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Research Article

Thermodynamic Analysis of The Organic Rankine Cycle For Diesel Engine Waste Heat Recovery

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Abstract

In this study, thermodynamic analysis of the organic Rankine cycle (ORC) for a diesel engine waste heat recovery was performed for different working fluids. R123, R245fa, R600a, R236ea and R134a are used as working fluid in the cycle. For temperature of the heat source in the exhaust of the diesel engine 80-180 ºC was chosen. The required thermodynamic values and calculations for the analysis were calculated by the Engineering Equation Solver (EES) program. For these working fluids, the performance values of the cycle were studied under different operating conditions. The highest efficiency values were obtained for all operating conditions analyzed in the organic Rankine cycle using R123 working fluid as %23. In addition, the turbine power is determined as 7.2 kW for the same operating conditions.

Keywords: Organic Rankine Cycle, Thermodynamic Analysis, Diesel Engine, Waste Heat Recovery.

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1. Introduction

Organic Rankine Cycle (ORC) is a highly efficient form of energy conversion and production that converts heat energy to electricity. In general, ORC converts the heat energy of the steam turbine into electrical energy through the electric generator connected to mechanical energy and then to the steam turbine. When water vapor is used as a fluid in conventional steam turbines, fluids with a molecular weight higher than water are preferred in ORC. Therefore, the turbine operates at lower speeds and the turbine parts operate at a lower pressure. This increases the life of the turbine. Higher energy efficiency is provided from the organic Rankine cycle using diesel engine waste heat recovery. Although a thermal loss of about 2% occurs during the energy conversion in the cycle, 72% -78% of the thermal power can be converted into mechanical energy in the turbine. The remaining 20%-25% is converted into electrical energy in the generator. For this reason, ORC is an effective electricity production method. ORC can be used in all systems with continuous waste heat release and is especially preferred for high efficiency at low temperatures [1].

Peris et al. have designed and built of ORC for tested. Their purpose is to determine system performance and system operating ranges. Their results show that the thermal power of ORC, produce electricity and useful heat increase with the rise of the thermal oil temperature and larger pressure ratios [2]. Zahra et al. have modeled and optimized an ORC for diesel engine waste heat recovery. R123, R134a, R245fa and R22 are selected as working fluids in their study. Results of their study show that the optimum working fluid is R123 in both of economical and thermo dynamical for of output power. They were showed that R123 has the highest investment cost but the environmental and fuel costs are the lowest [3]. Kolsch et al. have were investigated performance of methanol, toluene and SES36 in ORC. Results of their study show that methanol have the highest thermal performance, but also need the largest heat transfer area. Toluene has the lowest thermal efficiency for this study [4].

In the present study, the thermodynamic analysis of the organic Rankine cycle for the exhaust waste heat of a diesel engine as the heat source for five different working fluids was carried out. The exhaust gas outlet temperature is approximately 80-100 °C lower than the inlet temperature in diesel engines. This is because the exhaust gas temperature at the end of the combustion is equal to or above the dew point temperature. For this reason, approximately 80-100 ºC of heat is discharged from the exhaust of the diesel engine. Table 1 shows the characteristics of the diesel engine selected for this study.

Table 1. Characteristics of diesel engine

Electric power of diesel engine	235.8 kW
Exhaust gas flow rate	0.275 kg s^{-1}
Specific heat	1.063 kj kgK^{-1}
Exhaust gas temperature	519 ºC

The schematic diagram of the ORC are shown in Figure 1. In this study R123, R245fa, R600a, R236ea and R134a working fluids were selected. Thermo-physical properties of working fluids are given in Table 2.

