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Energy and exergy analysis of an organic Rankine cycle in a biomass-based forest products manufacturing plant

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Abstract: In this study, energy and exergy analysis of an organic Rankine cycle (ORC) unit was carried out at a biomass-based forest products manufacturing plant. The ORC unit is used for the production of electricity and heat, by using thermal oil as a heat source in the plant. The actual data were obtained from the ORC unit during the energy production process. Studies were realized for the energy and exergy analysis of the main components of the ORC unit, which are the evaporator, condenser, turbine, and regenerator, at two different working conditions. The effect of condenser pressure on the energy and exergy efficiencies of the system was studied in the context of this study. Under the working conditions of Case-1, the energy and exergy efficiencies were calculated as 12.59% and 33.26 %, respectively. As for Case-2, the energy and exergy efficiencies were calculated as 13.22% and 35.5%. The gradation of the exergy destructions of the components from greater to lower can be listed as evaporator, condenser, turbine, regenerator, and pump.

Key words: Organic Rankine cycle, biomass, thermal oil, organic working fluid, energy and exergy analysis

1. Introduction

Developing efficient power systems based on renewable energy sources and emitting fewer or no pollutants into the environment are main concerns of industrial sectors and governments. The consumption of fossil fuel sources and energy demands are increasing continuously in the world, including Turkey, with the passing of time. World energy consumption is expected to increase to around 40% between 2006 and 2030 [1]. On the other hand, generating energy from fossil fuel causes some problems for the environment, such as global warming, air pollution, water pollution, soil pollution, acid precipitation, ozone depletion, and so on. For this reason, using efficient systems is vital to increase the units of energy generated per unit of fuel consumed.

Turkey's dependence on foreign countries for energy imports, especially oil and nonrenewable fossil-originated natural resources (natural gas and hard coal), causes high energy costs. To solve energy problems and prepare for future developments, many countries like Turkey turn towards renewable energies like biomass, solar, wind, and geothermal for the production of clean energy. In addition, power generation from waste heat recovery is also an important subject for the solution of the energy problems [2–6].

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The Rankine cycle is one of the most important operating cycles that are widely used to convert thermal energy into power at high capacities. Nuclear power plants and coal plants can be given as examples for such applications. In these power plants, water is used as a working fluid, which can cause some technical problems, and these problems can be eliminated by using appropriate organic working fluids as a replacement for water in small- and medium-scale power cycles [7]. Compared to water, organic working fluids have higher molecular weights and lower critical temperatures. They are used in steam cycles, which are called organic Rankine cycles (ORCs). These ORCs have some advantages over conventional steam cycles [8,9]:

- They require less heat during evaporation;
- Their evaporation processes can be realized at low pressures and low temperatures;
- Their expansion processes finish in the vapor region, so there is no need to overheat and thus the corrosion risk of turbine blades can be almost completely eliminated;
- Their temperature differences between evaporation and condensation are low; the pressure drops will also be low during the expansion processes. Therefore, simple single-stage turbines can be used for expansion.

Although study of ORC systems began in the 1880s, it has not become widespread until today. It is inevitable to the use low-temperature heat sources for power generation when considering the future of energy, decreasing fossil fuels reserves, and increasing environmental concerns. ORC systems give the opportunity to work at low temperatures, which makes it possible to generate electricity from various energy sources like solar energy, geothermal energy, biomass, and waste heat [10–23].

