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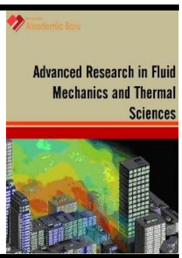

Performance Analysis of Supercritical Organic Rankine Cycle System with Different Heat Exchangers Design Configuration

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ABSTRACT

Recovering waste heat is one of the solutions found to lessen the emission and fuel consumption. Waste heat is heat energy produced by internal combustion wasted to the atmosphere. However, these low grade waste heats are not sufficient enough in generating power due to insufficient low temperature. Thus, to recover these waste heat, Organic Rankine Cycle (ORC) system is one of the beneficial exhaust heat recovery technologies which is widely used for the applications of low grade heat recovery rather than conventional Rankine cycle. This paper provides analytical study of the performance of supercritical ORC using exhaust aircraft engine as waste heat in order to find the best design configuration for the ORC system. The results show that supercritical ORC with superheater achieved higher net power output and thermal efficiency compared to the ORC system with preheater.

Keywords:
organic Rankine cycle; preheater; supercritical; superheater

1. Introduction

Worldwide, increasing unpredictable weather patterns are reported. Particularly in Malaysia, climate change studies show increases in temperature and changes in rainfall regimes [1]. The reserves of crude oil and natural gas in Malaysia are projected to be completely diminished by 30 to 40 years beginning from 2015 [2]. Increasing of population growth [3] and escalating process of electricity are mostly due to this climate changes caused by emission gases from the industry, vehicles, deforestation and others. In aerospace industry, engineers continuously search for new methods to enhance the efficiency of the engines and can be achieved through recovery waste heat [4] which help in reducing emission and fuel consumption [5]. Waste heat or low-grade waste heat is heat energy produced by internal combustion wasted to the atmosphere. However, these low-grade waste heats are not sufficient enough in generating power due to insufficient low temperature. Thus, to retrieve these waste heat, rather than Rankine Cycle, the Organic Rankine Cycle (ORC) system is one of the beneficial exhaust heat recovery technologies which is used for applications of low grade heat recovery widely [6]. Since energy is in demand, working fluid at higher temperature when exiting

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the evaporator (preheater) or before entering the turbine (superheater) is needed to increase the output power of ORC. When the output power increases, the thermal efficiency also increases. Between water and organic fluid, the thermal efficiency of organic fluid is greater than water, thus, the organic fluid mass flow rate is bigger than the mass flow rate of water, and ORC needs a bigger feed pump to further increase the thermal efficiency.

Combining an ORC to the energy system, such as in power plants, organic fluid of low boiling point is used to convert heat into electrical power. The organic fluids or refrigerants used in air conditioning systems accumulates heat from a volume of air and release it to different type of heat exchanger which increases the expansion of high vapour pressure in expander. The heat accumulated transform into mechanical power or electricity and leads to increase of thermal efficiency and overall performance of the engine. Thus, higher thrust could be obtained as aircraft engine requires less electrical power resulting lower engine bleed air [4-7]. Because of its small scale, bigger possibility incorporation in future distribution generated system [8] which could work at lower temperature, scaled down the total installed power into kW levels and use organic fluids instead of water, ORC is a promising energy conversion technology in low grade waste heat sources. Thus, ORC is advantageous in low to medium power range due to its cycle simplicity, less cost and stress level needed at boiler, easier to control and simpler usage of components [9].

Presently, there has not been any waste heat recovery (WHR) system added to an aircraft. Nevertheless, researchers suggest on adding WHR system to future engines and propose to make changes in current engines. However, it is a hassle to change the actual design of the engine as more costs will be used in research, tests and certifications and a lot of heat source needs to be taken into account. Pasini *et al.,* [10] analysed the possibilities of heat recovery results in overall efficiency of an aircraft engine by modelling waste heat recovery system in a jet engine and a turbo propeller engine, taking into account the nozzle works in off design conditions. The amount of heat discharged was found to be affecting the performance of the system.

An experimental observation [11] indicated that for ORC with superheat with R245fa when superheat at 1.8ºC was observed and as the superheat rises to 8.7ºC, the system stabilizes. Thus, even dry working fluid needs superheating. Superheat and internal heat exchanger from both thermodynamics were also found to be important for ORC. Note that Guo *et al.,* believed that combining superheat with internal heat exchanger results in more significant improvement [12]. Ismail *et al.,* [13] deduced that addition of superheated vapour in internal heat exchanger system increases ORC’s thermal efficiency. Together with superheated vapor, the system required lower mass flow compared to saturated vapor system. Superheater is therefore needed to reduce the mass flow rate, and together with the internal heat exchanger, the system performance is improved.

