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Investigation of Different Working Fluid Effects on Exergy Analysis for Organic Rankine Cycle (ORC)

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Abstract

In this study, energy and exergy analyses are performed for an Organic Rankine Cycle in a local power plant that is located southern of Turkey. The Organic Rankine Cycle was used for low temperature heat source as heat recovery process with various organic working fluids. The examined system consists of an evaporator, a turbine, a condenser, a pump and a generator as components. The evaluation is carried out using two different working fluids for each component of the system. The main purpose of this study is to model the ORC cycle for performance optimization in terms of the usage of two different working fluids with relevant temperature ranges. HFE7100 and FC72 working fluids are selected as performance parameters in order to show the effect of the working fluids on the system performance of the Organic Rankine Cycle.

Keywords: Organic rankine cycle, Exergy, Thermodynamic analysis, Heat recovery

Organik Rankine Çevriminde Farklı Soğutucu Akışkanların Ekserji Analizi Üzerine Etkisinin İncelenmesi

Özet

Bu çalışmada, Türkiye'nin güneyinde bulunan bir yerel güç santralindeki Organik Rankine Çevrimi için ekserji analizi yapılmıştır. Organik Rankine Çevrimi, düşük sıcaklıktaki ısı kaynağı için farklı organik soğutucu akışkanlar ile ısı geri kazanım işlemi olarak kullanılır. İncelenen sistem evaporatör, türbin, kondenser, pompa ve jeneratör bölümlerinden oluşmaktadır. Değerlendirme, her sistem bileşenine iki farklı soğutucu akışkan için yapılmıştır. Bu çalışmanın temel amacı, Organik Rankine Çevriminin performans optimizasyonunu sağlamak üzere iki farklı soğutucu akışkanın ilgili sıcaklık aralıklarında kullanılarak modellenmesidir. Soğutucu akışkanların Organik Rankine Çevriminin performansı üzerine etkisini göstermek amacıyla HFE7100 ve FC72 akışkanları performans parametresi olarak seçilmiştir.

Anahtar Kelimeler: Organik rankine çevrimi, Ekserji, Termodinamik analiz, Isı geri kazanım

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1. INTRODUCTION

Energy and energy production systems have being the major topic of the thermodynamics in recent years. The waste heat recovery is the most suitable source for the energy conversion due to lack of the fossil fuels and global warming. Waste heat recovery process provides the energy conservation and decrement of the thermal pollution. Although the steam turbine is the most common technology in the energy production process, due to necessity of high operational temperature and pressure, it is not suitable for low temperature and pressure condition. Organic Rankine Cycle is generally preferred for the processes having low temperature like $T<150^oC$.

There are a lot of studies about Organic Rankine cycle for power generation from waste heat recovery [1-4, 7-14]. Ozdil et al. [1] examined a thermodynamic analysis of an ORC in a local power plant using industrial data for four different water phases in the evaporator inlet. The relationship between pinch point and exergy efficiency was also observed in their study. Furthermore, exergy destruction and exergy efficiencies of components and overall system were separately calculated. The exergy efficiency of the ORC was calculated as 47,22%, 41,04%, 40,29%, 39,95% for saturated liquid form, water mixture form which has quality 0,3, water mixture form which has quality 0,7 and saturated vapor form, respectively. In addition, exergy destruction rate of the system was 520,01 kW for the system. Gomez et al. [3] implemented energy and exergy analyses for the power plant. They modelled and simulated a system using EES (Engineering Equation Solver) to present the effects of key parameters on the efficiency. The effects of the temperature, pressure and compression ratio on the power plant were observed in their study. They concluded that lower compression pressure ratio (r) caused high thermal efficiency due to the more effective regeneration process. Moreover, decrement of the helium temperature at the compressor inlet caused sharp drop in the compression work due to the decrement of the specific volume. There are several studies regarding to the working fluids which are used in ORC in literature [5-15]. As understood from these studies, the working fluid used in the ORC cycle has important effect on the performance of the power generation systems. Roy et al. [5] investigated the effect of different working fluids on the efficiency and irreversibility rate on the system. They demonstrated that R-123 working fluid used in ORC system, had positive impact on efficiency in turbine. Moreover, R-123 working fluid was observed as the best working fluid among the other working fluid options in their study

In this study, a detailed thermodynamic analysis was carried out for an Organic Rankine Cycle using two different working fluids. Using two different working fluids (HFE7100 and FC72), the system was modeled and the results were compared in order to obtain the best option between the working fluids. Based on the first and second law of thermodynamics, the energy and exergy analyses were performed for each component of the ORC system. Furthermore, the energy and exergy efficiencies, exergy destruction rate on the components were observed.