There are many academic studies [1,14,24–50] on energy and exergy analysis of ORCs published in the scientific literature. For example, Al-Sulaiman [26] carried out a study about detailed exergy analysis of selected thermal power systems driven by parabolic trough solar collectors. In that study, seven refrigerants for the ORC were examined: R134a, R152a, R290, R407c, R600, R600a, and ammonia. Key exergetic parameters were examined: exergetic efficiency, exergy destruction rate, fuel depletion ratio, irreversibility ratio, and improvement potential. The study revealed that there was an exergetic improvement potential of 75% in the systems considered. Al-Sulaiman et al. [28] also conducted a study about greenhouse gas emission and exergy assessments of an integrated ORC with a biomass combustor for combined cooling, heating, and power production. In that study, the results showed that when the trigeneration case was used, the exergy efficiency increased significantly to 27% as compared with the exergy efficiency of the electrical power case, which was around 11%. It was also found that the main two sources of exergy destruction were the biomass combustor and ORC evaporator. The study showed that the emissions of CO_2 in kg/MWh were significantly high for the electrical power case while, for the trigeneration case, the emissions per MWh of trigeneration dropped significantly to a relatively low level. El-Emam and Dincer [30] conducted a study of exergy and exergoeconomic analyses and optimization of a geothermal ORC. An optimization study was performed based on the heat exchanger's total surface area parameter. Parametric studies were performed to investigate the effect of operating parameters, and their effects on the system energetic and exergetic efficiencies and economic parameters were also investigated. Feng et al. [31] carried out a study on the comparison of a regenerative organic Rankine cycle (RORC) and basic organic Rankine cycle (BORC) based on thermoeconomic multiobjective optimization considering exergy efficiency and leveled energy cost (LEC). The study demonstrated that there was a negative correlation between thermodynamic performance and economic factors. The optimum exergy efficiency and LEC for the Pareto-optimal solution of the RORC were 55.97% and

0.142 \$/kWh, respectively, which were 8.1% higher exergy efficiency and 21.1% more LEC than that of the BORC under the considered conditions. Li [37] conducted a study on ORC performance evaluation and thermoeconomic assessment with various applications and also made energy and exergy performance evaluations. Working fluid candidates for various ORC applications based on the heat source temperature domains were investigated for the thermal efficiency, exergy destruction rate, and mass flow rate under different ORC configurations. Nafey and Sharaf [41] examined a combined ORC (solar collector, turbine, recuperator, condenser, and pump) and reverse osmosis unit for seawater desalination. Exergy and cost analysis were performed for saturation and superheated operating conditions. Exergy efficiency, total exergy destruction, thermal efficiency, and specific capital cost were evaluated for direct vapor generation processes. Toluene and water achieved minimum results for total solar collector area, specific total cost, and the rate of exergy destruction. Tchanche et al. [44] conducted a study about exergy analysis of microorganic Rankine power cycles for a small-scale solar-driven reverse osmosis desalination system. The study showed an increase of 7% in the energy efficiency of an ORC integrated with a reverse osmosis desalination system when a regenerator was used.

In this study, energy and exergy analysis of an ORC unit was carried out at a biomass-based forest products manufacturing plant. The ORC unit is used for the production of electricity and heat in the biomass-based energy production plant by using thermal oil as a heat source for the process. Hexamethyldisiloxane is used as an organic working fluid in the ORC unit. When studies were examined in the literature [51–66], no energy and exergy analysis of an ORC unit that used hexamethyldisiloxane as an organic working fluid was encountered. In this article, the energy and exergy analyses of an ORC unit were performed under two different operating conditions. In addition, the effect of condenser pressure on energy and exergy efficiencies of the ORC unit were investigated experimentally.

2. System description

In this paper, an energy and exergy analysis of an ORC unit has been performed at an integrated forest products manufacturing plant that manufactures wood products, such as laminate flooring with wood, door skin, wood panels, medium density fiberboard, and chipboard in Turkey. During production, waste like wood chips, shavings, and sawdust is burned in a fluidized bed biomass boiler to get thermal oil, which is used to meet the need for heat in the power production process. The temperature of the thermal oil ranges between 280 °C and 300 °C. A portion of the thermal oil is used in the process and the rest is used in the ORC unit for the production of power and heat.

The ORC unit comprises a preheater (thermal oil/working fluid), evaporator (thermal oil/working fluid), regenerator (working fluid liquid/working fluid vapor), condenser (working fluid/hot water), working fluid feed pump, low-voltage asynchronous electric generator, turbine with pertinent ancillary equipment, turbo generator auxiliaries (lubricating system, vacuum pump, etc.), and switchgear. A scheme of the concept is given in Figure 1, which explains the connections of the turbo generator to the thermal oil and cooling water loops [67].

The turbo generator uses the thermal oil to preheat and vaporize a proper organic working fluid in the evaporator. The organic working fluid vapor actuates the turbine, which is straight-coupled to the electric generator through an elastic coupling. The exhaust vapor flows through the regenerator where the organic working fluid is heated. The vapor is then condensed in the condenser. The organic working fluid liquid is eventually pumped to the regenerator and then to the evaporator, therefore finalizing the sequence of operations in the closed-loop circuit.