Recovering exhaust gas waste heat from the combined heat and power engine in supercritical and subcritical ORC was compared by Yagli *et al.,* [14] and shows that supercritical has better performance where the supercritical ORC rise at constant pressure with increased turbine inlet temperature. The performance of subcritical and transcritical ORCs based on the pinch point locations in the evaporators was investigated by Guo *et al.,* [12] with results of transcritical ORCs with better performance when outlet temperatures of heat source are lower.

Li *et al.,* [15] uses R245fa working fluid to conduct an experimental research in investigating the small-scale ORC performance with lower grade heat sources to generate electricity at various conditions. Lee *et al.,* [16] reported on the system performance of the exit superheat for plate and shell-and-tube heat exchanger and encounter that when the evaporator uses shell-and-tube, ORC system with stable oscillation was found for exits superheats. Recent study done by Nasir *et al.,* [17] has shown the performance analysis of ORC with preheater and superheater. However, the working fluid was in subcritical condition. Nevertheless, the study has proved that ORC with superheater exhibits lower TSFC compared to the base cycle and ORC with preheater.

The aim of this study is to model and analyse the thermal of an ORC systems with different heat exchangers design configuration to gain greater thermal efficiencies and power output of ORC that can be placed on aircraft able to initiate enough power output to compensate the power needed to carry it as well as generate extra free energy which were used in aircraft. This paper will focus on designing an efficient, cost effective ORC power plant that are able to utilize low-grade industrial waste heat or low to medium- temperature exhaust gas engine. Working fluid chosen is R245fa. Thus, the objectives of this study are

i. To investigate the effect of using working fluid at supercritical condition to power output ORC for better thermal efficiency
ii. To design an ORC model with better output power by using additional heat exchanger.

The addition of superheater is expected to increase the power output thus allowing the turbofan engine in ORC recovering more waste heat and produce greater power than a simple ORC. Due to increase in power output, system thermal efficiency is affected in ORC, working fluid in supercritical condition needs lower mass flow rate, thus, it is expected that less feed pump is needed to raise the ORC thermal efficiency.

2. Methodology

The energy equation will be the main equation to model and analyse the thermal of an ORC system with various design configuration of heat exchangers to achieve greater ORC thermal efficiencies and power output with working fluid of R245fa. In the proposed cycle, a preheater, superheater and supercritical condition is applied. In this application, the shell and tube heat exchanger are used. A model for ORC will be designed to observe the thermal efficiency of the cycle and a few graphs will be plotted to compare the energy efficiency of the working fluid at supercritical conditions to power output the cycle in low industrial waste heat or low to medium-temperature exhaust gas engine.

Two types of ORC system will be simulated in this study namely Design A and Design B. Figure 1 describes design A that will be used consisting an evaporator with preheater, a turbine, a condenser and a working fluid pump integrated to a turbofan engine between exit of low- pressure turbine (LPT) and exhaust nozzle. When entering the evaporator, the preheater heats up the organic fluid for a better thermal efficiency.

Design B (Figure 2) replaces the preheater with a superheater. The system begins at the outlet of the liquid side of the pump and used shell-tube heat exchanger evaporator which is convenient for higher-pressure application with several tubes inside and most used in several industries. Heat is the transferred inside the shell through the tube wall by infiltrating one fluid inside the tubes, and the other fluid flows outside of the tubes.

Figure 3 and 4 below shows the below shows the T-s (temperature-entropy) diagram of the ORC with superheater and preheater Instead of wasting the heat extracted from the nozzle directly into the air, the heat recuperated and ducted into the superheater and evaporator in Design B and into the evaporator in Design A. The transfer of heat in the exchanger to the organic fluid helps in cooling down the hot gas from the waste heat with organic fluid as the cold fluid this time.

