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Original Research Article

Energy and exergy analysis of an organic Rankine cycle under different heat source and turbine inlet temperature conditions

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ABSTRACT

In this study, the effect of turbine inlet temperature change on organic fluid performance in three different Organic Rankine Cycle (ORC) models designed using R113, R123 and isopentane fluid was determined. With the MATLAB and EES program, 17 different models have been formed for the heat source temperature that changes with the turbine inlet temperature. By analyzing the determined organic fluids on the generated models, the amount of heat entering the system, the work produced by the turbine, thermal efficiency, total exergy destruction and exergy efficiency were determined. While turbine inlet temperature is 80^{o}C and heat source temperature is 110^{o}C, isopentane fluid can reach maximum 8.8% while R113 fluid has reached 12.4% in same design conditions. With all cases examined, it is stated that isopentane fluid needs more heat input per unit mass compared to other fluids. While the maximum value of 531.7 kJ/kg heat input is required for isopentane fluid, R113 and R123 fluids require a maximum of 220.2 kJ/kg and 246.8 kJ/kg respectively. When the work values obtained from the turbine are examined, it is stated that R113 and R123 fluids show close properties. In this study, a maximum of 21.63 kJ/kg and 26.98 kJ / kg turbines were obtained for R113 and R123, while a 45.35 kJ/kg turbine work was obtained in the model using isopentane fluid. In exergy analysis, it was found that the best exergy efficiency performance was obtained in R113 fluid with 56.3%. In addition, the effect of overheating the organic fluid on the energy and exergy efficiency of the system was determined by the constant acceptance of the turbine inlet pressure.

Keywords: Organic Rankine Cycle (ORC), Engineering Equation Solver (EES), Energy, Exergy, Dry Fluids

1. Introduction

Traditionally, taking advantage of low temperature heat has several difficulties, since it is technically difficult and uneconomical. The traditional technology used in heat-power generation is a steam turbine, but it requires high temperature and pressure for proper operation. The preferred technology at low temperatures (<150°C) is Organic Rankin Cycle (ORC). Instead of water and high pressure steam, it is named as organic fluid is used. In ORC technology, it uses high molecular weight liquids that boil at a lower temperature than water. This feature allows the Rankine Cycle to obtain heat from traditionally very low heat sources for economic power generation [1].

When the literature is examined it is seen that there are different studies about ORC performance. Some of the work done in the scope of the thesis and article are presented below. Kardaş [2], examine the design and implementation of a small scale Organic Rankine Cycle test set. A flexible experimental setup has been created that allows for examination. The device is built with pressure, temperature and flow sensors to collect data. 13 fluids are compared with respect to environmental, physical and safety characteristics. The fluids satisfying these criteria were selected for further analysis R134a, R141b, R245ca and R245fa. As a result of the thermodynamic analyses, R134a was chosen as the cycle fluid for the test setup. The maximum received power and maximum cycle efficiency were 4.13 kW and 7.64% respectively. Soysal [3], has modelled a small scale ORC system powered by concentrated solar energy technology. The modelling of the cycle system and the solar collectors used to heat the fluid in the system was made according to the ORC test system at Bogazici University. By making the thermodynamic design of the Organic Rankine Cycle, it has designated the fluid to be used in the system as R245fa and sized the system to produce 10 kW in ideal conditions. Günaydın [4], worked on the design, thermodynamic analysis and prototype system manufacturing of the recuperated Organic Rankine Cycle system. At the end of the study, the highest ORC efficiency was obtained in the R365mfc fluid with 10.4%. This value has reached 110^{o}C heat source temperature, 80% turbine isentropic efficiency, 5^{o}C superheat temperature. The lowest efficiency (4.7%) was found in the R236ea fluid with 90^{o}C heat source temperature, 60% turbine isentropic efficiency, 15^{o}C superheat temperature conditions. Su et al. [5], reported that the Organic Rankine Cycle was influenced by the flow and ambient conditions used. According to the simulation, R254eb and R254cb were found as the most suitable candidates. Sun et al. [6], using the R113 as an organic fluid, the thermodynamic performance of the ORC system has been influenced by operational parameters such as evaporation temperature, overheat level and condensation temperature. Rahbar et al. [7], presented a mathematical approach to the development of efficient and small size radial turbines. It has been found that R152a has the highest turbine efficiency of 84% among the fluids with the degree of superheating of 7^{o}C. Li et al. [8] conducted the thermodynamic and thermo-economical study of organic Rankine cycle performance under different operating conditions for waste heat recovery using zeotropic mixtures as the organic fluid. The properties of the fluids were calculated with REFPROP 9.0. By using the mixture as a organic fluid, the result of the ORC system performance has not always improved. For the pinch point temperature difference, the mixtures lead to a reduction in the mean heat transfer temperature difference in the heat exchangers. Therefore, the mixed ORC system exhibits poor economic performance compared to the pure fluid ORC system. Le et al. [9] optimized the subcritical ORC using pure fluid and zeotropic mixture. Two pure fluids were used as pentane and R245fa organic fluid. Furthermore, the mixtures obtained by mixing these two fluids at different ratios were used as organic fluids. Two optimizations, such as exergy maximization and LCOE (Levelized Cost of Electricity) minimization, have been used to find the appropriate working conditions of the system and to determine the best organic fluids. Hot water was used for the simulation of heat source at 150°C and 5 bar pressure. The cooling water temperature taken from the environment is taken as 20°C. The mass flow rate is constant at 50 kg/s. The highest exergy efficiency was found for 53.2% and the lowest LCOE reduced to 0.086 $/kWh for the n-pentane based ORC.