2. SYSTEM DESCRIPTION

The investigated system has 249,9 kW net capacity and specifications of the system components are demonstrated in Table 1.

Table 1. Specifications of the system components

Components	Model/ Type	Capacity	Operating Pressure
Evaporator	Shell and tube	3161 kW (Max)	23,78 bar (max)
Condenser	Shell and tube	2885 kW (Max)	23,78 bar (max)
Turbine	CARRIER	272 kW (Max)	23,78 bar (max)
Pump	Grundfos/ KB-G-A-	72,82 m^3/h – 50 kW motor	9,307 bar (max)

The system involves an evaporator, a condenser, a turbine and a pump as subsystems. The generator, heating and cooling water collectors are accepted as the auxiliary components. The Organic Rankine

Cycle produces electricity using waste heat in low temperature in order to reduce the operating costs of company. The working fluids used in the ORC cycle are HFE7100 and FC72 which have good thermodynamic properties such as low specific heat and viscosity, low toxicity, low ozone depletion potential, low flammability. The thermophysical properties of the two working fluids can be seen in Table 2. The schematic diagram of the ORC system is illustrated in Fig. 1. In the system, working fluid is pumped, firstly. Namely, low pressure fluid is compressed to high pressure fluid by a pump as can be seen in Fig. 1. (state 5 to 6). Then high pressure fluid enters and passes through the evaporator. In the evaporator, high pressure fluid (6) has become heated and pressurized vapor (3) using the heat capacity of inlet water (state 1 to 2). After that the heated and pressurized vapor enters in turbine. And it leaves from turbine as low pressure vapor and generates electricity (state 3 to 4). Lastly, the low pressure vapor goes through the condenser, and the working fluid leaves from condenser as saturated liquid (state 4 to 5) and the cycle continues. For the analyses, some of data are measured on system and remaining data are read the computer aided control panel, directly. Dead state conditions of the working fluids and the water are accepted as 1 bar and 25^{o}C. Mass flow rate of the condenser cooling water is measured by GE-PT878 which is ultrasonic flowmeter equipment ranges from ½”-7,6mm with ± 1% accuracy. Pressure and temperature measurement devices are put on collectors in order to measure the properties of water and the working fluid.

Table 2. Thermophysical properties of working fluids

	HFE7100	FC72
Operating Temp.	Low	Low
Boiling Point (^{o}C)	61	56
Vapor Pressure (Pa)	26800	30900
Density (kg/m^3)	1650	1680
Kinematic Viscosity(cSt)	0.38	0.38
Specific Heat (Jkg^{-1}C^{o-1})	1180	1100

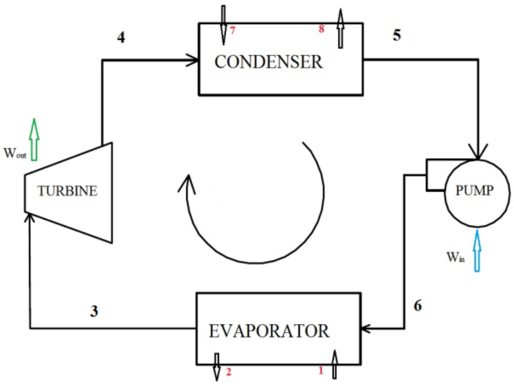

Figure 1. Schematic representation of ORC system

3. ANALYSIS

The first law of thermodynamics is explained as the conservation of energy, thermodynamically. While the second law of thermodynamics is described as the quality of energy, thermodynamically. The second law refers the change of the energy quality during the phase change in the processes. The mass flow rate of the cooling water through the condenser is measured as 13 kg/s. Mass flow rate of the working fluid is calculated as 10,61 kg/s and evaporator heating water is estimated as 13,48 kg/s with the help of energy balance equation based on first law of thermodynamics.