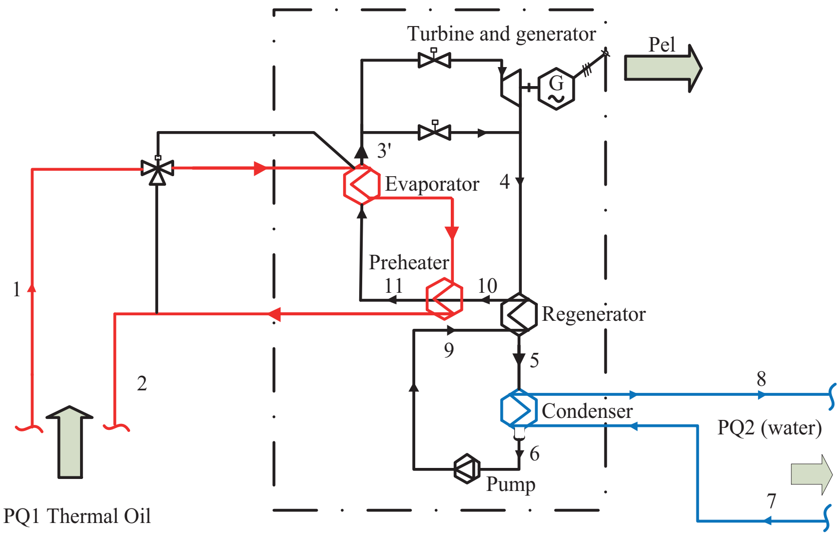

Figure 1. Main connections of the ORC unit to thermal oil and cooling water circuits.

The mass flow rate of the thermal oil has been measured by an orifice plate flowmeter. Thermal oil temperature measurements have been carried out by a thermocouple at the inlet and outlet of the evaporator. Condenser water flow rate has been determined by an ultrasonic flow meter (Panametrics PT D 878). The flow rate of the organic working fluid has been determined by electromagnetic flowmeter at a point between the pump and the regenerator. The temperature of the organic working fluid has been measured by a thermocouple at the inlet and outlet of each unit in the cycle. The pressure values of the organic working fluid have been determined by a pressure gauge at the outlet of the evaporator and the condenser. The pressure values of thermal oil and water have been read at the inlet of the evaporator and the condenser, respectively.

3. Energy and exergy analysis

After leaving the condenser, the organic working fluid (hexamethyldisiloxane) enters the main pump (organic working fluid pump), where its pressure is increased, and then it is directed to the regenerator. In the regenerator, the organic working fluid gains the heat that comes from the other side of the stream's recovered heat (of the organic working fluid, which is in the vapor phase) and exits the regenerator in the liquid phase. Then the organic working fluid enters the preheater, in which the thermal oil's heat is transferred to the organic working fluid. The temperature of the organic working fluid is increased to its bubbling point. After the preheater, the organic working fluid enters the evaporator, where the organic working fluid is vaporized by drawing heat from the thermal oil. When the organic working fluid is to reach a superheated state, it is sent to the turbine; the vapor is expanded through the turbine, the temperature and pressure of the vapor are both decreased, and this produces mechanical work, which is converted to power. In the state of vapor, the organic working fluid is sent to the regenerator and transfers its heat to the other side of the organic working fluid in the regenerator. After the regenerator, the organic working fluid is sent directly to the condenser, where it is cooled by transferring its heat to water and turns into the liquid phase (it condenses). Therefore, hot water is obtained for the purpose of heating in the process. Leaving the condenser in the liquid phase, the organic working fluid enters the main pump, where its pressure is increased and the cycle continues. A water-cooled condenser is used in the cycle. In the calculations, the pressure drops in the evaporator, condenser, and regenerator have been neglected.

ORC systems consist of several steady-state control volumes. General expressions of mass, energy, and exergy balances of any stead- state control volume, by neglecting the potential and kinetic energy changes, can be expressed respectively as:

$$\Sigma m_{in} = \Sigma m_{out}, \tag{1}$$

$$Q + W = \Sigma m_{out} h_{out} - \Sigma m_{in} h_{in}, \tag{2}$$

$$E_{heat} + W = \Sigma E_{out} - \Sigma E_{in} + I, \tag{3}$$

where the subscripts in and out represent the inlet and exit states, Q and W are the net heat and work inputs, E is the exergy rate, and I is the irreversibility rate.