The design and experimental investigation of the 1 kW Organic Rankine cycle system was carried out by Muhammad et al. [10] using R245fa organic fluid for low temperature steam waste heat recovery. The R245fa organic fluid was selected with the REFPROP program. A scroll compressor is used as an expander. The system achieves a thermal efficiency of 5.64%, a net efficiency of 4.66% and an isantropic efficiency of the expander of 58.3% at the maximum power production point. The maximum thermal efficiency was 5.75% and the maximum isantropic efficiency of the expander was found to be 77.74% according to experimental data. Liu et al. [11] performed parametric optimization and performance analysis of the Geothermal Organic Rankine Cycle using the R600a/R601a mixture as an organic fluid. The thermo-physical properties of the fluid were calculated using REFPROP. Using the R600a/R601a mixture for the geothermal ORC, the geothermal inlet temperatures reached 110, 130 and 150°C, respectively, resulting in ORC cycles producing 11%, 7% and 4% more power than using pure R600a.

In this study, thermodynamic design model of Organic Rankine Cycle containing three different dry fluids was created with the help of MATLAB and EES. With the created design, the effect of turbine inlet temperature and source temperature on ORC performance was determined. As dry fluid, R113, R123 and Isopentane fluids were selected. The turbine inlet pressure, condenser outlet temperature, pump and turbine isentropic efficiency are kept constant. The amount of heat required for the system, the work done by the turbine, the thermal efficiency, the exergy efficiency, the total irreversibility value in the system has been determined. The effect of the system components on the total irreversibility value is determined. Turbine inlet pressure was determined as 260 kPa and turbine inlet temperature range was determined so that three fluids would be in the case of superheated steam at the inlet of the turbine. The main purpose of this work is to clearly demonstrate the effect of turbine inlet temperature and heat source temperature on ORC performance by using three different dry fluids in the same operating range, producing a thermodynamic design model.

2. Material and Methods

An ORC technology based on a system for generating electricity from heat (Figure 1) uses heat from the hot source to vaporize the organic working fluid in the evaporator. The

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pressurized steam is then sent to the turbines and generates electricity when combined with the generator. The steam is condensed again into a liquid in the condenser. Here, either the cooling tower, groundwater or river water is used as a cooling fluid. Then, the pump sends the working fluid back to the evaporator and this closed cycle process repeats.

