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THERMODYNAMIC ANALYSIS OF A SMALL-SCALE HELIOTHERMAL PLANT OPERATING ON ORGANIC RANKINE CYCLE WITH RECUPERATOR

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Abstract. *Concentrated Solar Power (CSP) plants transform concentrated solar energy into thermal energy. In this first energy conversion, they use collector mirrors to concentrate solar radiation and increase the temperature of a thermal fluid that circulates within a closed circuit. Then, the thermal energy is transferred to a vapor generation circuit (Rankine cycle), where the turbine-generator set converts mechanical energy into electrical energy. In cases where the power cycle uses organic fluids, it is referred to as an Organic Rankine Cycle (ORC). Therefore, the performance of a solar thermal plant depends on two the conditions: the primary cycle (solar field) and the characteristics of the secondary circuit (power cycle). In this context, the present work aims to analyze the efficiency of a small-scale solar thermal plant operating with an Organic Rankine Cycle with a recuperator. The primary circuit operates with Therminol VP-1 as the thermal fluid, while the secondary circuit was simulated to operate with dry and isentropic organic fluids, all available in the EES software. It is noteworthy that the chosen organic fluids require the inclusion of a heat exchanger (recuperator) to complete the thermodynamic cycle. So, an algorithm was developed in EES, where the Rankine cycle was configured to operate up to a pressure of 2 MPa, while at the pump and condenser inlet the fluid has a temperature of 25°C and a quality of 0 and 1, respectively. As a result of the analysis, the performance of the ORC for each fluid was obtained, as well as an equation that relates the net work (generated electrical energy) to the collector area required in the solar field. It was evidenced that this parameter depends on the efficiency of the Rankine cycle, the efficiency of the heat exchanger, the efficiency and concentration factor of the solar collector, as well as the direct normal solar irradiation where the CSP plant is installed.*

Keywords: *Heliothermal Plants, Concentrated Solar Power, Organic Rankine Cycle, Rankine Cycle Efficiency, Solar field*

1. INTRODUCTION

Solar energy is an abundant and widely available resource that can be used to generate electricity. Heliothermal technology, also known as Concentrated Solar Power (CSP), uses thermodynamic processes to convert solar energy into electricity. According to Souza et al. (2024), in 2020 the world produced approximately 27 million GWh of electric energy, with most heliothermal power plants operating in Spain and the United States, which together hold over 80% of the global installed CSP capacity.

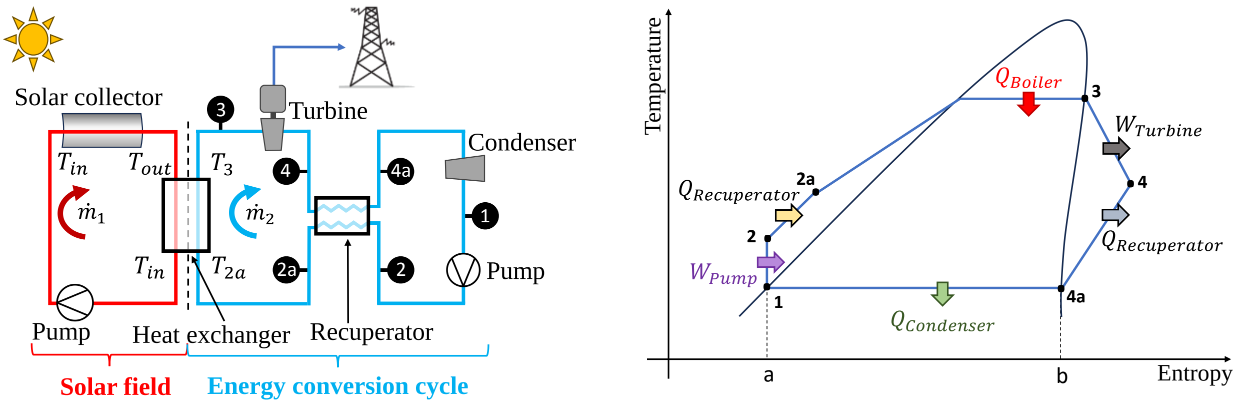
The distinguishing feature of this technology is its ability to generate electricity even in the absence of sunlight, due to thermal energy storage systems. Although these systems are optional, they increase the efficiency of the cycle. Additionally, CSP plants are classified as a clean technology since they do not emit greenhouse gases during operation (Costa and Neto, 2018). However, the main challenge for their implementation is the high initial cost, which is offset in the long term by low operation and maintenance costs (Heler, 2017).

