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Evaluation of Exergy Destruction in an Organic Rankine Cycle for Industrial Applications

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The cost of electrical energy in an organic Rankine cycle (ORC), using high-temperature heat, is 0.5946 USD/kWh, with an efficiency of 40.80 % (2024), these parameters change significantly when using low temperature heat, up to 12.12 % efficiency and 0.95 USD/kWh of energy cost (2019). Exergy destruction defines the minimum area of the ORC evaporator and condenser and their total cost. The temperature of the working fluid at the evaporator outlet has a significant impact on the thermal efficiency of the system. Propane, butane and isobutane were used as working fluids to evaluate the exergy destruction in an ORC. In the analysis, the fluid temperature at the evaporator outlet is varied in a range of 80 to 120 °C. An exergo-economic evaluation was carried out for each of the working fluids. The fluid enters the turbine and undergoes an isentropic expansion of 6 bar to produce 3147.3 kW of power. For the three working fluids, the ORC evaporator presents the highest exergy destruction, followed by the condenser, the turbine and the pump. Propane exhibits the highest exergy destruction in the evaporator, 79 %. The ORC operated with butane presents the lowest exergy destruction in the evaporator among the fluids used (70 %), with an energy efficiency of 7.78. At a temperature of 110 °C, using butane as the working fluid, the smallest total area of the heat transfer equipment of 1,924 m^2 and the lowest levelized cost of energy ($LCOE_{el}$), 0.022 USD/kWh, were obtained. The exergo-economic evaluation allows determining the working fluid with the lowest exergy destruction, the lowest total area of the heat transfer equipment and the lowest energy cost.

1. Introduction

The global energy crisis that began in 2021 due to the post-pandemic economic rebound and intensified by the increase in the price of natural gas and oil due to the conflict between Russia and Ukraine, has generated various economic, political and social problems associated with the use of fossil fuels for energy production (IEA, 2023). This phenomenon has mainly affected the industrial sector, which suffered an increase in electricity costs of up to 25 % from 2020 to 2023 (IEA, 2023). The use of solar thermal energy, as an alternative energy source, has proven to be a feasible option for the production of power electricity using an ORC, as reported by Martínez-Rodríguez et al. (2022a), who, using a network of flat plate solar collectors, reached an evaporation temperature of 105 °C and a thermal efficiency of 0.129 using R290. With the introduction of low temperature energy sources, the need to develop new and more efficient energy conversion systems has arisen.
In recent years, various ORC studies have been developed based on energy and exergetic analysis with the aim of generating improvement proposals based on the selection of the working fluid with the best thermodynamic properties that guarantee power production with the least impact to the environment. Raju and Rao (2022) reported that increasing the global heat transfer coefficient of the ORC heat transfer equipment, modifying the geometry and configuration of the heat exchanger, allows increasing efficiency and reducing exergy losses and destruction in the system. Jang and Lee (2019) conducted an experimental analysis of the impact of mass flow and source and sink temperature of an ORC using R245fa as the working fluid. The results showed that these variables have a direct relationship with the power output and the thermal efficiency of the cycle, the maximum power production was 0.246 kW for a source temperature of 140 °C and a sink temperature