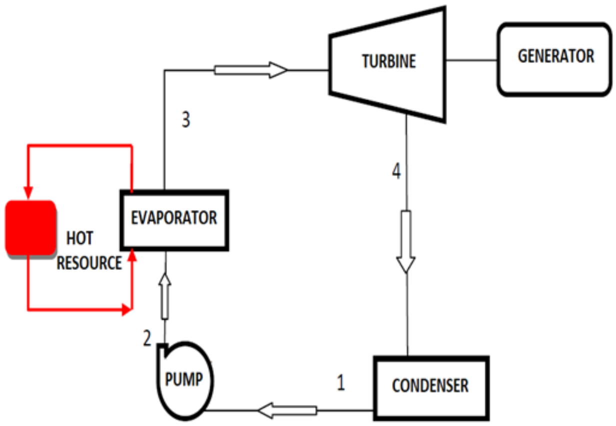

Figure 1. Basic ORC Scheme [12]

The physical and environmental properties of the three different dry flow fields identified in the study are given in Table 1. From the selected fluids, the boiling points of R123 and Isopentane fluids are the same but R113 fluid is seen to be more. It is seen that all three fluids have a high critical temperature value and the R123 fluid has the lowest critical temperature value. It has been given that ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) values are lowest in Isopentane fluid.

Table 1. Physical and environmental properties of fluids used in design [13]

Fluids/ Properties	R113	R123	Isopentane
ds/dT	Dry fluid	Dry fluid	Dry fluid
Molecular Mass (g/mol)	187.38	152.93	72.15
Normal Boiling Point (ºC)	47.6	27.8	27.8
Critical Temperature (ºC)	214.1	183.7	187.2
Critical Pressure (MPa)	3.39	3.66	3.38
ASHRAE 34 safety group	A1	B1	A3
ODP	1.000	0.020	0
GWP	6130	77	20
Saturation Temperature for 260 kPa (ºC)	79.16	56.68	58.27

Within the scope of the study, the turbine inlet pressure was set at 260 kPa. The saturation temperature values for the selected fluids at 260 kPa are 79.16ºC, 56.68ºC and 58.27ºC for R113, R123 and Isopentane, respectively. The lower limit of the inlet temperature of the turbine is set at 80ºC so that the three fluids in the turbine inlet are in the hot steam zone. The T-s diagram of the three different dry fluids is given in Fig. 2. to include the 260 kPa line.

The fixed values and the independent variables used in the thermodynamic design model of three different dry fluids with the integrated use of MATLAB and EES are given in Table 2 [14-15].

Table 2. Fixed values and independent variables for the thermodynamic design model

Fixed Values	Turbine Isentropic Eff.	85%
	Pump Isentropic Eff.	85%
	Turbine Inlet Pressure	260 kPa
	Sink Temperature	17ºC
	Condenser Outlet Temp.	20ºC
Independent Variables	Organic Fluids	R113/R123/Isopentane
	Turbine Inlet Temp. Range	80ºC-120ºC