Heliothermal plants can be either large-scale or small-scale. Large-scale plants, typically installed in regions with high solar radiation and low cloud cover, operate between 500°C and 1000°C (Ferrara, Gimelli, Luongo, 2014). To achieve these temperatures, an extensive energy collection area is required. On the other hand, small-scale plants, installed in regions with lower solar radiation, operate below 500°C and generally use the ORC (Giovannelli, 2015). These cycles use organic fluids with low boiling points, allowing for the generation of electricity from heat sources ranging from 60°C to 350°C (Tanuma, 2022). The advantages of are modularity and versatility, enabling integration with various heat sources, including geothermal, biomass, and solar (Quoilin, 2011). According to Orosz (2019), organic fluids are more effective than water in applications of low-temperature and small-scale applications, such as buildings, commercial establishments, and healthcare facilities.

Thus, this work aims to study a real ORC with recuperator, considering a small-scale heliothermal plant without thermal energy storage, and to establish criteria of selecting the best dry organic fluids available in the EES software.

2. CSP POWER PLANT

Heliothermal power plants are electricity generation facilities that operate through energy conversion processes. These plants typically employ two interconnected circuits, as shown in Fig. 1a. The first circuit (red circuit in Fig. 1a), reffers to the solar field, involves the conversion of solar energy into thermal energy, achieved through solar collectors that concentrate solar radiation. This energy is absorbed by the primary fluid and transferred to a heat exchanger, which then transfers it to the second circuit (blue circuit in Fig. 1a), known as the energy conversion cycle. In this cycle, thermal energy is converted into mechanical energy and subsequently electrical energy using a Rankine cycle. In the ORC systems operating with dry or isentropic fluids, a recuperator is incorporated, as indicated in Fig. 1a and thermodynamically illustrated in Fig. 1b.



(a) **(b)**

Figure 1 - (a) Schematic representation of a CSP plant, (b) Rankine cycle with recuperator.

Depending on the application, energy from the solar field can be stored thermally (in reservoirs) and used to generate electricity after sunset or during periods of adverse weather conditions (ensuring dispatchability of the plant, i.e., a way to store energy as a backup), which can be considered as a third subsystem working in conjunction with the solar field. However, following the objective of this work, these components will not be considered in the analysis.

2.1 Solar Field

In this study, the solar field considered consists of the following components: solar collector, pump, and heat exchanger (Fig. 1a). The solar collector concentrates solar radiation onto a receiver (region of highest temperature in the circuit, due to the concentrators), heating an internal thermal fluid that circulates. There are essentially four types of technologies that can be employed in CSP: Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR), Solar Parabolic Dishes (SPD), and Solar Power Tower (SPT). They all operate similarly concentrating radiation to achieve high temperatures, but the main difference lies in the concentration method, which allows for higher temperature attainment. The pump is responsible for providing work (energy) to the fluid, cyclically moving it through the solar field circuit. The heat exchanger transfers thermal energy to the secondary circuit.

The working fluids in the solar field commonly operate in a single-phase liquid state. They are manufactured or selected to withstand the high temperatures reached at the receivers and should not exhibit high degradation rates over their lifespan. Since CSPs employ the principle of solar concentration to increase the temperature of the primary fluid, which is then transferred to the secondary circuit via the heat exchanger, any variation in solar irradiance will directly impact the behavior of the Rankine cycle (Pabon et al., 2024).

2.2 Rankine Cycle

In this analysis, a real Rankine cycle with a recuperator was considered (Fig. 1b). The circuit is composed of five elements: (a) a pump that compresses the fluid (points 1→2); (b) a boiler (idealized as a heat exchanger) that adds heat at constant pressure (points 2a→3); (c) a turbine that converts mechanical energy into electrical energy (points 3→4); (d) a recuperator that uses energy from the turbine (points 4→4a) to preheat the working fluid (points 2→2a); and (e) a condenser that rejects heat at constant pressure (points 4a→1).

For the considered circuit, internal irreversibilities are neglected. The fluid enters the pump as saturated liquid and exits pressurized, achieving a subcooling region up to the boiler's operating pressure. In the boiler, the compressed liquid is transformed into vapor due to the addition of heat from the CSP plant's solar field. The high-energy vapor expands in the turbine, converting the thermal energy of the fluid into rotational kinetic energy. As the turbine and the electric generator share the same shaft, this rotational movement induces the production of electric energy. The remaining thermal energy in the expanded vapor is utilized in the recuperator to preheat the working fluid. Subsequently, the fluid enters the condenser as saturated vapor and, by rejecting heat to the environment, is transformed into saturated liquid, completing the phase change cycle of the secondary fluid and becoming available to be compressed again by the pump.