The thermal efficiency of the ORC may be expressed as:

$$\eta_{th} = W_{net,out}/Q_{in} = W_{net,out}/(m_{oil}(h_2 - h_1)), \tag{4}$$

$$W_{net,out} = W_{turb} - W_{pump}, \tag{5}$$

where η_{th} is the thermal efficiency of the system and Wturb is the turbine's work.

3.1. Exergy of the system

$$\mathbf{E} = (E - U_0) + P_0(V - V_0) - T0(S - S_0) \tag{6}$$

$$E = U + KE + PE. \tag{7}$$

Here **E** is the exergy of the system, E is the energy of the system, V is the volume of the system, and S is the entropy of the system.

Exergy efficiency of the turbine demonstrates how well the actual turbine output is achieved from the stream exergy. The overall exergy efficiency of the entire cycle can be expressed as:

$$\eta_{ex.cyc} = W_{net,out}/E_{in} = W_{net,out}/(m_{oil}(h_1 - h_2 - T_0(s_1 - s_2))). \tag{8}$$

4. Results and discussion

In this study, an energy and exergy analysis of an ORC unit was realized at a biomass-based forest products manufacturing plant. The ORC unit is used to produce electricity and hot water by using thermal oil as a heat source. The required heat for this thermal oil is obtained from biomass, which is burned in a fluidized bed biomass boiler. Hexamethyldisiloxane is used as the organic working fluid in the ORC unit. In this article, the real data have been obtained from the ORC unit during the energy production process. The studies are named Case-1 and Case-2 and they were carried out under two different operating conditions for the energy and exergy analysis of the main components of the ORC unit, which are evaporator, condenser, turbine, and regenerator. The effect of condenser pressure on the energy and exergy efficiencies of the system was also examined. The results of these studies are presented and discussed.

In the first study (Case-1), 6831 kW of heat was transferred from the thermal oil to the ORC unit and 947.36 kWe of gross power was generated. To circulate the organic working fluid in the cycle, the power drawn by the pump was about 87.3 kW. Hot water was obtained from the condenser at the temperature of 93.1 °C, with thermal capacity of 5483 kW. The net power generation of the ORC unit was 860.06 kW and electrical energy efficiency was calculated as 12.59%.

The highest exergy destruction occurred in the evaporator during the heat exchange process. The exergy destruction rate in the evaporator was 3920.81 kW. This was 60.25% of exergy input of 6507.05 kW. The condenser, turbine, regenerator, and pump followed the evaporator, respectively, in relation to the exergy destruction rate. The reason for high exergy loss in the evaporator is the high outlet temperature of the thermal oil (at the temperature of 217.1 °C). The thermal oil that is already leaving the evaporator is sent back to the biomass boiler to raise its temperature to 280 °C. The properties at various states for Case-1 are given in Table 1.

Table 1. The properties at various states for Case-1.

State no.	T (°C)	Fluid	Phase	P (bar)	h (kJ/kg)	s (kJ/kg K)	m (kg/s)	E (kW)
0	25.00	Water	Dead state	1.0	104.89	0.3674	-	-
0’	25.00	HMDSO	Dead state	1.0	–150.54	–0.4494	-	-
0”	25.00	Thermal oil	Dead state	1.0	61.88	0.7200	-	-
1	276.50	Thermal oil	Liquid	2.5	573.20	1.0306	49.73	20,821.22
2	217.30	Thermal oil	Liquid	2.5	431.58	0.9945	49.73	14,314.16
3	219.46	HMDSO	Sat. vapor	12.9	374.95	0.8348	30.64	
3’	221.80	HMDSO	Sup. vapor	12.9	381.48	0.8480	30.64	4448.64
4	185.10	HMDSO	Sup. vapor	2.1	346.09	0.8507	30.64	3339.89
5	129.60	HMDSO	Sup. vapor	2.1	240.36	0.6049	30.64	2345.91
6	126.10	HMDSO	Comp. liquid	2.1	55.41	0.1430	30.64	898.23
7	72.80	Water	Comp. liquid	3.0	304.75	0.9888	64.42	939.89
8	93.10	Water	Comp. liquid	3.0	390.02	1.2282	64.42	1835.60
9	126.80	HMDSO	Comp. liquid	12.9	57.33	0.1437	30.64	950.95
10	171.80	HMDSO	Comp. liquid	12.9	158.51	0.3833	30.64	1862.39
11	214.70	HMDSO	Comp. liquid	12.9	264.05	0.6095	30.64	-
11’	219.46	HMDSO	Sat. liquid	12.9	277.00	0.6359	30.64	-
12	127.30	HMDSO	Sat. vapor	2.1	236.09	0.5942	30.64	-