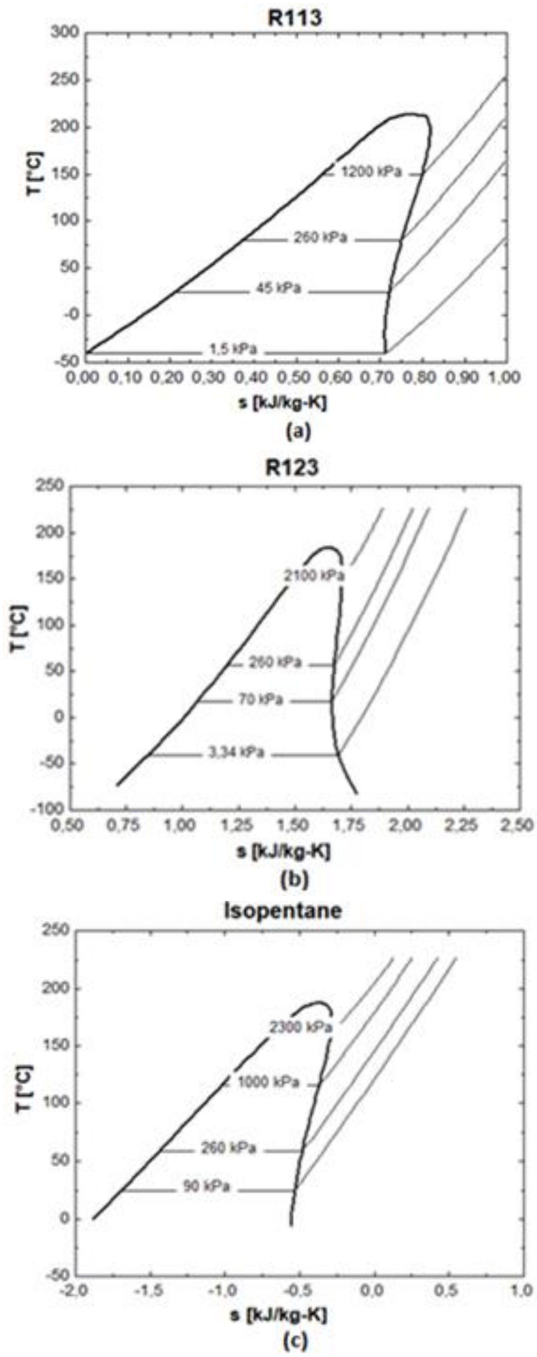

Fig. 2. T-s diagram of three different dry fluid (a) R113; b) R123; c) Isopentane

The heat source temperature was also varied between 110ºC and 130ºC depending on the turbine inlet temperature.

The purpose of this study is to demonstrate the effect of the simultaneous increase in turbine inlet temperature and source temperature on ORC performance. By highlighting three different dry fluids under the same input parameters, the importance of fluid selection in energy and exergy analysis is highlighted. In addition, the total irreversibility value generated by the turbine inlet temperature and the source temperature on the system is determined, and the percentage of this irreversibility in the system components is specified. It has been tried to explain in which organic fluid the need to improve on which component.

3. Results and Discussion

In this study, for the selected R113, R123 and Isopentane fluid, the input parameters are determined by checking the conformity of the second law of thermodynamics. The model is designed to have a much lower turbine inlet pressure value than the conventional cycle. For the specified turbine inlet pressure value of 260 kPa, the ORC performance was determined by the influence of turbine inlet temperature and source temperature. In the prepared design model, the turbine inlet temperature was changed between 80ºC and 120ºC and the source temperature was changed between 110ºC and 130ºC to analyze the energy and exergy of the ORC system. For 102 different input numeric test values determined among these values, 612 output numeric test values were obtained and some data are given in Table 3.

Figure 3 shows the effect of turbine inlet temperature and source temperature change on the amount of heat required for the system. Three fluids seem to require more heat as the turbine inlet temperature and source temperature increase. While the heat input values for R113 and R123 fluids are close to each other, it seems that much more heat input is required in Isopentane. For a system with an average of 100ºC turbine inlet temperature and 120 ºC source temperature, the heat input value for R113 and R123 fluids is 205.4 kJ/kg and 230.3 kJ/kg, while this value for isopentane fluid is 489.6 kJ/kg.

Table 3. Analysis some data of different models for ORC performance evaluation based on organic fluid

a) R123; **b)** R113; **c)** İsopentane

(a)

Organic Fluid	Case	Turbine Inlet Temp. (ºC)	Heat Source Temp. (ºC)	Heat Input (kJ/kg)	Turbine Work (kJ/kg)	Thermal Efficiency	Exergy Destruction (kJ/kg)	Exergy Efficiency
R123	**1**	80	110	214.3	19.01	0.088	33.15	0.3647
	2	82.5	111.3	216.2	19.18	0.08796	34	0.3609
	3	85	112.5	218.2	19.34	0.08792	34.86	0.3572
	…	…	…	…	…	…	…	…
	15	115	127.5	242.6	21.3	0.8717	45.77	0.3178
	16	117.5	128.8	244.7	21.47	0.08709	46.73	0.315
	17	120	130	246.8	21.63	0.08701	47.7	0.3122

(b)

Organic Fluid	Case	Turbine Inlet Temp. (ºC)	Heat Source Temp. (ºC)	Heat Input (kJ/kg)	Turbine Work (kJ/kg)	Thermal Efficiency	Exergy Destruction (kJ/kg)	Exergy Efficiency
R113	**1**	80	110	190.7	23.81	0.124	18.62	0.563
	2	82.5	111.3	193.1	24.08	0.1238	19.89	0.5494
	3	85	112.5	195.6	24.35	0.1236	21.18	0.5366
	…	…	…	…	…	…	…	…
	15	115	127.5	217.7	26.72	0.1219	33.36	0.4464
	16	117.5	128.8	219	26.85	0.1218	34.06	0.4424
	17	120	130	220.2	26.98	0.1217	34.77	0.4385