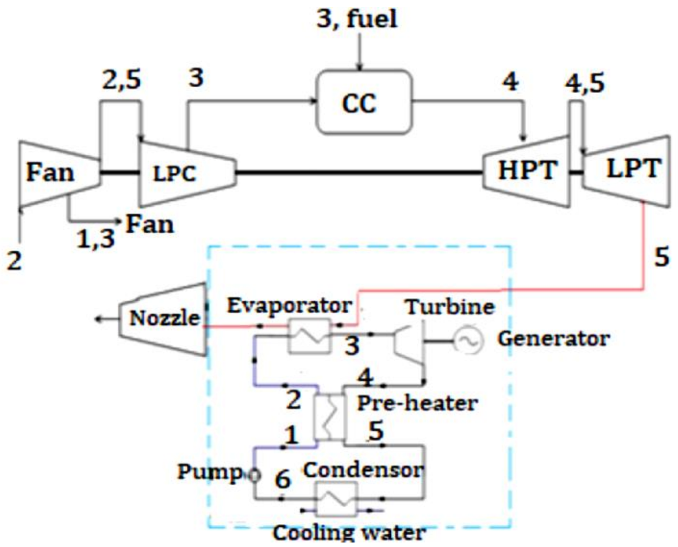

Fig. 1. ORC system schematic diagram with preheater integrated to a turbofan engine [17]

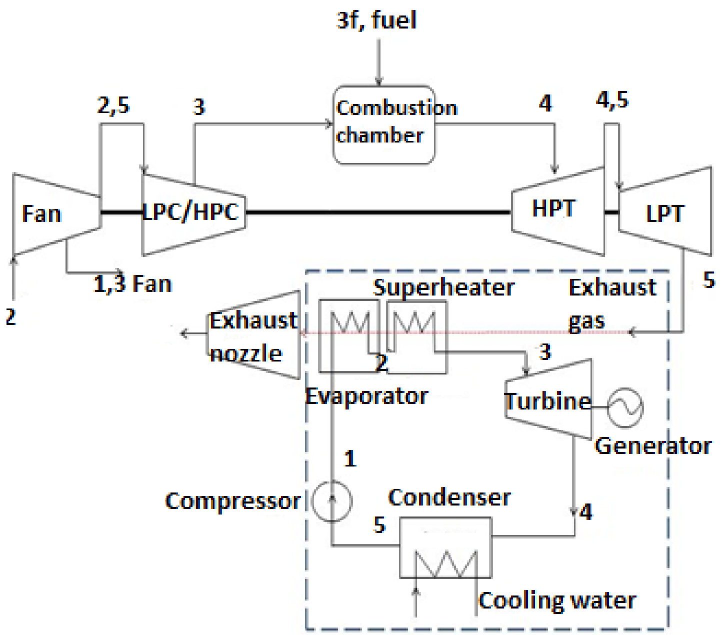

Fig. 2. ORC system schematic diagram with superheater integrated to a turbofan engine [17]

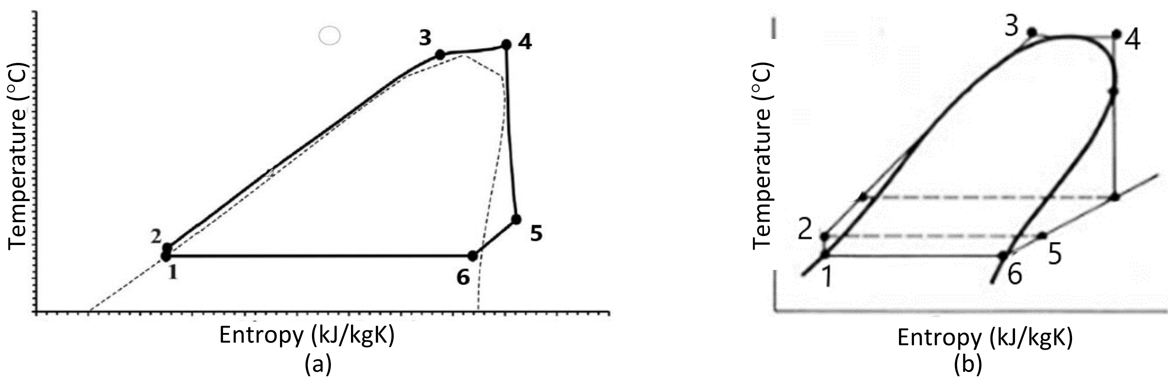

Fig. 3. (a) T-s diagram of an ORC system with superheater at supercritical condition (b) T-s diagram of an ORC system with preheater at supercritical condition

Number of Transfer Units (NTU) is used in order to calculate the evaporator efficiency. Figure 4 shows three different segments, *i-1, i, i+1.* 20 segments were divided in the evaporator and it was assumed that organic working fluid capacity and waste heat is constant in every discrete section. Due to the absorption of heat from exhaust engine, the organic working fluid enthalpy is enlarged for each segment of *i*.