In order to obtain the performance of the different working fluids on the effectiveness of the Organic Rankine cycle, two working fluids are selected as HFE7100 and FC72 in terms of similar environmental conditions and thermophysical properties. The following assumptions are made in this study; pressure drops, potential and kinetic energy changes are neglected on the system. The system operates in a continuous steady state flow process. The system is adiabatic which means there is no heat loss.

General definitions and equations are given as below.

General mass balance;

Total Mass Inlet = Total Mass Outlet

$(\rightarrow \Sigma\dot{m}_{in} = \Sigma\dot{m}_{out})$ (1)

General energy and exergy balance;

Total Energy Initial = Total Energy Final (→$\dot{Q} + \dot{W} = \Sigma\, \dot{m}_f h_f - \Sigma\, \dot{m}_{in} h_{in}$) (2)

Exergy transfer by heat at the temperature T_s is defined by Eq. (3)

→$\dot{E}x_{heat} = \dot{Q}(1 - T_0/T_s)$ (3)

Total Exergy Initial = Total Exergy Final + Total Exergy Consumed + Total Exergy Destruction (→$\dot{E}x_i = \dot{E}x_f + \dot{E}x_{cons} + \dot{E}x_{D,total}$) (4)

→$\dot{E}x = \dot{m}\, ex$ (5)

where the "$\dot{E}x$" is exergy rate.

→$ex = h - h_0 - T_0(s - s_0)$ (6)

When we applied the first and second law of thermodynamic on the system we obtain the results for each component and entire cycle, as described below.

Energy and exergy balance of evaporator

Energy and exergy balance equations through the evaporator can be written as Eq. (7) – (8)

→ $\dot{m}_1 h_1 + \dot{m}_6 h_6 = \dot{m}_2 h_2 + \dot{m}_3 h_3$ (7)

→ $\dot{m}_1 ex_1 + \dot{m}_6 ex_6 = \dot{m}_2 ex_2 + \dot{m}_3 ex_3 + \dot{E}x_{D,evp}$ (8)

$\dot{m}_1$ and $\dot{m}_2$ are the mass flow rate of the heating water of the evaporator and $\dot{m}_3$ and $\dot{m}_6$ are the mass flow rate of the working fluids.

The exergy efficiency of evaporator is given by Eq. (9)

→ $\eta_{2,evp} = \dot{m}_3(ex_3 - ex_6)/m_1(ex_1 - ex_2)$ (9)

Energy and exergy balance of Turbine

Energy and exergy balance equations through the turbine which is assumed as adiabatic, can be written as Eq. (10) – (11)

→ $\dot{m}_3 h_3 = \dot{m}_4 h_4 + \dot{W}_{turb}$ (10)

→ $\dot{m}_3 ex_3 = \dot{m}_4 ex_4 + \dot{W}_{turb} + \dot{E}x_{D,turb}$ (11)

$\dot{m}_3$ and $\dot{m}_4$ are the mass flow rate of the working fluids.

The exergy efficiency equation of turbine is given by Eq. (12)

→ $\eta_{2,turb} = \dot{W}_{turb}/(\dot{E}x_3 - \dot{E}x_4)$ (12)

Energy and exergy balance of Condenser

Energy and exergy balance equations through the condenser can be calculated with the help of Eq. (13) – (14)

→ $\dot{m}_4 h_4 + \dot{m}_7 h_7 = \dot{m}_5 h_5 + \dot{m}_8 h_8$ (13)

→ $\dot{m}_4 ex_4 + \dot{m}_7 ex_7 = \dot{m}_5 ex_5 + \dot{m}_8 ex_8 + \dot{E}x_{D,cond}$(14)

$\dot{m}_7$ and $\dot{m}_8$ are the mass flow rate of the cooling water of the condenser and $\dot{m}_4$ and $\dot{m}_5$ are the mass flow rate of the working fluids.