(c)

Organic Fluid	Case	Turbine Inlet Temp. (ºC)	Heat Source Temp. (ºC)	Heat Input (kJ/kg)	Turbine Work (kJ/kg)	Thermal Efficiency	Exergy Destruction (kJ/kg)	Exergy Efficiency
İsopentane	**1**	80	110	448.8	39.91	0.08809	69.39	0.3654
	2	82.5	111.3	453.9	40.26	0.8789	71.38	0.3609
	3	85	112.5	458.9	40.61	0.08768	73.39	0.3565
	…	…	…	…	…	…	…	…
	15	115	127.5	521.1	44.68	0.08505	99.39	0.3104
	16	117.5	128.8	526.4	45.02	0.0848	101.7	0.3071
	17	120	130	531.7	45.35	0.08459	104.1	0.3038

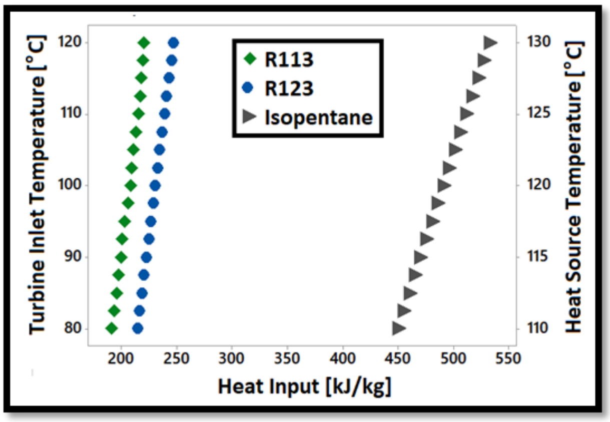

Figure 3. Change of heat input with turbine inlet temperature and heat source temperature

Figure 4 shows the effect of turbine inlet temperature and source temperature change on the turbine work. For three fluids, the turbine work seems to increase as the turbine inlet temperature and source temperature increase. Although R113 fluid requires less heat input than R123 fluid, it seems to have done more turbine work. It is seen that the system containing isopentane fluid still contains more turbine work than the others. For a system with an average of 100ºC turbine inlet temperature and 120ºC source temperature, the turbine work value for R113 and R123 fluids is 25.41 kJ/kg and 20.33 kJ/kg, while this value for isopentane fluid is 42.67 kJ/kg.

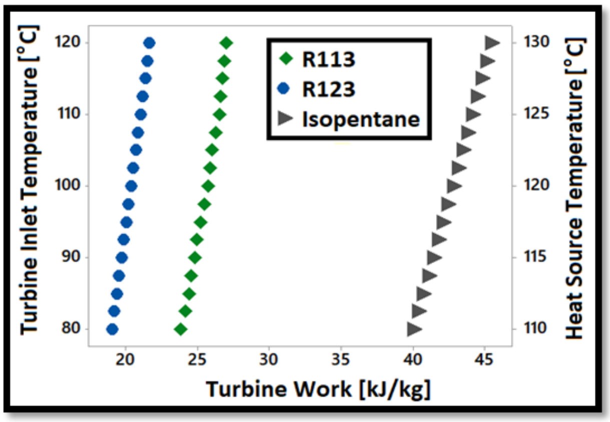

Figure 4. Change of turbine work with turbine inlet temperature and heat source temperature

Figure 5 shows the effect of turbine inlet temperature and source temperature change on the thermal efficiency of the system. For three fluids, it is observed that the thermal efficiency does not increase as the turbine inlet temperature and source temperature increase. More turbine work was obtained in the system containing isopentane fluid. However, Isopentane fluid is also required for the most heat requirement. Therefore, the thermal efficiency is lower than the others. The maximum thermal efficiency is seen in the R113 fluid, which achieves average turbine work with less heat input. For a system with 80ºC turbine inlet temperature and 110ºC source temperature, the maximum thermal efficiency achieved for R113 was 12.4%, while the thermal efficiency for the same input values was 8.8% for other fluids.