It is important to note that Fig. 1b is out of scale, as points 1 and 2 are closer than shown. This happens because all pressure lines for the subcooled liquid are very close to the saturation curve. The pump and the boiler add work and energy to the system, while the turbine and the condenser extract work and energy from the system, respectively. The difference between the work extracted by the turbine and the work added by the pump results in the net work to produce electricity, while the ratio between the net work and the heat added in the boiler represents the thermal efficiency of the cycle.

2.3 Modeling the CSP Power Plant Operating With Organic Fluids

The values of the energy potential of a CSP plant are linked to the solar energy flux (W/m²), specifically the Direct Normal Irradiance (DNI) from the sun, which depends on the plant's location. It is important to note that other factors should be considered, such as the amount of rainfall and cloud cover in the region. Therefore, the design of a CSP plant should take into account collector field area (A) and concentration factor (F_c), which is related to the type of technology used. A larger collector area and concentration factor result in a higher heat transfer rate to the primary fluid. However, not all incident solar energy is transferred to the primary fluid, so the collector efficiency ($\eta_{Collector}$) must be considered to estimate the useful heat flux from the solar field.

In this model, a PTC solar collector was considered, which concentrates solar rays onto an absorber tube. The PTC uses parabolic mirrors to focus solar radiation along its focal line. A high-absorptivity metal tube is located on this line, surrounded by an evacuated glass tube to minimize heat loss by convection. This assembly forms the receiver, where the internal fluid is heated when direct solar radiation strikes it (Lampkowski, 2017). To maximize fluid heating, many PTCs are equipped with solar tracking systems that follow the sun's movement to maintain perpendicular solar incidence on the collector aperture.

Due to construction complexity, heat transfer phenomena, and material quality, approximately 55% of incident solar energy on the collectors is lost. Major losses include cosine factor (12%), thermal losses in the receiver and piping (18%), reflectance (6%), and other losses such as cleaning, shading, transmittance, and absorptance (19%) (Heller, 2017). Thus, around 45% of solar energy is converted into thermal energy.

Thus, analyzing the above, the equation that determines the amount of energy absorbed by the primary fluid is:

$$Q_1 = \eta_{Collector} \cdot F_c \cdot A \cdot DNI \tag{1}$$

where the collector efficiency ($\eta_{Collector}$) and concentration factor (F_c) are dimensionless parameters, while the collector area (A) is measured in m^2, and the DNI is given in $\mathrm{W/m}^2$. According to Sanchez et al. (2020), F_c values dependes on the CSP concentrator technology used; PTC technology typically has concentration factors below 50.

Since the primary circuit generally uses single-phase working fluids, the temperature increases of the primary fluid passing through the PTC can be calculated using the sensible heat equation:

$$Q_1 = \dot{m}_1 \cdot c_{p_1} \cdot (T_{out} - T_{in}) \tag{2}$$

where $\dot{m}_1$ represents the mass flow rate of the fluid in the solar field circuit (kg/s), c_{p_1} is the specific heat of the primary fluid (kJ/kg·K), and ΔT is the temperature difference (K). According to Fig. 1a, T_{out} and T_{in} are the outlet and inlet collector temperatures, respectively.

To determine the radiant energy incident on the receiver, is necessary consider collector efficiency as 1 in Eq. 1. Thus, the incident solar energy is given by:

$$Q_{Sun} = F_c \cdot A \cdot DNI \tag{3}$$

The present model assumes that a portion of the total energy absorbed by the primary circuit is transferred to the secondary circuit through the heat exchanger. Therefore, considering the heat exchanger efficiency, one obtains:

$$Q_{Boiler} = \eta_{HE} \cdot Q_1 \tag{4}$$

To model the energy conversion cycle (secondary circuit), the methodology of thermodynamic analysis of a Rankine cycle was employed.

Assumptions of the ORC. The parameters and boundary conditions of a real Rankine cycle with recuperator were established as follows:

- **Point 1:** Saturated liquid with quality equal to zero and temperature of 25°C;
- **Point 2:** Pump outlet pressure of 2 MPa;
- **Point 2a:** Compressed liquid at 2 MPa and reheating from the recuperator;

- **Point 3:** Same pressure as point 2a and quality equal to 1;
- **Point 4:** Turbine expansion, pressure equal to point 1 pressure;
- **Point 4a:** Saturated vapor with quality equal to one and temperature equal to 25°C.