The T-S diagram of the ORC for Case-1 can be seen in Figure 2.

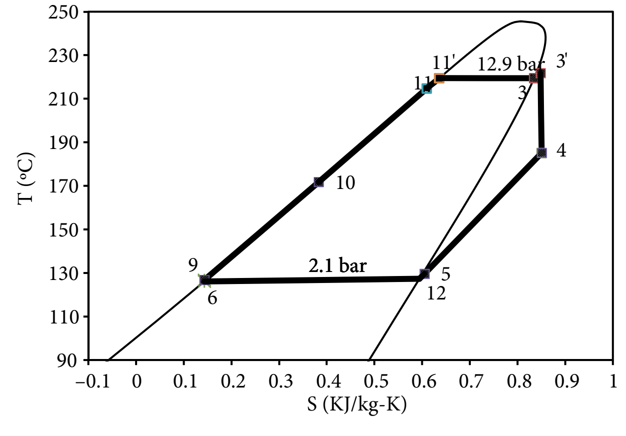

Figure 2. T-S diagram of organic Rankine cycle for Case-1.

Representative exergy and energy performance data for Case-1 can be seen in Table 2.

Table 2. Representative exergy and energy performance data for Case-1.

Energy		Exergy	
Qr (ev, kW)	6831.00	η_{evap} (%)	39.75
Qr (con, kW)	5666.27	η_{con} (%)	61.87
W (tur, kW)	947.36	η_{tur} (%)	85.44
W (pump, kW)	87.30	η_{reg} (%)	91.70
W (rev, pump, kW)	58.75	$\eta_{exc,cyc}$ (%)	33.26
Qw (con, kW)	5493.00	-	-
η (pump, %)	67.30	-	-
η (cycle, %)	12.59		

An exergy losses diagram for Case-1 is given in Figure 3.

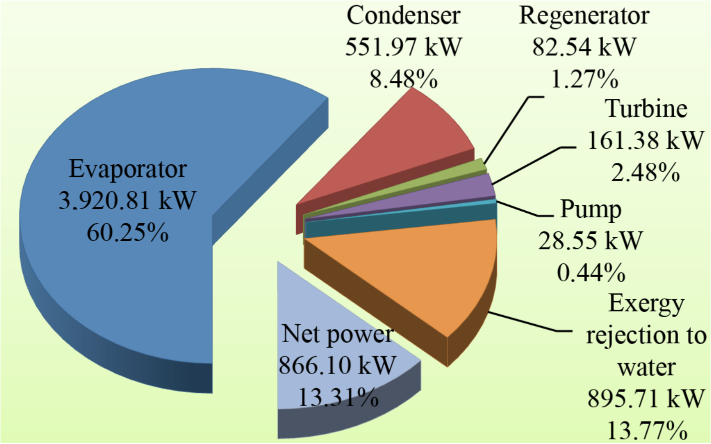

Figure 3. Exergy losses diagram for Case-1 (given as the percentages of exergy input).