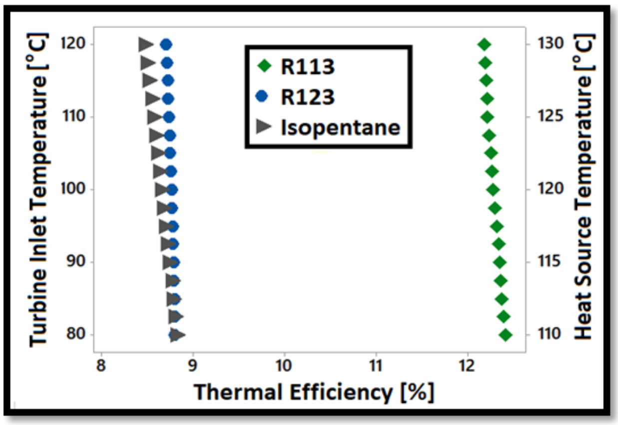

Figure 5. Change of thermal efficiency with turbine inlet temperature and heat source temperature

Figure 6 shows the effect of turbine inlet temperature and source temperature change on the total irreversibility value. For three fluids, the total irreversibility does not seem to increase at the same rate as the turbine inlet temperature and source temperature increase. It is seen that the irreversibility increases more in the Isopentane fluid and the least irreversibility is in the R113 fluid. As the 80ºC turbine inlet temperature increased to 120ºC and the 110ºC source temperature increased to 130ºC, the total irreversibility of the R113 and R123 fluids increased by 16 kJ/kg and 14 kJ/kg, respectively. As a result of this change, the total irreversibility of the system containing Isopentane fluid increased by 35 kJ/kg.

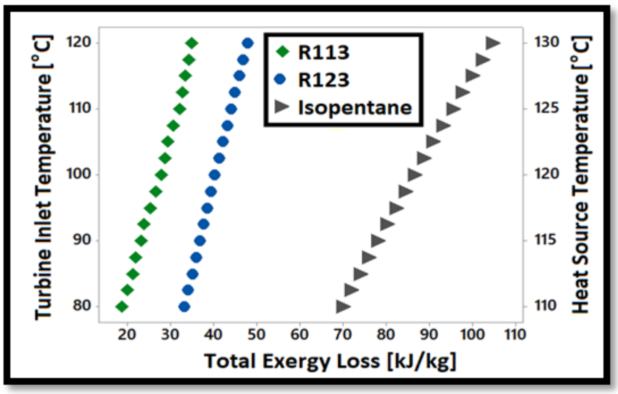

Figure 6. Change of total exergy loss with turbine inlet temperature and heat source temperature

Figure 7 shows the effect of turbine inlet temperature and source temperature change on the exergy efficiency of the system. For three fluids, as the turbine inlet temperature and the source temperature increase, the efficiency of exergy decreases, but it does not decrease for the same effect. It is seen that the least is the exergy efficiency in the most irreversible isopentane fluid, and the most is the exergy efficiency in the least irreversible R113 fluid. As both the turbine inlet temperature and the source temperature increase, the exergy efficiency of R113 fluid is reduced more rapidly than other fluids. For a system with 80°C turbine inlet temperature and 110°C source temperature, the maximum exergy efficiency obtained for R113 was 56.3%, while the exergy efficiency for the same input values in other fluids was 36.5%.

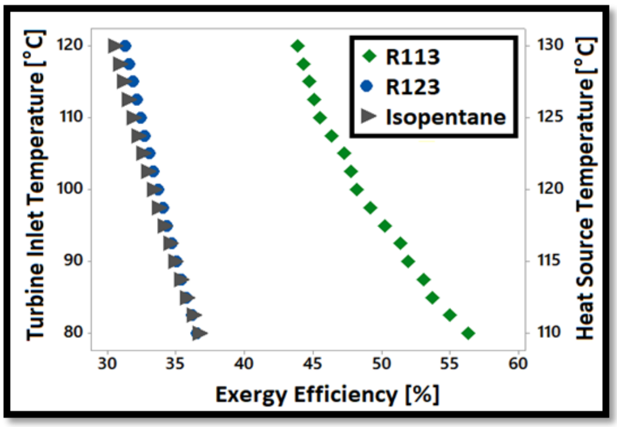

Figure 7. Change of exergy efficiency with turbine inlet temperature and heat source temperature

Figure 8 shows the percentage of irreversibility in the total irreversibility of the system components when three different dry fluids reached maximum thermal efficiency and exergy efficiency. For the three fluids, the most irreversible is seen in the evaporator. The percentage of irreversibility that occurs in the evaporator is 80% for R123 and Isopentane, while it is 67% for R113. In the system containing R113 fluid, it is seen that the irreversibility of the turbine is higher than that of other fluids. It is seen that the irreversibility of the condenser is close to each other for the three fluids. The irreversibility of the water in the pump is not specified as it is around 0.08% for the three fluids.

