrust and its fuel consumption. As expected, the TSFC of the engine with ORC system combined with superheater exhibits a lower value compared to the other design. Parametric optimization shall be continued in the future in order to study other cause root and potential maximization of the thermal efficiency of the system. The presented study however already proved that an ORC cycle with superheater gives potential advantages when integrated to exhaust engine and could be as an option to manage the extensive waste heat in the environment.

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