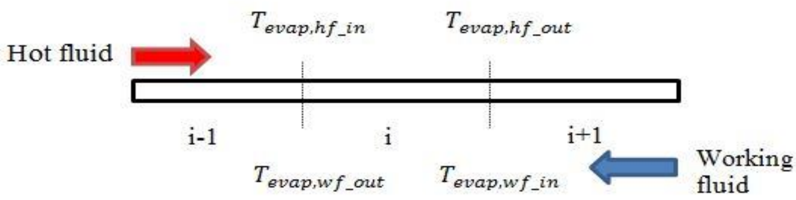

Fig. 4. Discrete evaporator segments [18]

The numerical model starts from evaporator and continues towards the superheater with energy moved from waste heat to organic fluid based on Eq. (1) and (2), where $q_{evap,max}$ is the evaporator maximum heat transfer, T_{evap,hf_in} is the hot fluid inlet temperature at evaporator, T_{evap,wf_out} is the outlet working fluid temperature at the evaporator, $\dot{m}_{evap,wf}$ is the working fluid mass flow rate, $\dot{m}_{evap,hf}$ is the hot fluid mass flow rate, $C_{p\_evap,wf}$ is the specific heat of working fluid and $C_{p_evap,hf}$is the fluid specific heat.

$$q_{evap,max}(i) = C_{evap,min}(i)[T_{evap,hf_{in}}(i) - T_{evap,wf_{out}}(i)] \tag{1}$$

$$C_{evap,min}(i) = MIN\{\dot{m}_{evap,wf}C_{evap,wf}\dot{m}_{evap,hf}C_{evap,hf}\} \tag{2}$$

The definition of effectiveness, ε_{evap}

$$\varepsilon_{evap}(i) = \frac{q_{evap,}(i)}{q_{evap,max}(i)} \tag{3}$$

$$C_{r,evap} = \frac{C_{evap,min}}{C_{evap,max}} \tag{4}$$

$$NTU_{evap}(i) = \frac{UA_{evap}(i)}{C_{evap,max}} \tag{5}$$

With *U* as overall heat transfer coefficient and A_{evap} is area of evaporator.

Q_{evap} is the total heat transfer rates of all parts denoted in Eq. (6).

$$Q_{evap} = \sum_{i=1}^{N_{evap}} q_{evap}\,(i) \tag{6}$$

$$Q_{sup} = \dot{m}_{wf}C_{pwf}(T_{\exp\_in} - T_{\mathrm{evap}\_out}) \tag{7}$$

where Q_{sup} is the superheater total heat transfer rate, $T_{\exp\_in}$ is the turbine inlet temperature and T_{evap_out} is the evaporator outlet temperature.

Eq. (8) describes the equation of pump power consumption from the pump section, W_{pump} where $\pi^{(\gamma-1/\gamma)-1}$ is the pressure ratio, η_{pump} is the efficiency of pump and γ is the specific heat ratio.

$$W_{pump} = \frac{\dot{m}_{wf} C_{pwf} (\pi^{\left(\gamma - \frac{1}{\gamma}\right)-1} - 1)}{\eta_{pump}} \tag{8}$$

$$W_{exp} = \dot{m}_{wf} C_{pwf} \eta_{exp} T_{\exp\_in} (1 - \pi^{\left(\gamma - \frac{1}{\gamma}\right)-1}) \tag{9}$$

where W_{exp} is turbine power and η_{exp} is turbine efficiency.

$$W_{net} = W_{exp} - W_{pump},\ W_{net} \text{ is net power output} \tag{10}$$

$$\eta_{net} = \frac{W_{exp} - W_{pump}}{Q_{evap} + Q_{sup}},\ \eta_{net} \text{ is system efficiency} \tag{11}$$

3. Results and Discussions

3.1 Analysis Performance of ORC with Preheater and Superheater

The ORC systems with preheater and superheater were compared to present the thermal performance analysis. Table 1 shows the parameter used for the simulation in both models in MATLAB configuration. The working fluid used here is R245fa with specific heat of 1.36kJ/kgK. 2.01 kJ/kg.K is used as the specific heat of fuel.

Table 1
ORC system design parameter [17]

Description	Unit	Value
Exhaust gas mass flow rate	kg/s	20
Working fluid mass flow rate	kg/s	21.2
Evaporation temperature	K	350
R245fa turbine inlet temperatre	K	438
Efficiency of pump	-	0.8
Efficiency of turbine	-	0.6

Figure 5 depicts the results of the ORC system net power output based on the inlet temperature of waste heat recover from exhaust engine. It could be observed that the system with superheater gives slightly higher net power output compared to the preheater system. Compare to preheater, the pump needs more power in heating the organic fluid upon entering evaporator for the ORC system with superheater. As the temperature increases, the net power output of the cycle increases.