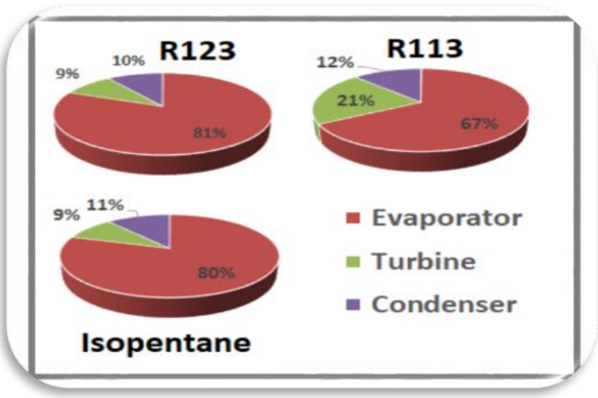

Figure 8. Total exergy loss percentage in each component for highest thermal and exergy efficiency position of cycle

Figure 9 summarizes thermal and exergy efficiency values for three fluids in a single graph. It is seen that both the thermal efficiency and the exergy efficiency of the system containing R113 fluid are higher than those of other fluids. Isopentane and R123 fluids show close results.

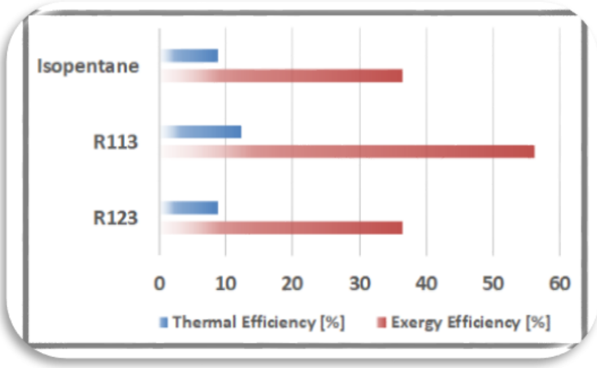

Figure 9. Comparison of energy and exergy efficiency of three different dry fluids with change turbine inlet temperature and heat source temperature

4. Conclusion

In this study, energy and exergy analysis were performed with the help of MATLAB and EES to determine the effect of using different dry fluids in the ORC on the performance of the system. At the end of the change of turbine inlet temperature [80°C-120°C] and source temperature [110°C-130°C], the ORC system containing Isopentane fluid performed about 40 kJ turbine per unit mass more than other systems but the thermal efficiency value was at least (8.8%). Much more heat input is required than other systems, resulting in lower thermal efficiency. In the system containing R113 fluid, more heat efficiency value (12.4%) was determined than other systems, although less turbine work was observed.

The effect of turbine inlet temperature and source temperature on the total irreversibility value is determined. It has been determined that the system containing isopentane has the maximum irreversibility value (105 kJ/kg). The exergy efficiency was inversely proportional to the total irreversibility value obtained in R113 fluid with a maximum of 56.3%. Turbine inlet temperature and source temperature changes are the result that the irreversibility value of the evaporator is affected the most. For all three fluids, it was seen that the percentage of irreversibility in the evaporator was greater than the other components. Moreover, in the system containing R113 fluid, it is stated that irreversibility value in the turbine is also important. When the results were evaluated, R113 fluid showed better results than the others. R123 and Isopentane fluids, which are close to each other in terms of thermophysical properties, also showed close results in thermal efficiency and exergy efficiency parameters.

As a result, we show that the thermodynamic design model developed by MATLAB and EES for the Organic Rankine Cycle in this study can be successfully applied to energy and exergy analysis of different dry fluids at the same operating intervals.

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