Besides that assumptons, no power limitations were considered for the heat required by the boiler or for the heat removed by the condenser. Therefore, the ORC performance is constrained by the thermophysical properties of the evaluated fluids under the previously established conditions. Since boiler Rankine cycle is represented by the heat exchanger in the CSP plant, Fig. 1a, it follows that, for a given mass flow rate, the energy of the secondary circuit equals the boiler heat, thus:

$$Q_2 = Q_{Boiler} = \dot{m}_2 \cdot (h_3 - h_{2a}) \tag{5}$$

where $\dot{m}_2$ represents the mass flow rate of the organic fluid in the energy conversion cycle (kg/s), while h_{2a} and h_3 are the enthalpies at the inlet and outlet of the boiler, respectively (kJ/kg).

Similarly, the equations governing the other elements of the Organic Rankine Cycle are:

✓ ***Pump:***

$$W_{Pump} = \dot{m}_2 \cdot (h_2 - h_1) \tag{6}$$

since the device is considered real, h_2 is obtained using the pump isentropic efficiency, which is assumed to be 80% for the studied cases. Thus:

$$\eta_{Pump} = (h_{2s} - h_1)/(h_2 - h_1) \tag{7}$$

The term h_{2s} refers to the enthalpy under isentropic conditions, that is, $h_{2s} = h(P_2; s_{2s})$, in other words, the enthalpy at point 2s is obtained from the pressure at point 2 and the entropy at point 1 (since $s_{2s} = s_1$, due to the isentropic condition).

✓ ***Turbine:***

$$W_{Turb.} = \dot{m}_2 \cdot (h_3 - h_4) \tag{8}$$

Since the turbine is considered real, h_4 is obtained using its isentropic efficiency, which is assumed to be 80% for the cases studied. Thus:

$$\eta_{Turb.} = (h_3 - h_4)/(h_3 - h_{4s}) \tag{9}$$

The term h_{4s} refers to the enthalpy under isentropic conditions, i.e., $h_{4s} = h(P_4; s_{4s})$, where $s_{4s} = s_3$ due to the isentropic condition, with units of kJ/kg.

✓ ***Condenser:***

$$Q_{Cond} = \dot{m}_2 \cdot (h_{4a} - h_1) \tag{10}$$

where h_{4a} and h_1 correspond to the enthalpies at the inlet and outlet of the condenser, respectively, measured in kJ/kg.

✓ ***Recuperator:***

Since it is considered a real device, a portion of the recovered energy for heating the fluid is lost. Therefore, an efficiency must be considered for this device, as follows:

$$\eta_{Rec} = (h_{2a} - h_2)/(h_4 - h_{4a}) \tag{11}$$

In this study, an efficiency of 80% was considered for the recuperator. As mentioned earlier, the cycle net work corresponds to the electrical generation of the CSP plant, determined by:

$$W_{NW.} = W_{Turb.} - W_{Pump} \tag{12}$$

So, the thermodynamic efficiency of the Rankine cycle is given by:

$$\eta_{Rankine} = (W_{NW.}/Q_{Boiler}) \cdot 100\% \tag{13}$$

Given that the Rankine cycle is a thermodynamic cycle, its efficiency can be compared to the maximum theoretical efficiency of a heat engine (Carnot efficiency), which is determined by:

$$\eta_{Carnot} = \left(1 - \frac{T_1}{T_3}\right) \cdot 100\% \tag{14}$$

where the temperatures at point 1 and point 3 correspond to the minimum and maximum temperatures of the Rankine cycle, respectively. In the adopted methodology, it was considered that the heat exchanger has an infinite thermal exchange area. Therefore, the inlet temperature of the primary fluid into the heat exchanger (T_s) is equal to the outlet temperature of the secondary fluid (T_3) after passing through the exchanger.

The efficiency of a CSP plant is determined by the ratio of the net work obtained from the secondary circuit to the incident solar energy from the primary circuit, given by:

$$\eta_{CSP} = (W_{NW.}/Q_{Sun}) \cdot 100\% \tag{15}$$

With these previous equations and the assumptions established for the ORC, it is possible to compare the electrical production of a CSP operating with real Rankine cycle with recuperator using differents dry and isentropic organic fluids.

The performance of the plant was simulated using the Engineering Equation Solver (EES) software. The Table 1 show the parameters and boundary conditions for both subsystems.

Table 1 - Parameters and boundary conditions of the CSP plant.