Figure 6 below depicts that system thermal efficiency with superheater is 24.62% and for the preheater is 24.36%. Again, the system with superheater provides higher thermal efficiency than the preheater. This situation arises due to lower total heat transferred along the superheater and evaporator in design B as the pinch point temperature (difference between temperature of organic fluid and the hot gas from exhaust engine) is lower in design B than design A. Before entering the evaporator, the hot gas is cooled down in superheater first.

Figure 7 shows the working fluid output mass flow rate of the ORC system. It shows the system with superheater gives higher output mass flow rate than the system with preheater. As the heat source increases, the mass flow rate rises. The highest output mass flow rate of superheater system exhibits a value of 5.754 kg/s, meanwhile, the system with preheater exhibits a highest value of 5.3894 kg/s where the difference between the two system is quite low.

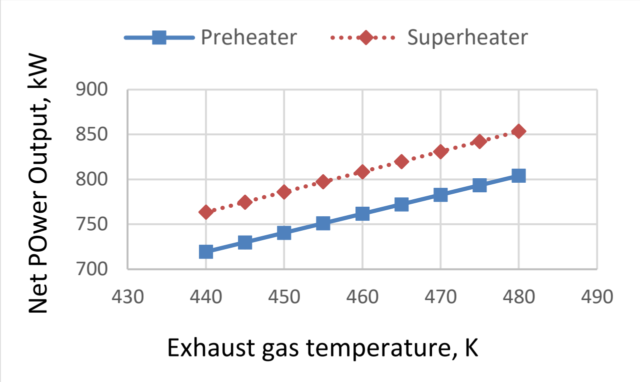

Fig. 5. Net power output graph to the temperature of exhaust gas

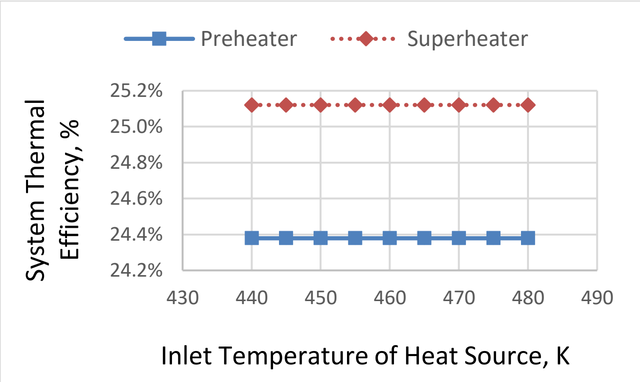

Fig. 6. Graph of thermal efficiency system to exhaust gas temperature

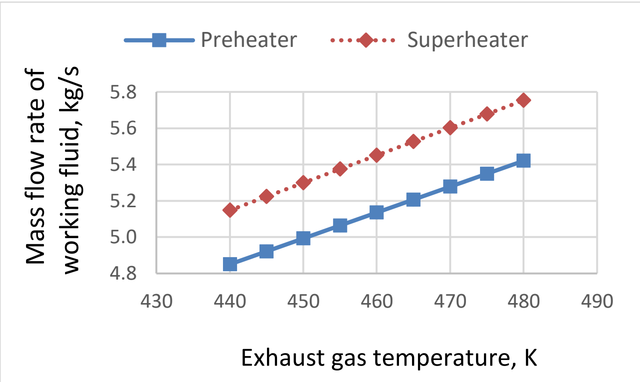

Fig. 7. Graph of output mass flow rate of working fluid to the exhaust gas temperature

3.2 Simulation of ORC Implemented to a Turbofan Engine

In this section, the ORC system is implemented to a CFM56- 7B27 turbofan engine on an aircraft size of 737-800. The working fluid used is the same as the previous part. Table 2 shows the parameter designs used. Heat transfer out of the exhaust heat engine varies until equivalent with heat transfer calculations with detailed design of evaporator area and heat transfer coefficient.

