

Parametric optimization and performance analysis of a waste heat recovery system using Organic Rankine Cycle (ORC)

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Abstract. Organic Rankine Cycle (ORC) has been proven to be the most effective solution to utilize fully the waste heat energy produced from manufacturing and power plant. In this paper, thermodynamic analysis and performance optimization of an ORC waste heat recovery system is performed for an aircraft engine and R245-fa is chosen as the refrigerant. The main concern of this study is to maximize the total heat transfer rate through the evaporator, thus the optimization of the Thrust Specific Fuel Consumption (TSFC) and the Specific Thrust of the engine can be performed. The main parameter to conduct the optimization is Turbine Inlet Temperature (TIT) and preheating temperature of R245fa. From the analysis, by increasing the Turbine Inlet Temperature and the preheating temperature, the TSFC and Specific Thrust of the engine can be optimized.

1. Introduction

Organic Rankine Cycle (ORC) is widely known for its capability to convert low grade heat into some form of energy that can be used. The ORC can effectively recover the low grade heat source due to its distinctive thermodynamic performance. The history of internal combustion engine exhaust waste heat recovery has been reviewed in [1], focusing on ORC since this thermodynamic cycle works well with the medium-grade energy of the exhaust. The primary focus of the review is the selection of the cycle expander and working fluid since they have been regarded as having the largest impact on the system performance. The results shows that a potential fuel economy improvement around 10% with modern refrigerants and advancements in expander technology.

To increase the efficiency of ORC, the most suitable working fluids are recommended. Tian *et al.* [2] has studied the fluids and parameters optimization for ORCs used in the exhaust heat recovery of the Internal Combustion Engine (ICE). From the study, it has been demonstrated that R141b, R123 and R245fa present the highest η_{th} and P_{net} values ranging from 16.6% to 13.3% (η_{th} value), and from 60 to 49 kJ/kg (P_{net} value). Meanwhile, the three fluids also correspond to the lowest E_{pc} values ranging from 0.30 to 0.35\$/kWh and lowest A/W_{net} values ranging from 0.436 to 0.516 m²/kW. The optimum evaporating pressures for R141b, R123, and R245fa are ranging from 2.8 MPa to 3.6 MPa. Zhu *et al.* [3] have performed a thermodynamic analysis in order to select appropriate working fluids and optimized parameters for medium-temperature geothermally-powered ORC. In this paper, R245fa is mixed with R601a at geothermal water temperature of 110°C. Based on the thermodynamic analysis, the results show that the zeotropic mixture R245fa/R601a (0.4/0.6) has the highest performance. When the



evaporating temperature reaches 67°C, the outlet temperature of geothermal water is 61°C, the net power output is the highest and the thermal efficiency is about 9%.

Parametric optimization is the main concern in ORC in order to achieve the higher efficiency of the cycle. Kai *et al.* [4] have conducted a parametric optimization of a low temperature ORC system. To conduct the optimization, net power output per unit mass of geothermal water is set to be the objective function in Genetic Algorithm. From the optimization, under the assumption condition that the optimal level constitution of system parameters is determined as the working fluid of R227ea, it demonstrates that the power output of the system of 596 kW and the corresponding power output per unit mass of geothermal water of 11.91 kJ/kg. The effect of pinch temperature in evaporator on the power output per unit mass is more seriously than that of superheating. It is about 7 times in terms of increasing 1K of R227ea. A thermo-economic multi-objective optimization of ORC for exhaust waste heat recovery of a diesel engine has been performed by Yang *et al.* [5]. The effects of the four key parameters that include evaporation pressure, superheat degree, condensation temperature and exhaust temperature at the outlet of the evaporator on the thermodynamic performance and economic indicators of the ORC system are investigated. Six different working fluids are used to conduct the optimization and R245fa has been considered as the most suitable working fluid for ORC waste heat application of the diesel engine with consideration of thermoeconomic performances, environmental impacts and safety levels. To determine the most suitable working fluid for power generation from a low temperature geothermal heat source, Caceres *et al.* [6] have performed the optimization of an ORC. For each working fluid, an optimal configuration is obtained by conducting the optimization of the second law efficiency. The result shows that propylene and R1234yf are the best working fluid with a critical temperature close to the maximum temperature of the cycle that gives the highest plant efficiencies. Yang *et al.* [7] have conducted the parametric optimization and performance analysis of the ORC system by using Genetic Algorithm to recover the exhaust waste heat of a diesel engine. Three key parameters: evaporation pressure, superheat degree and condensation temperature, are analysed to study their effects on the system performance with POPA (net power output per unit heat transfer area) and also EDR (exergy destruction rate) are set as objective functions. From the analysis, at engine maximum rated power point, the ORC system can achieve maximum POPA of 0.74 kW/m², and the ratio of maximum effective heat transfer area to the actual area of the evaporator is 69.19%.