SUBSYSTEM	PARAMETER	VALUE
Solar Field	Primary Fluid	Therminol VP-1
	Mass flow rate of primary circuit	1 kg/s
	PTC concentration factor	5
	PTC collector efficiency	45%
	Direct Normal Irradiance (DNI)	830 W/m²
	Heat Exchanger Efficiency** (η_{HE})	100%
Energy Conversion Cycle	Secondary Fluid	Diverse organic fluids
	Mass flow rate of secondary circuit	0,03 kg/s

** Technically, the heat exchanger is part of both subsystems, serving as the boiler for the energy conversion cycle

The calculation methodology implemented in the EES software is summarized in the flowchart shown in Fig. 2.

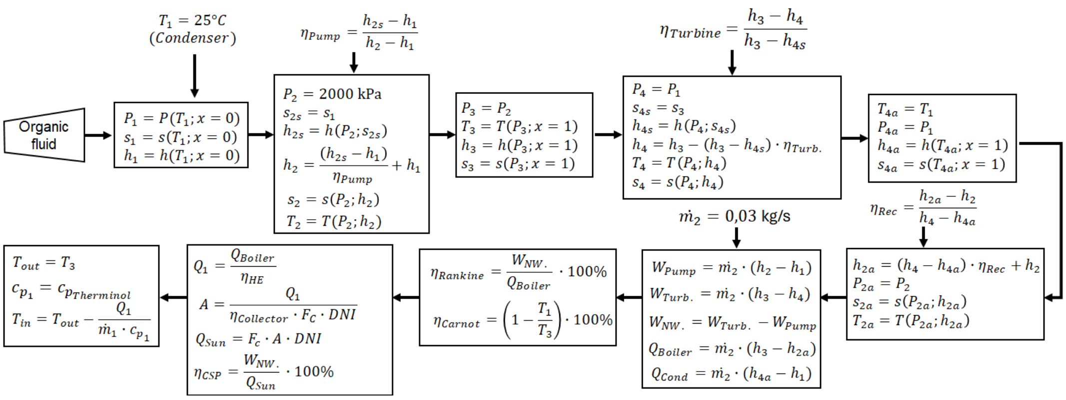


Figure 2 – Calculation flowchart for the CSP plant operating with organic fluids.

The organic fluids were selected based on their critical pressures and temperatures above 2MPa and 100°C, respectively. This ensures that the working fluid in the secondary circuit operates under saturated conditions, thereby reducing the process total irreversibility (Somayaji et al., 2006).

In this analysis, dry and isentropic organic fluids were considered, i.e., fluids where the saturation curve on the vapor side exhibits positive slopes for temperature and entropy ($ds/dT_{vapor} > 0$) and nearly zero ($ds/dT_{vapor} \sim 0$), respectively. This condition necessitates the implementation of the Rankine cycle with a recuperator, as depicted in Fig. 1b. Compared to a simple Rankine cycle, this configuration incorporates an additional component, the recuperator, positioned after the turbine expansion to recover thermal energy from the superheated vapor and promote its condensation. According to Tchanche et al. (2011), the values of ds/dT for organic fluids impact the efficiency of the Rankine cycle and the arrangement of its components.

3. RESULTS AND DISCUSSION

The fluid selection was based on organic fluids available in the EES software that satisfy the predefined conditions. Table 2 presents the 23 analyzed fluids, indicating their thermodynamic states as specified for the ORC cycle. It is noted that a significant portion of the energy exiting the turbine (T_4) is absorbed by the fluid after passing through the recuperator (T_{2a}); this preheating of the fluid reduces the boiler's energy requirement, thereby lowering the amount of energy needed to achieve the cycle's maximum efficiency. Additionally, among the 23 fluids analyzed, 12 operate at pressures below 101.3 kPa (P_1), necessitating the ORC to operate under vacuum conditions for these fluids.

Table 3 presents the performance of the Rankine cycle with recuperation for each fluid, based on the thermodynamic states from Tab. 2, demonstrating that the results meet the criteria established in Tab. 1. The Rankine cycle was designed to ensure cooling (25°C) and heating (until each fluid reaches the saturation temperature at 2 MPa). Its performance depends exclusively on the thermodynamic properties of the organic fluid.

Table 2 – Thermodynamic Parameters of the Fluids According ORC Considerations.