Table 2
ORC system characteristics used in engine of turbofan [19]

Description	Unit	Value
Working fluid mass flow rate	kg/s	21.2
Surface area needed for evaporator	m^2	23.72
Heat transferred needed for an evaporator (preheater)	kW	783.53
Heat transferred needed for an evaporator (superheater)	kW	841.73
Temperature of exhaust gas	K	843
The temperature of exhaust gas (evaporator inlet)	K	438
Working fluid temperature at inlet	K	282
Working fluid temperature at outlet	K	430
Critical temperature of working fluid	K	427
Pressure of inlet turbine	MPa	1.31
Pressure of outlet turbine	MPa	0.59
Pump efficiency	-	0.87
Turbine efficiency	-	0.8

Graph comparing the TSFC to thrust force with the base cycle without ORC for exhaust waste heat recovery is shown in Figure 8. The turbofan engine with lowest TSFC for design A and B is at 0.9138 lbm/lbfh and 0.9109 lbm/lbfh respectively. As less thrust force is produced, les fuel is needed which helps in reducing the weight of aircraft. This confirms the theory that superheater ORC provides better thermal performance and fuel consumption.

Figure 9 shows the burning of fuel compared with base cycle considering the weight of aircraft while flying. TSFC's fuel burning effect is referred to "Regen + Bleed Saving" and the effect of adding 430 kg per engine on the ORC system is denoted by the "Add 430 kg/engine". Comparing the ORC system with preheater and superheater, the ORC system with superheater gives 1.4% reduction in fuel burn as weight is added compared to ORC with preheater results in 1.1% reduction in fuel burn. Although the difference is not big, it clearly shows that the superheater ORC exhibits more reduction in fuel burn.

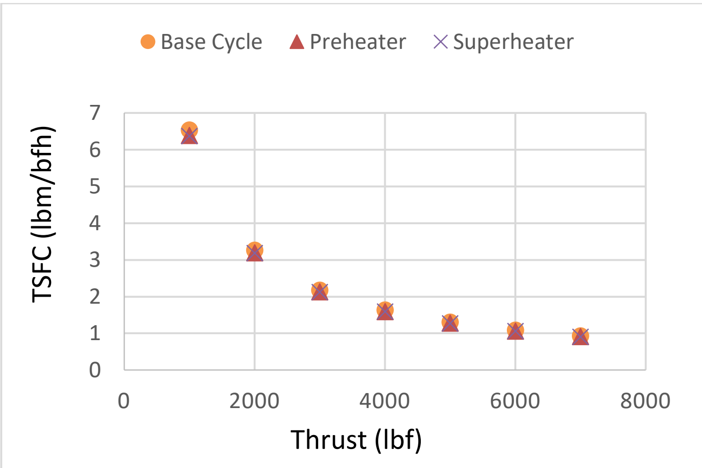

Fig. 8. ORC engine with TSFC effects

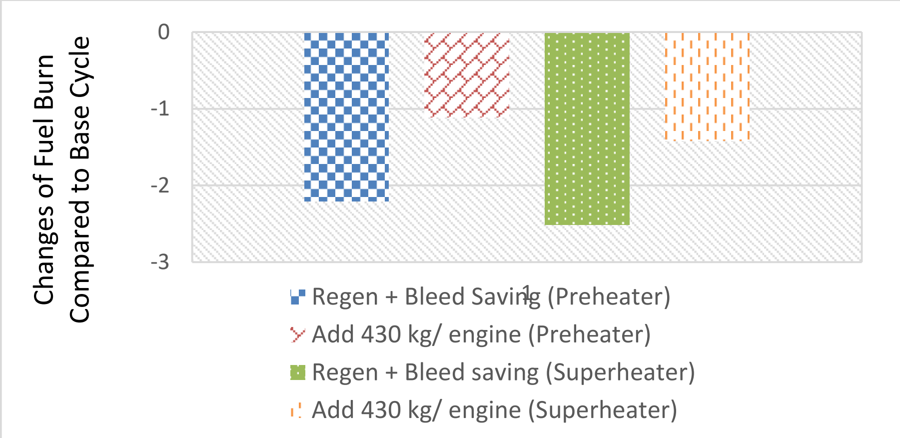

Fig. 9. ORC engine with TSFC effects on mission fuel burn

4. Conclusions

This paper shows two types of heat exchanger configuration design for a better ORC system to be applied in turbofan engine. The system with better thermal performance and how the configuration affects the overall cycle performance can be seen based on the results obtained. The results then applied the ORC system into the turbofan exhaust engine studying the effect of both systems to engine thrust and fuel consumption. The TSFC of the engine with ORC system together with superheater gives lower value than the preheater. In future studies, parametric optimization should be continued to study the potential maximization of the system thermal efficiency. However, this study has proven that an ORC cycle with superheater incorporated to exhaust engine gives benefits in managing the waste heat released to the environment.

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