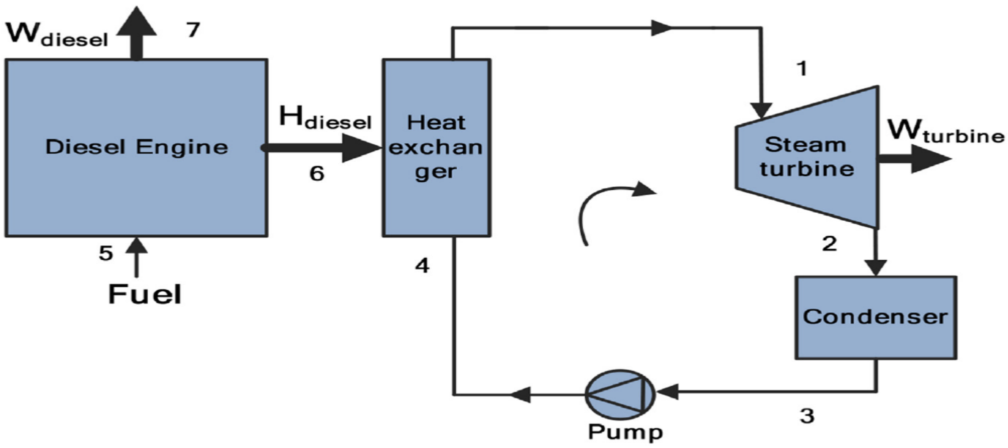

Figure 1. Schematic diagram of the diesel engine - ORC combined system

Table 2. Thermo-physical properties of working fluids

Fluid	Molecular weight (kg kmol^{-1})	Critical temperature (K)	Critical pressure (MPa)
R245fa	134.04	427	3.65
R123	152.9	183.7	36.6
R600a	58.1	407.8	3.64
R236ea	152	412.44	3.5
R134a	102	101.1	40.6

2. Material and Method

All of the machines (pump, turbine, boiler and condenser) constituting the steam power plant of continuous flow machine. Therefore, ORC consists of four continuous flow open systems. For this reason, the equation of the conservation of energy in the open flow system is written as follows [5-6];

$$q - w = h_{out} - h_{in} \tag{1}$$

The boiler and condenser do not work. When state change of pump and turbine were changed as isentropic, the equation of energy conservation for each element of the cycle can be expressed as follows;
Pump,

$$w_{p,in} = h_4 - h_3 \tag{2}$$

Boiler,

$$q_{in} = h_1 - h_4 \tag{3}$$

Türbine,

$$w_{t,out} = h_2 - h_1 \tag{4}$$

Condenser,

$$q_{out} = h_3 - h_2 \tag{5}$$

The thermal efficiency of ORC is calculated from the following correlation [7-10];

$$\eta_{ORC} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \tag{6}$$

$$w_{net} = q_{in} - q_{out} = w_{t,out} - w_{p,in} \tag{7}$$

The thermodynamic values and calculations used in the analyzes were performed with EES program. Newton Rapson and Jacobi methods are used in the calculations.

3. Results and Discussion

Efficiency of ORC was calculated and are given in in Figure 2 for different condenser temperatures (Ty = 25-30-35 oC), R123, R245fa, R600a, R236ea and R134a organic working fluids and different evaporator temperatures. It is seen that the efficiency values also increase when the evaporator temperature in ORC increases. In Figure 2, it is seen that the highest efficiency value is 23.5% under operating conditions with working fluid R123, evaporator temperature Tb=182oC and condenser temperature Ty=25oC. In cycle, the lowest efficiency value is for refrigerant R134a.

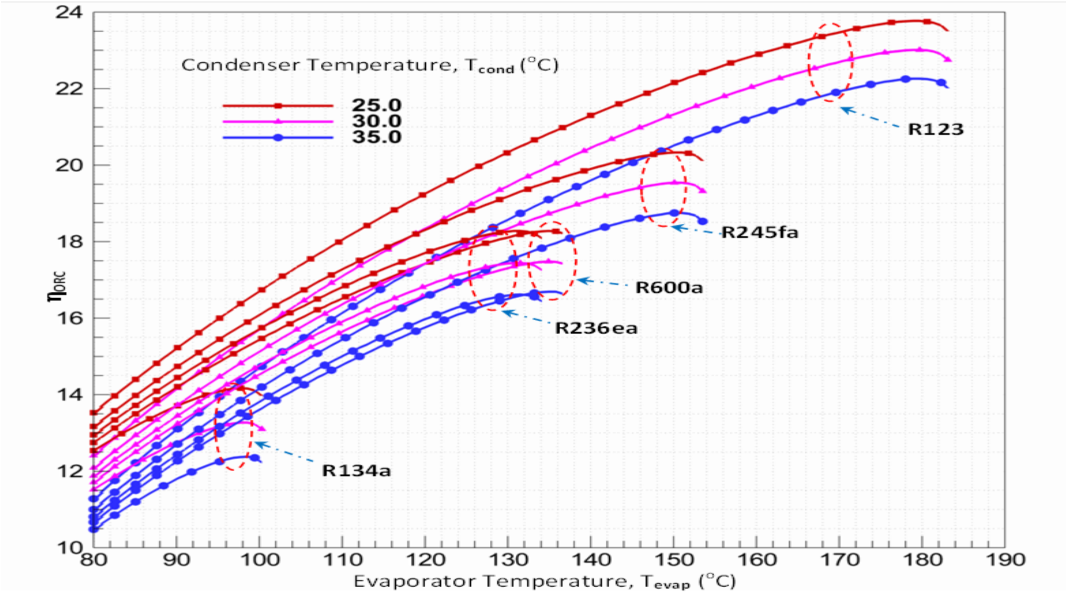

Figure 2. Variation of the efficiency value with condenser and evaporator temperature for different organic working fluids