Secondary Fluids	Chemical Formula	T_{Cr} [°C]	P_{Cr} [kPa]	$P_1 = P_4$ [kPa]	$T_1 = T_{4a}$ [°C]	T_2 [°C]	T_{2a} [°C]	T_3 [°C]	T_4 [°C]	H_1 [kJ/kg]	H_2 [kJ/kg]	H_{2a} [kJ/kg]	H_3 [kJ/kg]	H_4 [kJ/kg]	H_{4a} [kJ/kg]
O-Xylene	C_8H_{10}	357,10	3738	0,90	25	25,58	112,80	306,60	163,80	-234,60	-231,70	-65,57	602,70	382,30	174,70
N-Decane	$C_{10}H_{22}$	344,50	2103	0,18	25	25,71	156,80	340,80	219,50	-372,10	-368,60	-46,85	605,40	391,20	-11,01
N-Nonane	C_9H_{20}	321,40	2281	0,58	25	25,73	143,30	312,70	201,60	-309,70	-306,20	-18,93	612,20	411,90	52,92
Toluene	C_7H_8	318,60	4126	3,79	25	25,78	83,45	262,80	123,10	-158,20	-155,30	-51,63	571,10	384,10	254,40
N-Octane	C_8H_{18}	296,20	2497	1,84	25	25,76	123,40	279,90	174,20	-0,09	3,48	239,60	840,50	659,50	364,30
Cyclohexane	C_6H_{12}	280,50	4075	13,02	25	25,87	81,47	226,40	116,90	32,36	35,57	146,20	719,30	562,90	424,50
Benzene	C_6H_6	288,90	4894	12,69	25	25,80	57,36	221,40	84,59	-100,10	-97,26	-41,11	564,70	403,20	333,00
Dimethylcarbonate	$C_3H_6O_3$	284,20	4909	7,20	25	25,60	63,31	223,80	92,40	-125,10	-119,50	-51,02	541,90	381,70	296,10
N-Pentane	C_5H_{12}	196,50	3364	68,92	25	25,97	60,90	163,30	82,56	-2,11	1,77	85,47	573,30	468,80	364,20
Isopentane	C_5H_{12}	187,20	3370	91,69	25	26,01	59,45	154,10	79,07	-350,00	-346,20	-267,60	186,40	92,89	-5,31
R141b	$C_2H_3Cl_2F$	204,20	4249	78,47	25	27,31	41,99	156,50	52,42	67,51	70,17	87,44	374,30	315,90	294,30
Hfe7000	$C_4F_9OCH_3$	164,60	2478	69,47	25	27,60	69,63	152,50	90,01	75,53	78,30	126,10	307,40	270,60	210,80
R11	CCl_3F	198,00	4408	105,60	25	27,49	34,65	146,90	38,18	55,60	57,76	64,02	286,50	243,30	235,50
R245fa	$C_3H_3F_5$	154,00	3651	147,80	25	25,89	40,32	121,80	50,25	232,50	234,20	253,40	485,10	446,80	422,80
Cis-2-Butene	C_4H_8	162,60	4226	213,60	25	26,12	33,47	118,30	38,71	47,03	50,65	67,21	537,10	461,10	440,40
N-Butane	C_4H_{10}	152,00	3796	243,70	25	26,15	41,02	114,40	49,89	259,40	263,20	299,90	735,90	666,00	620,10
Trans-2-Butene	C_4H_8	155,50	4027	234,00	25	27,27	36,35	114,90	41,51	57,75	61,42	82,75	537,00	464,50	437,90
R114	$CClF_2CClF_2$	145,70	3289	213,20	25	27,13	45,95	118,40	58,04	60,78	62,95	82,58	239,40	213,70	189,10
Butene	C_4H_8	146,10	4005	303,50	25	26,05	35,07	106,80	40,46	69,97	73,57	94,52	518,50	456,20	430,00
R236fa	$C_3H_2F_6$	124,90	3200	272,00	25	26,01	37,29	101,60	44,77	230,40	232,00	246,00	417,00	393,20	375,70
Rc318	C_4F_8	115,20	2778	312,40	25	26,06	43,14	98,69	53,78	227,10	228,50	247,80	372,30	355,40	331,30
R124	C_2HClF_3	122,30	3624	383,50	25	26,06	32,01	91,36	35,37	227,70	229,20	236,00	403,90	382,70	374,30
R1234ze	$C_3H_2F_4$	109,40	3632	500,10	25	26,02	29,66	79,83	31,07	234,30	235,90	241,00	427,40	407,20	400,80