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of 10 °C, with an efficiency of 5.72 %. Feng et al. (2023) evaluated the effect of evaporation temperature on the work production and thermal efficiency of an ORC, and also estimated the levelized cost of energy using three working fluids with low values of ozone depletion potential (ODP) and global warming potential (GWP): R236ea, R245fa and R601a. It was determined that thermal efficiency of the cycle increases as the evaporation temperature increases, while the work production and the levelized cost of energy present a minimum as the evaporation temperature increases. By applying exergy analysis, it is possible to identify the variables that have the greatest potential for improvement in the system based on the destruction of exergy.
Sun et al. (2017) evaluated the effect of evaporation temperature on the exergetic efficiency of an ORC using R113 as a working fluid. The exergetic efficiency presented a minimum in relation to the evaporation temperature, this minimum value was 42.62 % at a temperature of 108 °C. Abam et al. (2018) analyzed various configurations of the ORC using R245fa, R1234yf and R1234ze to evaluate the exergetic performance of the cycle as a function of the working pressure of the evaporator. They found that exergetic efficiency of the cycle increased from 30.26 to 38.82 %, with increasing pressure in the evaporator in the range of 2-3 MPa for R245fa. Beiranvand et al. (2021) carried out an optimization of an ORC assisted with solar energy using R123 as a working fluid, its objective function was to maximize the exergetic efficiency and minimize the electricity cost of the cycle, considering the operating pressures of the evaporator and condenser as decision variables. The exergetic efficiency of the cycle improved by increasing the pressure in the evaporator, and decreases by increasing the pressure in the condenser, finding its optimal efficiency values in the range of 7.83 – 10.29 %. Elahi et al. (2022) carried out the analysis of an ORC using R1233zd(E), R1234ze (Z), R1234ze (E) and R1234fy as working fluids, varying the inlet pressure to the turbine in the range of 1000 to 3500 kPa. The results showed that R1233zd (E) presented the highest exergy efficiency in the range of 51 – 55 %, in addition, the highest exergy destruction using this fluid occurred in the evaporator and condenser with values of 21 kW and 12 kW, respectively. Fergani and Morosuk (2023) carried out an exergo-economic analysis of an ORC, using cyclohexane as a working fluid, under two base scenarios: the first considers a constant heat reservoir, and the second a fixed power production, the analysis showed that in both cases, the heat exchangers present the greatest destruction of exergy in the system, and it is also indicated that more than 90 % of this destruction can be avoided through better individual design of the components and system operation modifications, such as evaporation temperature, the degree of superheating of the working fluid and the Pinch Point in the heat exchangers, reducing their total cost. The importance of area minimization of heat transfer equipment is highlighted by the work of Zhang et al. (2019) who showed that the cost of heat transfer equipment in an ORC, using R123 and R245fa, represents 52 % and 58 % of the total cost of investment ORC.
The studies presented show the impact of some variables related to heat transfer equipment such as source and sink temperatures, the Pinch Point and the degree of superheating of the refrigerant, on the overall performance of the cycle and the power production from the point from an energetic point of view. By applying an exergetic analysis it is possible to identify the components of a system or process with the greatest potential for improvement in the system based on the destruction of exergy.
In the present work, the relationship between the temperature of the working fluid at the outlet of the evaporator of an ORC and the heat transfer area of the evaporator and condenser was evaluated. Three working fluids with low environmental impact were used, propane, butane and isobutane. The analysis includes the determination of the exergy destruction in each component of the cycle and the evaluation of the thermal and exergy efficiencies of the system, identifying that the evaporator and the condenser are the equipment where there is the greatest exergy destruction of the ORC, which at in turn, it depends on the working fluid. Butane presented the greatest exergy destruction with the lowest energy cost of 0.022 USD/kWh.

2. Methodology

For an evaporator outlet temperature of 105 °C, the cost of the evaporator represents 7.2 % of the total cost of the ORC as reported by Martínez – Rodriguez et al. (2022b). The authors analyzed the thermal efficiency of an ORC by varying the temperature of the heat source from 65 - 105 °C. The results show a levelized cost of electrical energy of 0.1089 USD/kWh with a thermal efficiency of 11 %.
The selection of the working fluid to produce electrical energy, using an ORC, defines the operating conditions in each of the stages of the cycle, and the size of the heat exchangers for a fixed production of 3147.3 kWh of electrical energy. Three working fluids belonging to the hydrocarbon family with low GWP and ODP values equal to zero were selected. The thermodynamic properties of these fluids are in Table 1.
For each working fluid, exergy destruction and the total exergetic efficiency of the cycle are calculated by varying the evaporator outlet temperature in the range 80 – 120 °C. In the exergy analysis, the following assumptions were made: 1) the cycle operates in a steady state, 2) the fluid undergoes an isentropic expansion of 6 bar in the turbine, 3) there is a heat source with a constant temperature at 135 °C, 4) cooling water at 30 °C is fed to the condenser, 5) the isentropic efficiencies of the pump and turbine were set at 0.85, 6) the overall heat transfer

coefficients are reported in Table 1 (Yang and Yeh, 2016), 7) the reference state for the exergy analysis is T_0= 298 K and P_0= 1 atm, and 8) the thermodynamic properties of the fluids were taken from the database of the National Institute of Standards and Technology (NIST, 2024).