This paper presents the thermodynamic analysis and performance optimization of an ORC as waste heat recovery system on an aircraft engine. The primary objective is to investigate the effect of the parameters design on engine performance, including Thrust Specific Fuel Consumption (TSFC) and Specific Thrust of the engine.

2. Thermodynamic model of an ORC system

An ORC consists of the same principle as ideal Rankine cycle with a different in the type of working fluid. ORC is a closed-loop system where the working fluid circulates through four main components: an evaporator, a pump, a turbine and a condenser. In this study, a regenerator is integrated to the ORC cycle to increase the thermal efficiency of the system. The ORC system is integrated in the middle of the low pressure turbine exit duct and core nozzle of an aircraft engine. Figure 1 shows the schematic diagram of a basic ORC system with regenerator integrated to a jet engine of an aircraft. ORC system is composed of an evaporator, a condenser, a turbine and a working fluid pump and a regenerator with a specific function to preheat the working fluid before entering the evaporator. This function is being considered in order to increase the thermal efficiency of the system. The system described in this study is integrated to the jet engine in the middle of the low pressure turbine exit duct and the core nozzle.

Figure 1 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, which is at station 1 in Figure 1, with a specific heat transfer from the exhaust jet engine and a specific evaporator outlet temperature. The inlet temperature of the working fluid flow to the evaporator is estimated by the formula described in the analysis section and the system is analyzed to obtain the parametric

optimization. Figure 2 shows the T-s diagram of the cycle involved in the system. The T-s diagram described is of the ORC system with regenerator integrated to a jet engine.