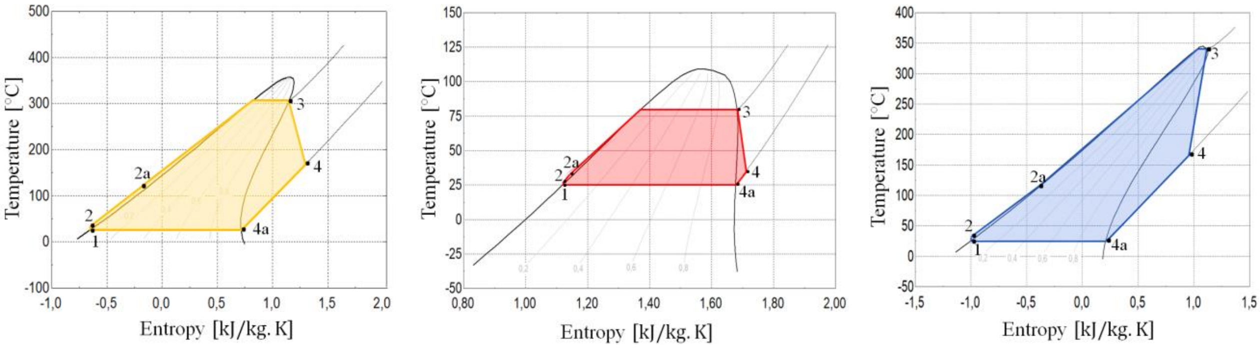
In the assumptions, the heat required by the boiler was not restricted. Since all this energy will be supplied by the solar field, this allows the simulation to determine the necessary PTC collector area according to the demand. Once the heat is supplied to the boiler and the fluid is in saturated vapor at 2 MPa, the turbine work depends on the thermodynamic properties of the fluid analyzed. Therefore, Tab. 3 presents, in its last column, the ratio between the net work and the solar collector area for each simulated ORC. This parameter relates the potential electrical energy produced in the secondary circuit to the collector area of the primary circuit, allowing the comparison of the performance of the 23 fluids studied. This parameter is organized in descending order, as higher values indicate that the fluid can produce more electrical energy per square meter of collector area.

Table 3 – Performance of the CSP Plant Operating with Various Organic Fluids, According to the Parameters in Tab. 1.

Secondary Fluids	Q_{Boiler} [kW]	Q_{Cond} [kW]	W_{Pump} [kW]	$W_{Turb.}$ [kW]	$W_{NW.}$ [kW]	$\eta_{Rankine}$ [%]	η_{Carnot} [%]	Q_1 [kW]	A [m²]	Q_{Sun} [kW]	η_{csp} [%]	T_{out} [°C]	T_{in} [°C]	$P_{Turb.}/P_{cr}$ [-]	$W_{NW.}/A$ [W/m²]
O-Xylene	20,05	12,28	0,09	6,61	6,53	32,55%	48,57%	20,05	10,74	44,55	14,65%	306,60	303,20	0,54	516,64
N-Decane	19,57	10,83	0,11	6,43	6,32	32,30%	51,44%	19,57	10,48	43,49	14,54%	340,80	338,50	0,95	512,78
N-Nonane	18,93	10,88	0,11	6,01	5,90	31,18%	49,11%	18,93	10,14	42,08	14,04%	312,70	309,70	0,88	494,98
Toluene	18,68	12,38	0,09	5,61	5,52	29,56%	44,37%	18,68	10,00	41,51	13,31%	262,80	259,10	0,48	469,28
N-Octane	18,03	10,93	0,11	5,43	5,32	29,53%	46,09%	18,03	9,66	40,06	13,28%	279,90	276,50	0,80	468,69
Cyclohexane	17,19	11,76	0,10	4,69	4,60	26,73%	40,32%	17,19	9,21	38,21	12,02%	226,40	222,70	0,49	424,31
Benzene	18,17	12,99	0,09	4,85	4,76	26,19%	39,71%	18,17	9,73	40,38	11,79%	221,40	217,50	0,41	415,73
Dimethylcarbonate	17,79	12,64	0,17	4,81	4,64	26,07%	40,00%	17,79	9,53	39,53	11,73%	223,80	220,00	0,41	413,90
N-Pentane	14,63	10,99	0,12	3,14	3,02	20,63%	31,69%	14,63	7,84	32,52	9,28%	163,30	159,90	0,59	327,41
Isopentane	13,62	10,34	0,11	2,81	2,69	19,76%	30,22%	13,62	7,29	30,27	8,89%	154,10	151,00	0,59	313,66
R141b	8,61	6,80	0,08	1,75	1,67	19,43%	30,61%	8,61	4,61	19,13	8,74%	156,50	154,50	0,47	308,44
Hfe7000	5,44	4,06	0,08	1,10	1,02	18,77%	29,95%	5,44	2,92	12,09	8,45%	152,50	151,20	0,81	297,95
R11	6,67	5,40	0,06	1,30	1,23	18,45%	29,02%	6,67	3,57	14,83	8,31%	146,90	145,30	0,45	292,82
R245fa	6,95	5,71	0,05	1,15	1,10	15,80%	24,51%	6,95	3,72	15,44	7,11%	121,80	120,20	0,55	250,75
Cis-2-Butene	14,10	11,80	0,11	2,28	2,17	15,40%	23,83%	14,10	7,55	31,32	6,93%	118,30	114,90	0,47	244,51
N-Butane	13,08	10,82	0,11	2,10	1,98	15,16%	23,07%	13,08	7,00	29,07	6,82%	114,40	111,30	0,53	240,65
Trans-2-Butene	13,63	11,40	0,11	2,18	2,06	15,15%	23,17%	13,63	7,29	30,29	6,82%	114,90	111,70	0,50	240,53
R114	4,70	3,85	0,07	0,77	0,71	15,00%	23,85%	4,70	2,52	10,46	6,75%	118,40	117,30	0,61	238,18
Butene	12,72	10,80	0,11	1,87	1,76	13,84%	21,53%	12,72	6,81	28,26	6,24%	106,80	103,80	0,50	219,77
R236fa	5,13	4,36	0,05	0,71	0,67	12,98%	20,44%	5,13	2,75	11,40	5,85%	101,60	100,30	0,63	206,08
Rc318	3,74	3,13	0,04	0,51	0,47	12,45%	19,82%	3,74	2,00	8,30	5,60%	98,69	97,81	0,72	197,63
R124	5,04	4,40	0,05	0,64	0,59	11,73%	18,21%	5,04	2,69	11,19	5,28%	91,36	90,16	0,55	186,25
R1234ze	5,59	5,00	0,05	0,61	0,56	9,98%	15,53%	5,59	2,99	12,43	4,49%	79,83	78,49	0,55	158,40