Table 1: Thermodynamic properties of the selected working fluids and overall heat transfer coefficients (U) used in the analysis.*

Working fluid	Fluid type	T_c (°C)	P_c (bar)	ODP	GWP	$U_{evap}\left(\frac{kW}{m^2K}\right)$	$U_{cond}\left(\frac{kW}{m^2K}\right)$
Propane	Wet	96.75	42.5	0	3	2.83	2.45
Butane	Dry	151.85	38.1	0	4	2.23	2.62
Isobutane	Dry	134.55	36.5	0	3	2.43	2.41

*(Yang and Yeh, 2016)

2.1 Energy analysis

An energy evaluation was carried out for each ORC equipment and subsequently the exergy analysis of the system. The inlet and outlet turbine pressures for each temperature are the same and the difference of pressures were set at 6 bar. What changes for each temperature is the degree of superheating. The temperatures evaluated range from 80 to 120 °C with increments of 5 °C for each working fluid. The turbine inlet and outlet pressures for butane are 10 to 4 bar, for isobutane they are 11.5 to 5.5 bar and for propane 20 to 14 bar. These operating conditions prevent the formation of the liquid phase in the turbine, guaranteeing its correct operation. With the energy flows evaluated for each of the ORC equipment, the energy efficiency of the cycle is calculated from Eq(1).

$$\eta_{th} = \frac{W_{neto}}{Q_{evap}} \tag{1}$$

Where, W_{neto}, is the difference in the work of the turbine and the pump, kW; and Q_{evap}, is the heat load of the evaporator, kW.

2.2 Exergy analysis

The exergy analysis evaluates the destruction of exergy in each of the equipment of an ORC, using equations derived from the general exergy balance in steady state, as shown in Eq(2).

$$\dot{E}x_{work} + \dot{E}x_{heat} + \sum\dot{E}x_{m,in} - \sum\dot{E}x_{m,out} = \dot{E}x_{dest} \tag{2}$$

Where $\dot{E}x_{work}$ is the exergy flow associated with the network of the system, kW; $\dot{E}x_{heat}$ is the exergy flow associated with the heat flow ($\dot{Q}$) in the system, kW; $\sum\dot{E}x_{m,in}$ and $\sum\dot{E}x_{m,out}$ are the exergy flows associated with the total mass flows entering and leaving the system, kW; and $\dot{E}x_{dest}$ is the exergy destruction rate in the system, kW. The exergy flow associated with each of the currents that crosses the system can be estimated from Eq(3).

$$\dot{E}x_m = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{3}$$

Where $\dot{m}$ is the mass flow rate through the system, kg/s; h is the specific enthalpy of the substance at the input or output conditions of the system, kJ/kg; h_0 is the specific enthalpy of the substance in the reference state, kJ/kg; s is the entropy of the substance in the conditions of entry or exit to the system, kJ/kg °C and s_0 is the entropy of the substance in the reference state, kJ/kg °C (for butane h_0= 627.53 kJ/kg and s_0 = 2.561 kJ/kg °C). The exergetic efficiency of the ORC is defined as the ratio of the useful exergy ($\dot{E}x_{util}$) and the total exergy ($\dot{E}x_{total}$) entering the system, Eq(4).

$$\eta_{ex} = \frac{\dot{E}x_{util}}{\dot{E}x_{total}} \tag{4}$$

2.3 Evaporator and condenser sizing

The heat transfer area of the evaporator is a variable that defines the total cost of the system, its magnitude is estimated with Eq(5).

$$A = \frac{Q}{U\Delta T_{ML}} \tag{5}$$

Q is the heat flow required for fixed electrical power production, kW; U is the global heat transfer coefficient, kW/m^{2}K, reported in Table 1 and ΔT_{ML} is the logarithmic mean temperature difference, °C that is calculated with Eq(6). Countercurrent flow is considered in the evaporator and condenser.

$$\Delta T_{ML} = \frac{(T_{H_{in}} - T_{C_{out}}) - (T_{H_{out}} - T_{C_{in}})}{\ln\left((T_{H_{in}} - T_{C_{out}})/(T_{H_{out}} - T_{C_{in}})\right)} \quad (6)$$

Variable T_H is the temperature of the hot fluid, °C; while T_c is the temperature of the cold fluid, °C; the subscripts in and out correspond to the currents that enter and leave each device.