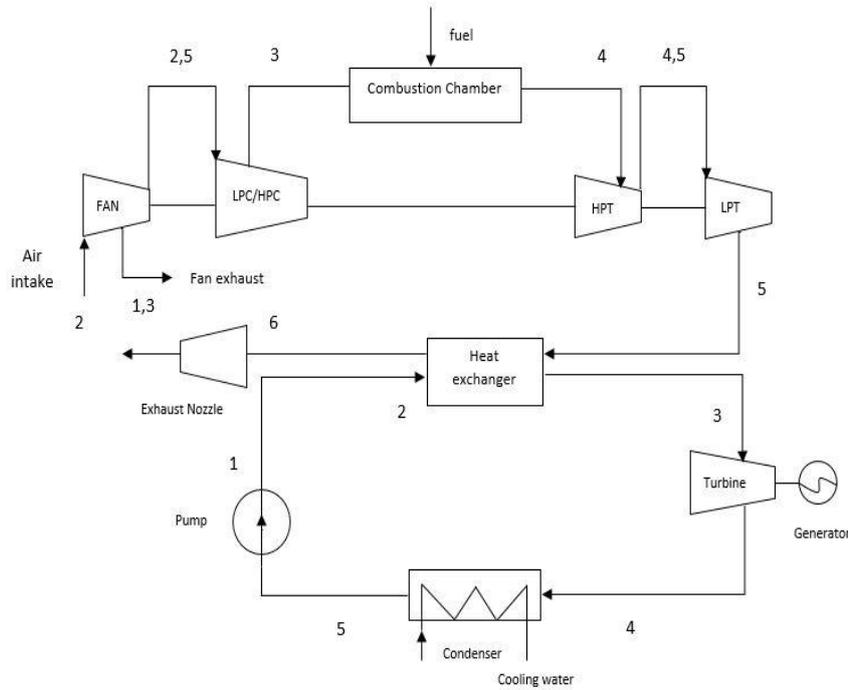


Figure 1. Schematic diagram of the Brayton-Rankine combined cycle

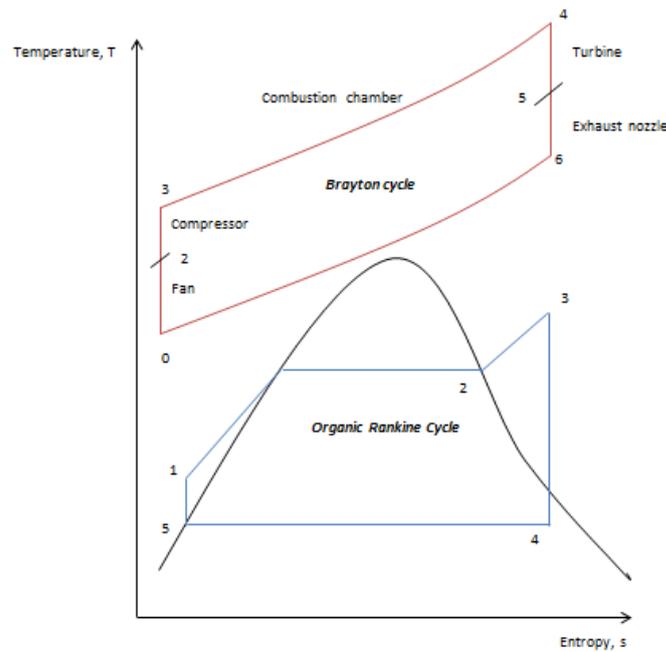


Figure 2. T-s diagram of the Brayton-Rankine combined cycle

The type of evaporator used in this study is the shell and tube heat exchanger, with one pass tube-side. Shell and tube heat exchanger consist of a series of tubes mounted inside a cylindrical shell. One set of these tubes contains the fluid that must be either heated or cooled. Then, the second fluid runs over the tubes that are being heated or cooled such that it can either provide the heat or absorb the heat required. From the counter flows, the heat is being exchanged between the two different fluids with different temperatures. In this study, several assumptions for the thermodynamic model are listed as follows:

1. The ORC system operates under steady state conditions.
2. There is no pressure drop in the pipes and the components.
3. The heat losses in each component are also neglected.
4. The isentropic efficiencies of the pump and the expander are 0.7 and 0.87 respectively.
5. The heat transfers to or from the surrounding environment are neglected.

Table 1. Main parameters of ORC system with R245fa as the working fluid for the turbofan engine

Description	Unit	Value
Mass flow rate of R245fa	kg/s	3.837
Exhaust heat temperature	K	720 – 1040
Turbine inlet pressure	Mpa	2.2
Turbine inlet temperature	K	392
Inlet temperature of R245fa	K	282
Outlet temperature of R245fa	K	393
Turbine efficiency	-	0.87
Pump efficiency	-	0.7
Estimated required surface area of evaporator	m ²	23.72

A parametric optimization of Turbine Inlet Temperature (TIT) and the preheating temperature of the working fluid is performed to obtain the minimum value of TSFC along the saturated vapor line in sub-critical region for R245fa working fluids. In this study, TSFC and Specific Thrust are evaluated as objective functions with TIT and preheating temperature of the working fluid are chosen as the main variables. The genetic algorithm optimization functions can be described as:

$$\text{Max (Specific Thrust)} = f(\text{TIT}, \text{preheating temperature})$$

$$\text{Min (TSFC)} = f(\text{TIT}, \text{preheating temperature})$$

Table 2: The lower and upper bounds of decision variables

Decision variable	Upper bound	Lower bound
Turbine inlet temperature (K)	350	450
Preheating temperature (K)	250	350

TIT can be defined as the temperature of the air gas mixture at the inlet of the gas turbine and it is one of the most critical parameters that influences the gas turbine performance. For a better gas turbine performance, it is desirable to have a higher turbine inlet temperature. Both the power output and the thermal efficiency can be improved by increasing the TIT.

3. Result and discussion

Figure 3 and 4 show the variation of TSFC and Specific Thrust of the engine. The range of TIT set for this system is between 350 K – 450 K whereas for the preheating temperature, it is set between 250 K – 350 K. It is obvious that, as the TIT and preheating temperature increases, the Specific Thrust of the engine increases linearly with decrease in TSFC. The optimization of TIT and preheating temperature provide a huge impact on the performance of the engine. Thus, by performing parametric optimization on the engine system, the performance of the engine can be improved.