The exergy efficiency eqn. of condenser is calculated by Eq. (15)

→ $\eta_{2,cond} = \dot{m}_7(ex_8 - ex_7)/\ \dot{m}_4(ex_4 - ex_5)$ (15)

Energy and exergy balance of Pump;

Energy and exergy balance equations through the pump which is assumed as adiabatic, can be written as Eq. (16) - (17)

→ $\dot{m}_5 h_5 + \dot{W}_{pump} = \dot{m}_6 h_6$ (16)

→ $\dot{m}_5 ex_5 + \dot{W}_{pump} = \dot{m}_6 ex_6 + \dot{E}x_{D,pump}$ (17)

The exergy efficiency eqn. of pump is calculated by Eq. (18)

→ $\eta_{2,pump} = (\dot{E}x_6 - \dot{E}x_5)/\ \dot{W}_{pump}$ (18)

Overall exergy destruction is occurred in the cycle, the overall exergy rate of the system is defined by Eq. (19)

→ $\dot{E}x_{cyc,in} = \dot{E}x_{evp} + \dot{E}x_{turb} + \dot{E}x_{cond} + \dot{E}x_{pump} + \dot{E}x_{cond,rej} + \dot{W}_{turb}$ (19)

The exergy destruction rate based on heat rejection on the condenser using cooling water is calculated by Eq. (20)

→ $\dot{E}x_{cond,rej}= \dot{E}x_{cyc,in} - \dot{E}x_{evp} - \dot{E}x_{turb} - \dot{E}x_{cond} - \dot{E}x_{pump} - \dot{W}_{turb}$ (20)

The $\dot{E}x_{cond,rej,}$is called as outgoing exergy rate through the ambient.

The overall exergy efficiency is defined by Eq. (21)

→ $\eta_{2,cyc}= \dot{W}_{net}/\dot{E}x_{cyc,in}$ (21)

The exergy rate of cycle is defined by Eq. (22)

→ $\dot{E}x_{cyc,in}= m_{w,evp}(h_1-h_2)-T_0(s_1-s_2)$ (22)

The overall cycle efficiency is the ratio of the net turbine power to the net heat transfer rate as Eq. (23)

→ $\eta_{1,cyc}= \dot{W}_{net}/\dot{Q}_{cyc,in}$ (23)

$\dot{Q}_{cyc,in}$ which is the heat input on the evaporator, can be defined as Eq. (24);

→$\dot{Q}_{cyc,in}= m_{w,evp}(h_1-h_2)$ (24)

The thermophysical properties of the system for two different working fluids are shown in Table 3 - 4.

Table 3. The thermophysical properties of the system using HFE7100 as working fluids

State no	Fluid Type	Mass flow rate (kg/s)	Temperature (K)	Pressure (bar)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Exergy Rate (kW)
0	Water	----	298	1	104,9	0,367	----
0	HFE7100	----	298	1	52,98	0,193	----
1	Water	13,48	400	2,7	533,6	1,603	814,80
2	Water	13,48	356,9	2,2	350,8	1,119	294,79
3	HFE7100	10,61	390	11,4	161,1	0,507	156,88
4	HFE7100	10,61	326	2,4	85,04	0,296	16,39
5	HFE7100	10,61	303	2,4	58,73	0,212	1,57
6	HFE7100	10,61	303,17	11,4	59,54	0,213	8,26
7	Water	13	300,5	1,37	115,1	0,402	-1,44
8	Water	13	305,4	1,37	135,2	0,467	5,72

Table 4. The thermophysical properties of the system using FC72 as working fluids

State no	Fluid Type	Mass flow rate (kg/s)	Temperature (K)	Pressure (bar)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Exergy Rate (kW)
0	Water	----	298	1	104,9	0,367	----
0	FC72	----	298	1	69,92	0,261	----
1	Water	13,48	400	2,7	533,6	1,603	814,80
2	Water	13,48	356,9	2,2	350,8	1,119	294,79
3	FC72	10,61	392	11,4	174,2	0,564	147,44
4	FC72	10,61	326	2,4	102,9	0,366	16,03
5	FC72	10,61	303	2,4	75,97	0,281	1,27
6	FC72	10,61	303,17	11,4	76,7	0,281	7,12
7	Water	13	300,5	1,37	115,1	0,402	-1,44
8	Water	13	305,4	1,37	135,2	0,467	5,72

4. RESULTS and DISCUSSIONS

In this study, the thermodynamic analysis is applied based on the first and second law of thermodynamics to calculate exergy destructions and exergy efficiency of the system in an Organic Rankine Cycle based power plant. Two working fluids are selected as HFE7100 and FC72, in order to show the effect of the different working fluids on the system performance. The exergy destructions and exergy efficiencies are calculated using the values shown in Table 3-4 as can be seen in Table 5-6 for both working fluids.