Turbine power in organic Rankine cycle was determined to depend on evaporator temperature, condenser temperature and fluid flow rate and was given in Figure 3. it is seen that turbine power in organic Rankine cycle higher for low fluid flow and condenser temperatures. It is seen that the highest turbine power value is 7.2 kW in operating conditions where the working fluid R123, condenser temperature is 25 oC and the fluid flow rate is 128 g/s. The lowest turbine power was found to 3.1 kW in the cycle for refrigerant R236ea.

Efficiency of cycle was determined to depend on evaporator pressure and condenser temperature for R123, R245fa, R600a, R236ea ve R134a and was given Figure 4. Low condenser temperature and high evaporator pressure increases the efficiency in organic rankine cycle. In Figure 4, it is seen that the highest efficiency in ORC for R123 working fluid. In cycle, the lowest efficiency value was found to 10.5% for refrigerant R134a.

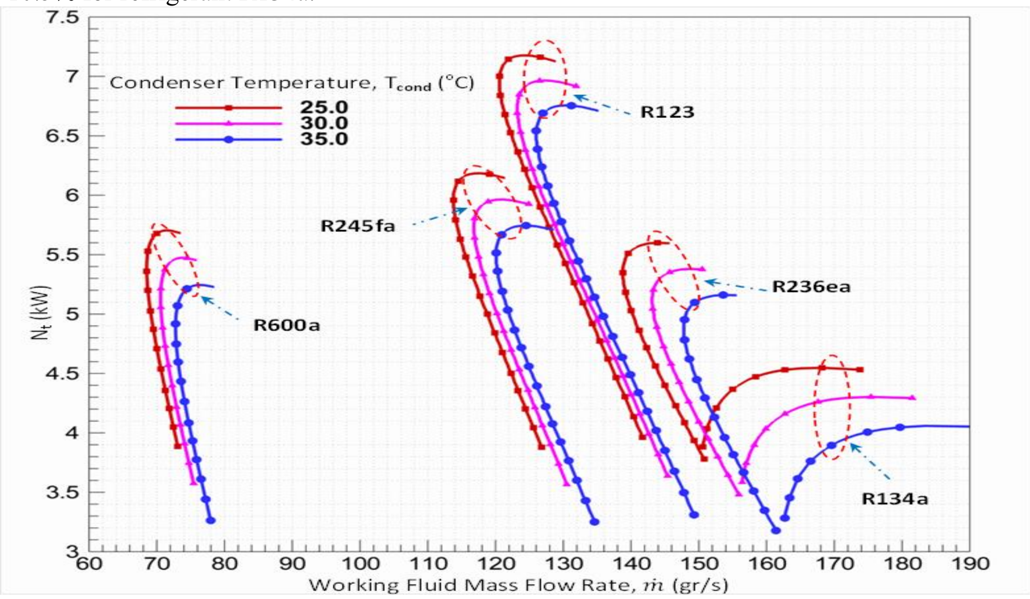

Figure 3. Variation of the turbine power with mass flow rate for different organic working fluids