2.4 Costs analysis

The total cost of the ORC is the sum of the cost of its main components, Eq(7).

$$Z_{total} = Z_{turb} + Z_{pump} + Z_{evap} + Z_{cond} \quad (7)$$

Where Z_{total} is the total cost of the ORC, USD; Z is the unit cost of each of the components of the ORC, USD; which was estimated from the relationships reported by Martínez-Rodríguez (2023) Eq(8-10).

$$Z_{hx} = 516.621A + 265.45 \quad (8)$$

$$Z_{pump} = 200\ W_{pump}^{0.65} \quad (9)$$

$$Z_{turb} = 10^{2.6259 + 1.4389 log(W_{turb}) - 0.1776 log(W_{turb})^2} \quad (10)$$

Where the subscripts $hx, pump$ y $turb$ refer to the heat exchange equipment (evaporator and condenser), the pump and the turbine, respectively. The auxiliary costs of operation, maintenance, installation, infrastructure, contingencies, supervision and labor were also considered, whose contribution is equal to 3 %, 25 %, 20 %, 20 %, 15 %, and 15 % of the total cost of the main equipment before financing. The total cost of equipment after financing can be determined from the Eq(11).

$$Z_{tot,eq} = (Z_{eq})(1 + i)^n \quad (11)$$

Where $Z_{tot,eq}$ is the total cost of the equipment after financing, USD; Z_{eq} is the cost of each piece of equipment calculated using Eq(8-10), USD; i is the annual interest rate (8 %) and n is the financing period (25 years). The levelized cost of energy is determined with Eq(12). Considering that the cycle operates for 18 hours in 350 days of the year.

$$LCOE_{el} = \frac{Z_{tot,eq} + Z_{tot,op\&mant}}{18 * 350 * 25 * W_{ORC}} \quad (12)$$

Where $Z_{tot,op\&man}$ is the sum of the contributions of the auxiliary costs already described.

3. Results

The results of the energy balance for each of the working fluids at the temperature level where they present the highest energy and exergetic efficiency are shown in Table 2. Butane presents the lowest heat load in the evaporator and condenser, and also requires a lower pumping power to operate and has the highest energy efficiency, 7.78 %, and exergetic efficiency, 28.88 %, and the lowest exergy destruction in each of the equipment that makes up the ORC. Furthermore, the greatest exergy destruction per equipment occurs in the evaporator for all the working fluids evaluated. Propane has an exergy destruction 2.56 times greater than that of butane.

Regarding the total destruction of exergy per equipment, using butane in the best operating conditions, from the exergetic point of view, the evaporator presents the highest destruction of exergy with 70 %, the total destruction of exergy in the condenser is 18 %, 8 % of the turbine and 4 % of the pump.

Destruction of exergy represents that the efficiencies of the equipment that make up the ORC can be increased, raising the global heat transfer coefficient of each of the main equipment of the ORC. Exergy destruction is directly related to the isentropic efficiencies of the devices used. Since the increase in isentropic efficiency reduces the destruction of exergy, that is, the pump transfers the work in a greater proportion to the fluid and in the case of the turbine, a greater amount of energy is used to generate the turbine shaft work. The total exergy destruction in the evaporator for isobutane is 75 % and for propane it increases to 79 %.

Table 2: Results of the energy balance at the point of maximum energetic and exergetic efficiencies.

Fluid	T_{eva} (°C)	Turbine	Pump		Evaporator		Condenser		Efficiency	
		$Ex_{d,turb}(kW)$	W_{pump} (kW)	$Ex_{d,pump}(kW)$	$Q_{evap}(kW)$	$Ex_{d,evap}(kW)$	Q_{cond} (kW)	$Ex_{d,cond}(kW)$	$\eta_{th}(\%)$	$\eta_{ex}(\%)$
Propane	85	555	277.49	513	74,149	12,469	70,682	2,304	3.87	14.36
Butane	80	555	145.01	268	38,574	4,912	34,994	1,041	7.78	28.88
Isobutane	80	555	161.44	299	44,709	6,286	41,144	1,184	6.68	24.78

Figure 1 shows the effect of the temperature at the evaporator outlet on the energy and exergy efficiency of the ORC for butane, which is the working fluid with the highest efficiency. In Figure 1a, a clear correspondence is observed between the decrease in thermal and exergetic efficiency with the increase in temperature. This behavior occurs because by increasing the temperature in the evaporator, the energy losses rise due to the increase in the temperature gradient between the evaporator temperature and the ambient temperature.