The system produces 2464,70 kW heat from heat source and generates 130 kW gross power. Pump consumes 20 kW power in order to circulate the working fluid in the system and the net power is found as 110 kW. The exergy destruction rates and exergy efficiencies of the both system can be seen in Table 5-6. The exergy efficiencies of the system using HFE7100 and FC72 are both calculated as 21,15% while exergy destructions of the cycle using HFE7100 and FC72 are calculated as 402,82 kW and 402,85 kW, respectively. The highest exergy destructions, which are 371,39 kW and 379,69 kW for HFE7100 and FC72 respectively, occur in the evaporator among the components for the both systems. In the evaporator, the system using FC72 working fluid has higher exergy destruction than that of the system using HFE7100. On the other hand, exergy destruction of the turbine in the system using HFE7100 has higher exergy destruction than that of the system using FC72 as 10,49kW and 1,41kW, respectively. Moreover, the exergy efficiencies of evaporator, turbine, condenser, and pump for the system using HFE7100 as working fluid are calculated as 28,58%, 92,53%, 48,34%, and 33,48%, respectively. The exergy destruction rates of the components and exergy efficiencies of the components and cycle for HFE7100 are illustrated in Figure 2-3. The exergy efficiencies of evaporator, turbine, condenser and pump for the system using FC72 as working fluid are calculated as 26,98%, 98,93%, 48,54%, and 29,24%, respectively. Figure 4-5 show exergy destruction rates of the components and efficiencies for each component and the entire cycle for FC72.

Table 5. The exergy destructions and exergy efficiencies of the main components in ORC power plant using HFE7100 as working fluids

Components	$\dot{E}x_D$ (kW)	η_{II} (%)
Evaporator	371,39	28,58
Turbine	10,49	92,53
Condenser	7,66	48,34
Pump	13,30	33,48
Cycle	402,84	21,15

Table 6. The exergy destructions and exergy efficiencies of the main components in ORC power plant using FC72 as working fluids

Components	$\dot{E}x_D$ (kW)	η_{II} (%)
Evaporator	379,69	26,98
Turbine	1,41	98,93
Condenser	7,60	48,54
Pump	14,15	29,24
Cycle	402,85	21,15

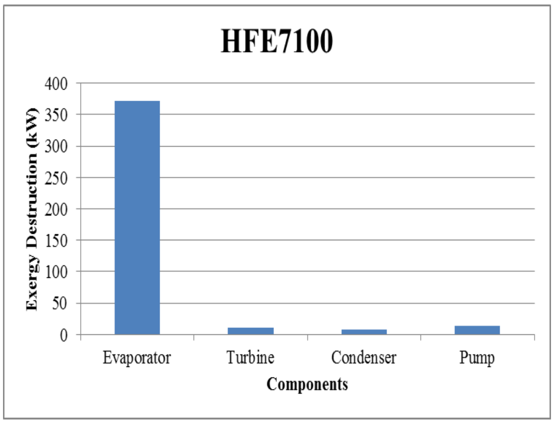

Figure 2. Exergy destructions for each component of the system using HFE7100 as working fluid

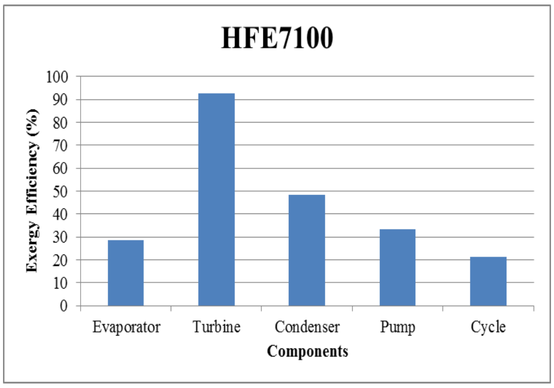

Figure 3. Exergy efficiencies for each component and entire cycle using HFE7100 as working fluid