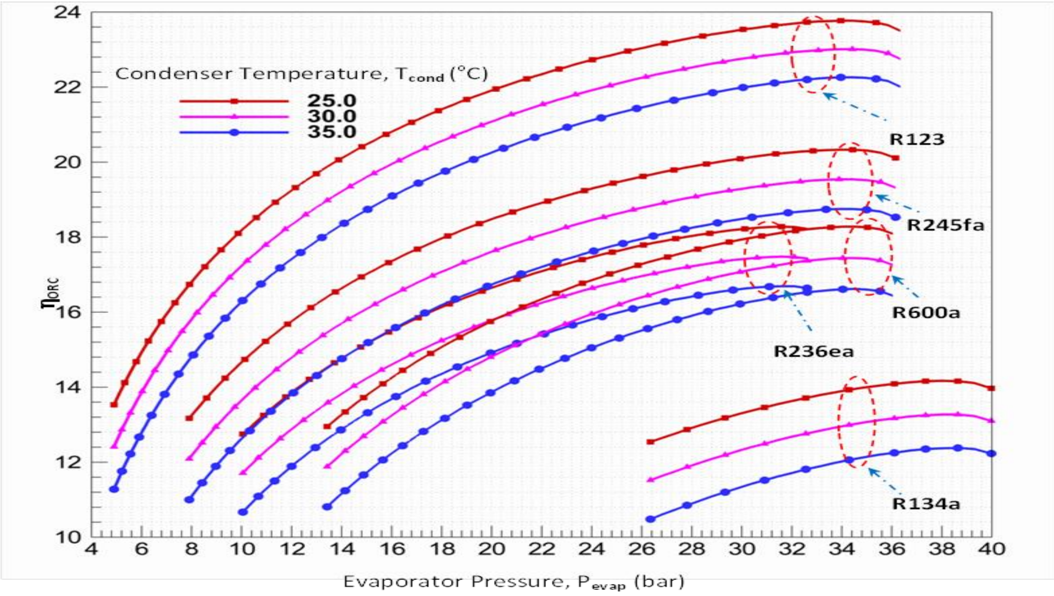

Figure 4. Variation of the efficiency values with evaporator pressure for different organic working fluids

When the relationship between evaporator temperature and turbine power in ORC is examined, increasing the evaporator temperature causes to increase turbine power. In Figure 5, it was seen that the highest turbine power is 7.2 kW under operating conditions where the evaporator temperature is 185 oC, working fluid R123 and condenser temperature is 25 oC. In the cycle, the lowest turbine power was found to 3.1 kW for refrigerant R134a.

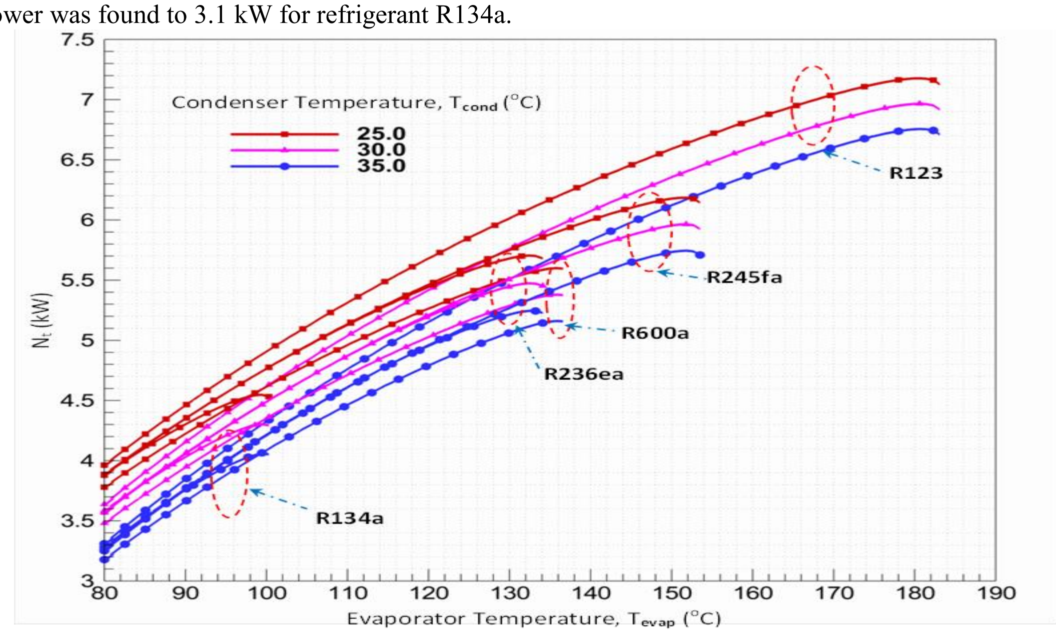

Figure 5. Variation of the turbine power with evaporator temperature for different organic working fluids

4. Conclusions

In this study, thermodynamic analysis of the organic Rankine cycle (ORC) for a diesel engine waste heat recovery was performed for different working fluids. R123, R245fa, R600a, R236ea and R134a are used as working fluid in the cycle. For temperature of the heat source in the exhaust of the diesel engine 80-180 oC was chosen. The required thermodynamic values and calculations for the analysis were calculated by the Engineering Equation Solver (EES) program.

According to the results obtained from the analysis; the highest efficiency of the organic Rankine cycle is 23.5% for the working conditions analyzed. Based on this, it can be concluded that the optimum working fluid is R123 in organic Rankine cycle for this analysis of work. In addition, low condenser temperature and high evaporator temperature in organic Rankine cycles increase the efficiency of ORC.

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