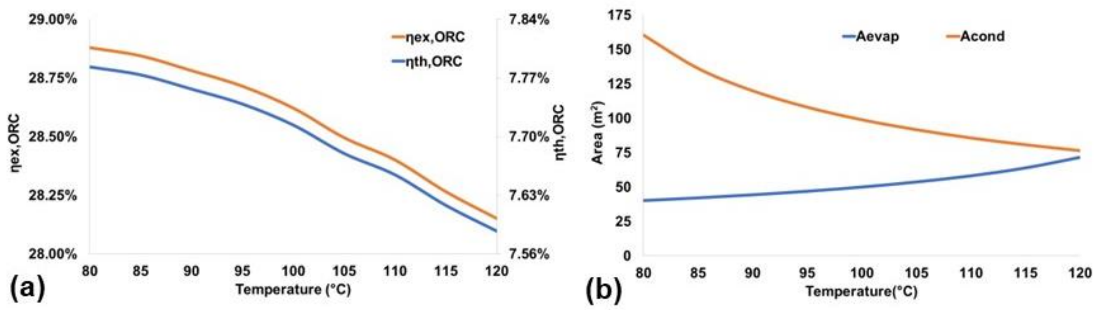

Figure 1: Behavior with respect to the temperature at the outlet of the ORC evaporator: (a) Exergy and energy efficiency, (b) Condenser area and evaporator area

The change in the gradient between the temperature of the working fluid at the outlet of the evaporator and the outlet temperature at the outlet of the heat source determines the size of the heat exchange equipment. In Figure 1b the behavior of the evaporator heat exchange area and the condenser heat exchange area with respect to the evaporator temperature are opposite. The condenser area increases with a smaller slope and the evaporator area decreases with a significantly larger slope. The value of ΔTML in the evaporator decreases as the evaporator outlet temperature approaches the source temperature (135 °C), while in the condenser the gradient values increase as the condenser inlet temperature moves away from the cooling water temperature (30 °C).

Figure 2 shows that the relationship of the total heat transfer area and the total cost of the ORC versus the evaporator outlet temperature presents a parabolic behavior, using butane as working fluid. The parabolas have a minimum value when the temperature is equal to 110 °C, the energy and exergetic efficiency values for butane in the economic optimum are 7.65 and 28.40 %, respectively, at this point the total heat transfer area is 1,924 m^2 and the total cost is 11,160,921 USD. There is a reduction in the evaporator heat transfer area of 24 % and a saving of 3,526,388 USD compared to the scenario with the best exergetic performance of the system. Butane, with a temperature at the evaporator outlet of 110 °C and a temperature at the condenser outlet of 42 °C, had the lowest levelized cost of energy, which is 0.022 USD/kWh.

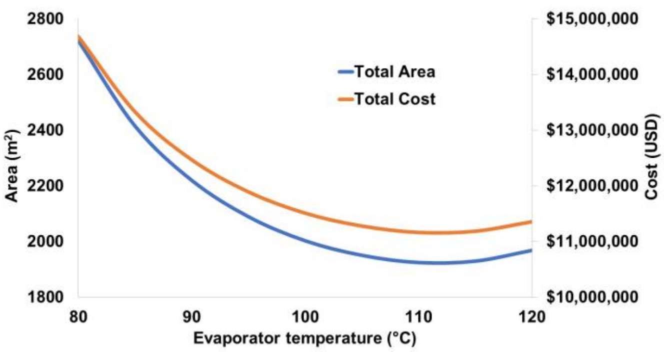

Figure 2: Effect of temperature on the area of the ORC evaporator and condenser. The working fluid is butane

4. Conclusions

The use of working fluids with low environmental impact such as propane, butane and isobutane allow the use of heat from low temperature sources, having an exergetic efficiency of 28.88 % for butane and 14.20 % with propane, this highlights the importance of selection of the working fluid for the operation of the ORC.
From the results, butane is the thermal fluid that presents the greatest exergy destruction, therefore, the greatest potential to increase its efficiency and reduce the area of the evaporator and condenser, representing between 88 to 94 % of the total destroyed ORC exergy.
The destruction of exergy increases with the increase in temperature at the evaporator outlet, which in turn causes the overall exergy efficiency of the ORC to decrease. This data is important to increase the efficiency of the equipment and the ORC.
The minimum levelized cost of energy was for butane (0.022 USD/kWh), with a condenser outlet of 42 °C and an evaporator outlet of 110 °C.

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