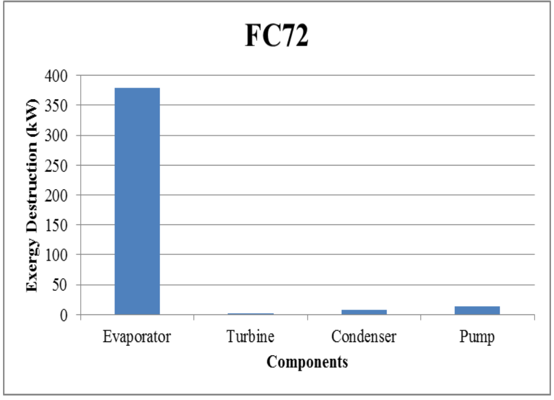

Figure 4. Exergy destructions for each component of the system using FC72 as working fluid

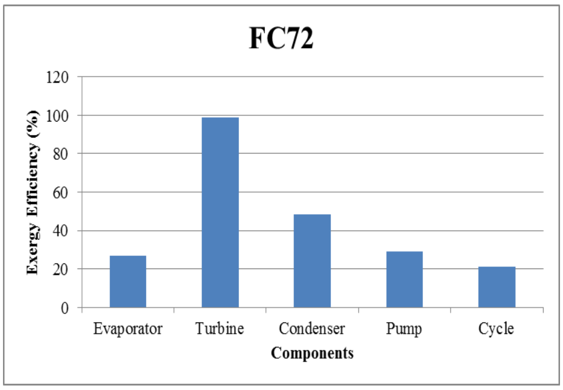

Figure 5. Exergy efficiencies for each component and entire cycle using FC72 as working fluid

NOTATIONS

ex	specific exergy (kJ/kg)
$\dot{E}x_D$	Exergy Destruction (Kw)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (bar)
$\dot{Q}$	rate of heat transfer (kW)
s	specific entropy (kJ/kg K)
S_{gen}	entropy generation
T	temperature (K)
$\dot{W}$	rate of work (kW)
Subscripts	
Cond.	Condenser
Cons.	Consumed
Cyc.	Cycle
Dest.	Destruction
Evp.	Evaporator
rej	rejection
Sat.	Saturation
Turb.	Turbine
0	reference state
Greek symbols	
Δh	enthalpy difference
Δs	entropy difference
ΔT	temperature difference
ηI	first law efficiency
ηII	second law efficiency

5. CONCLUSIONS

This study presents a detailed energy and exergy analysis of an ORC cycle in steel industry. Two different working fluids are selected as HFE7100 and FC72 in order to show the performance of the Organic Rankine Cycle under different working fluids condition. The main idea of this study is maximization of the system efficiency with the choosing of suitable working fluid for ORC in the range of operational temperatures. It is hard to figure out the best fluid, which has high latent heat, high density and low liquid specific heat, super-atmospheric saturation pressure, high cycle efficiency, low vapor specific volume at turbine outlet, low toxicity, low environmental impact, and has non-combustion characteristics. In this study, the best choices for the all aspects are considered as HFE7100 and FC72.

Mass, energy and exergy balance equations are solved using the first and second laws of thermodynamics. The major exergy destruction occurs in the evaporator for both systems with 371,39 kW for HFE7100 and 379,69 kW for FC72. In the system using HFE7100 as working fluid, the exergy destruction rates ordered from high to low as evaporator, pump, turbine and condenser, respectively. However, in the system using FC72 as working fluid, the exergy destruction rates ordered from high to low as evaporator, pump, condenser and turbine, respectively. For the both systems, the main reason of the high inefficiency occurred in the evaporator is high heat input. The major difference between the two working fluid usage is the decrement of the exergy rate in the turbine. The decrement of the exergy rate causes the increment of the exergy efficiency of the system. Otherwise, the exergy efficiencies of the ORC systems are almost same as 21,15%. As understood from the results obtained in this study, in order to reduce the exergy destruction of the turbine, FC72 is better option as working fluid.

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