In the second study (Case-2), 6746 kW of heat was transferred from the thermal oil to the ORC unit and 977.21 of kWe gross power was generated. The net power generation of the ORC unit was 891.76 kW and electrical energy efficiency was calculated as 13.22%. The thermal capacity of hot water obtained from the condenser was 5376.46 kW and its temperature was 85.6 °C. In the second study, the effect of condenser pressure on the performance of the ORC unit was investigated by reducing condenser pressure to 1.6 bar. When condenser pressure was reduced from 2.1 bar to 1.6 bar, the cycle efficiency (net power production rate) increased from 12.59% to 13.22%. When condenser pressure was reduced, the water temperature at the outlet of the condenser was lowered, too. If the water exiting from the condenser is used for heating purposes in the process, the water temperature at the condenser outlet should be checked to meet the needs of heating in the process. Water coming from the condenser was used to preheat the air (which was taken from the atmosphere) during the studies and it was also used for the purpose of space heating. In this process, the temperature of the water was decreased from 93.1 °C to 85.6 °C. This does not affect the production process. To cool organic working fluid in the condenser efficiently, the flow rate of condenser cooling water was raised from 64.42 kg/s to 120.33 kg/h. Therefore, the energy consumption of the condenser cooling water circulation pump was increased.

The properties in various states for Case-2 are given in Table 3.

Table 3. The properties at various states for Case-2.

State no.	T (°C)	Fluid	Phase	P (bar)	h (kJ/kg)	s (kJ/kg K)	m (kg/s)	E (kW)
0	25.00	Water	Dead state	1.0	104.89	0.3674	-	-
0'	25.00	HMDSO	Dead state	1.0	–150.54	–0.4494	-	-
0"	25.00	Thermal oil	Dead state	1.0	61.88	0.7200	-	-
1	281.60	Thermal oil	Liquid	2.6	586.00	1.0334	47.88	20,620.33
2	221.30	Thermal oil	Liquid	2.6	440.74	0.9972	47.88	14,182.73
3	218.97	HMDSO	Sat. vapor	12.8	374.36	0.8338	27.93	
3'	219.40	HMDSO	Sup. vapor	12.8	375.56	0.8362	27.93	3987.93
4	178.90	HMDSO	Sup. vapor	1.6	335.51	0.8406	27.93	2833.00
5	122.10	HMDSO	Sup. vapor	1.6	229.08	0.5892	27.93	1954.18
6	115.40	HMDSO	Comp. liquid	1.6	32.22	0.0844	27.93	659.86
7	74.90	Water	Comp. liquid	3.1	313.74	1.0155	120.33	1879.37
8	85.60	Water	Comp. liquid	3.1	358.42	1.1413	120.33	2743.30
9	116.03	HMDSO	Comp. liquid	12.8	34.09	0.0848	27.93	708.03
10	161.20	HMDSO	Comp. liquid	12.8	134.02	0.3276	27.93	1477.31
11	213.90	HMDSO	Comp. liquid	12.8	261.96	0.6053	27.93	-
11'	219.00	HMDSO	Sat. liquid	12.8	275.70	0.6333	27.93	-
12	116.67	HMDSO	Sat. vapor	1.6	219.25	0.5641	27.93	-

The T-S diagram of the ORC for Case-2 can be seen in Figure 4.

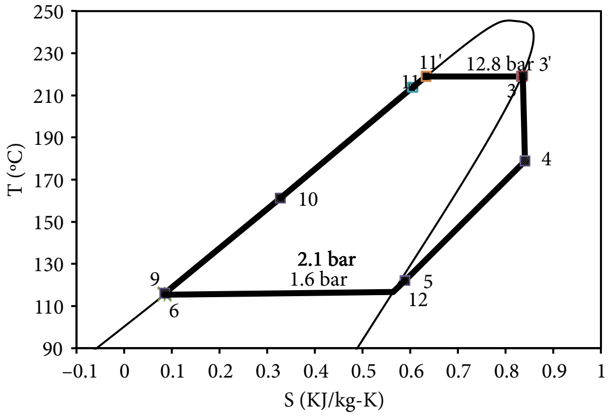

Figure 4. T-S diagram of organic Rankine cycle for Case-2.

Representative exergy and energy performance data for Case-2 can be seen in Table 4.

Table 4. Representative exergy and energy performance data for Case-2.