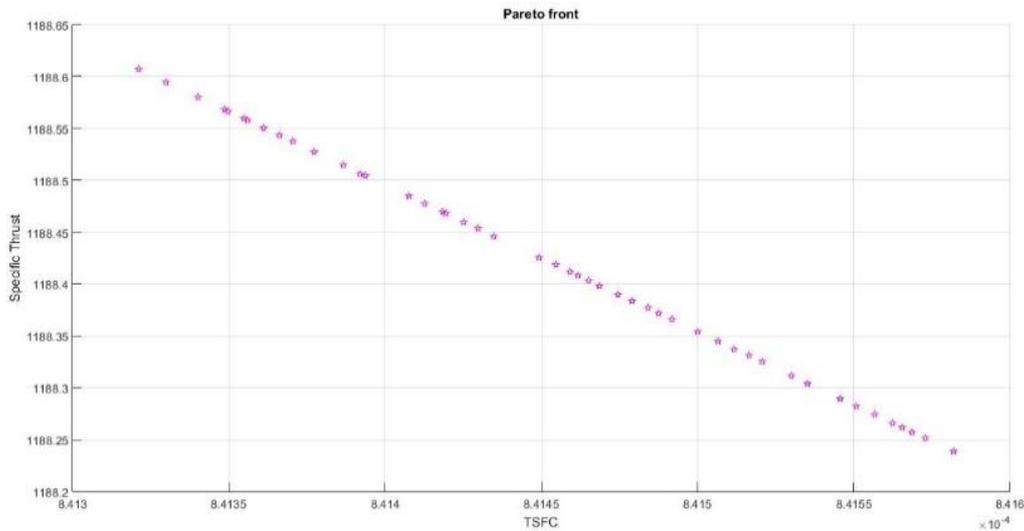


Figure 3. Optimization of TIT on the TSFC and Specific Thrust

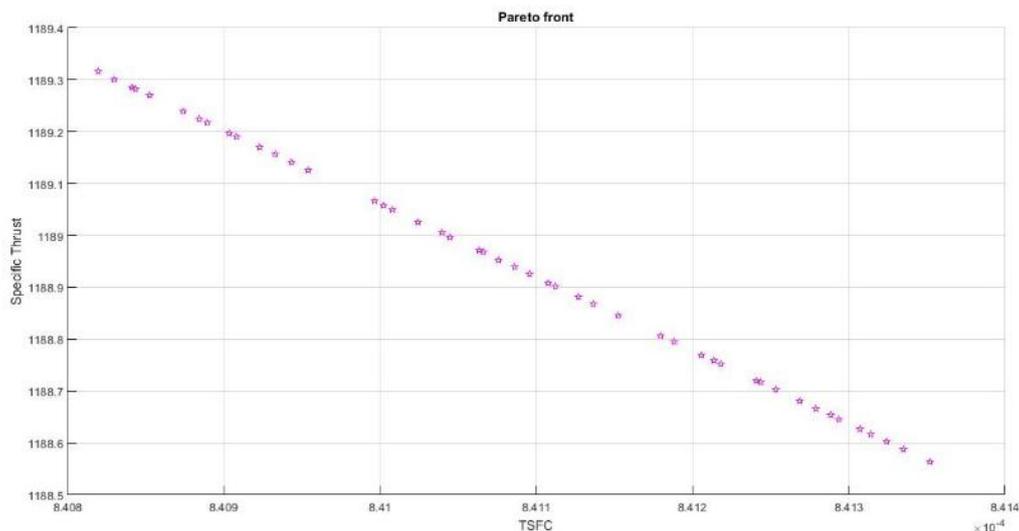


Figure 4. Optimization of preheating temperature on the TSFC and Specific Thrust

4. Conclusion

In this study, thermodynamic analysis and parametric optimization of the ORC Waste Heat Recovery for turbofan engine are conducted. Two-spool mixed flow turbofan engine is used in this study to investigate the beneficial of using ORC as waste heat recovery method in the engine. The working fluid

used in this study is R245fa. Based on the first and second law of thermodynamics, the turbine inlet temperature and preheating temperature of the working fluid are the parameters that can affect the performance of the system. By using Genetic Algorithm, parametric optimization can be conducted. The optimization of TIT and preheating temperature is performed and it shows that increases in TIT and preheating temperature of the working fluid will increase the net power output of the system. The presented research proves that ORC cycle for waste heat recovery provides potential advantages when integrated to an aircraft engine. It is significant that, by using ORC as heat recovery, the minimization of TSFC and maximization of specific thrust of a turbofan engine can be achieved.

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