Energy		Exergy	
Qr (ev, kW)	6,746.00	η_{evap} (%)	39.0
Qr (con, kW)	5498.08	η_{con} (%)	66.7
W (tur, kW)	977.21	η_{tur} (%)	84.6
W (pump, kW)	85.45	η_{reg} (%)	87.5
W (rev, pump, kW)	52.12	$\eta_{exc, cyc}$ (%)	35.5
Qw (con, kW)	5376.46	-	-
η (pump, %)	61.00	-	-
η (cycle, %)	13.22	-	-

In the second study, the highest exergy loss took place in the evaporator, just as in the first study. The evaporator was followed by the condenser, turbine, regenerator, and pump, respectively, in relation to the exergy destruction rate. While the energy and exergy efficiency were calculated as 12.59% and 33.26% in the first experiment, the values of the energy and exergy efficiency in the second experiment were calculated as 13.22% and 35.5%, respectively. Reducing the condenser pressure affected the energy and exergy efficiency significantly. When condenser pressure was reduced, the energy and exergy efficiency of the ORC increased. The main reason for this is the decrease of the transferred energy amount to the cooling water of the condenser. If the energy that is transferred to the condenser is used as a heat source in the process, the condenser operating pressure should be selected in accordance with the required temperature at the point where the heat source is used. If the heat obtained from the condenser is not used in the process and is rejected to the atmosphere by the cooling tower, it is necessary to select the lowest pressure for the condenser to increase the energy and exergy efficiencies, considering atmospheric conditions.

Exergy losses diagram for Case-2 can be seen in Figure 5.

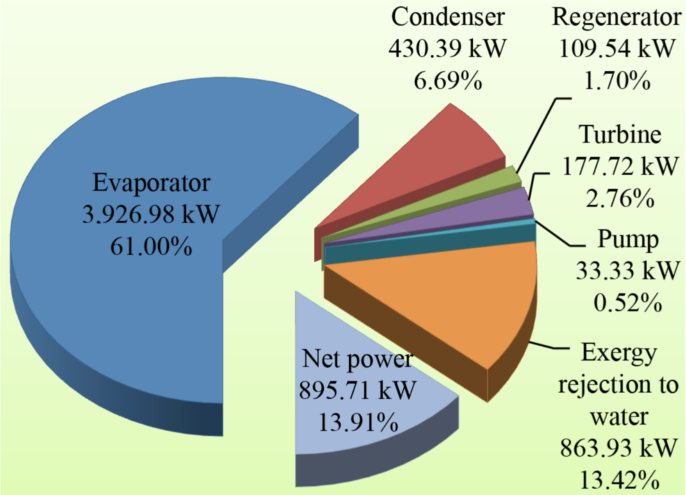

Figure 5. Exergy losses diagram for Case-2.

5. Conclusions

In this work, energy and exergy analysis of an ORC unit was implemented at a biomass-based forest products manufacturing plant. The ORC unit is used for the production of electricity and heat in the plant by using thermal oil as a heat source for the process. Genuine data were obtained from the ORC unit during the energy production process. The studies were realized under two different working conditions to analyze the energy and exergy situations of the main components of the ORC unit. The results were compared. The following can be concluded from the context of these studies:

- In the first study, the evaporator pressure was set at 12.9 bar and the condenser pressure was set at 2.1 bar. Under these conditions, 6831 kW of heat was transferred from thermal oil to the ORC unit and 860.06 kW of net electricity production was realized. In these circumstances, the energy and exergy efficiencies were calculated as 12.59% and 33.26%, respectively. Hot water was obtained from the condenser at a temperature of 93.1 °C and with the thermal capacity of 5483 kW.

- In the second study, evaporator pressure was set at 12.8 bar and condenser pressure was set at 1.6 bar. In these circumstances, 6746 kW of heat was transferred from thermal oil to the ORC unit and 977.21 kW of gross electricity generation was realized. Energy and exergy efficiency of the system were calculated as 13.43% and 35.5%, respectively.

- When condenser pressure was reduced from 2.1 bar to 1.6 bar, the efficiency of the cycle (net power production rate) increased from 12.59% to 13.22% and the exergy efficiency increased from 33.26% to 35.5%. When the condenser pressure was lowered, the temperature of the water leaving the condenser decreased from 93.1 °C to 85.6 °C.
- In both studies, the gradation of the exergy destructions of the components from greater to lower can be listed as evaporator, condenser, turbine, regenerator, and pump. The reason for high exergy loss in the evaporator is the high outlet temperature of the thermal oil (at a temperature of 217.1 °C) exiting from the evaporator.

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