The descending organization of the parameter ($W_{NW.}/A$) in Tab. 3 is similar to that observed for the plant efficiency (η_{CSP}) and the Rankine cycle efficiency ($\eta_{Rankine}$), indicating a direct correlation between these parameters. Columns T_{in} and T_{out} in Tab. 3 respectively show the inlet and outlet temperatures of Therminol VP 1, the primary fluid passing through the solar collector. For this analysis, this thermal fluid remained in liquid state under simulated conditions.

Figure 3 presents the organic Rankine cycle with recuperator for the fluids O-Xylene, R1234ze, and n-Decane, respectively, all as described in the thermodynamic conditions of Tab. 2.



a) O-Xylene. b) R1234ze. c) n-Decane.

Figure 3 – Representation of the Actual Rankine Cycles with Recuperator for Three Analyzed Fluids.

When comparing the ORC of the fluids O-Xylene and R1234ze with n-Decane (Fig. 3), it is observed that the n-Decane cycle is near its critical point. This occur because the pressure imposed at the turbine (2 MPa) is 0.95 times its critical pressure, as indicated in the penultimate column of Tab. 3. This column relates the inlet pressure at the turbine to the critical pressure of the analyzed fluid. The lower this value, the greater the potential of the fluid to increase net work production, provided that the turbine can operate at higher pressures. Therefore, despite n-Decane presenting the second highest Rankine efficiency (32.30%), the increase in net work from raising the working pressure in the turbine is quite limited. On the other hand, O-Xylene and R1234ze, despite having similar pressure ratios of 0.54 and 0.55 respectively, are entirely different fluids, in other words, O-Xylene has the highest Rankine efficiency (32.55%), while R1234ze has the lowest Rankine efficiency (9.98%). Although both fluids indicate potential work increment with pressure increase, the critical temperature of R1234ze limits the amount of net work that can be increased. For R1234ze, according to the Carnot cycle, the maximum achievable efficiency is 22%, considering the boiler temperature near critical temperature and the condenser temperature at 25°C. Under simulated conditions, due to the low boiler temperature, the collector area required for R1234ze was among the smallest. This factor is relevant for small-scale CSP plants operating at low temperatures, despite the fluid's lower efficiency.

Analyzing the parameter $W_{NW.}/A$ and rearranging the equations involved, the following expression is obtained:

$$\frac{W_{NW.}}{A} = \eta_{Rankine} \cdot \eta_{HE} \cdot \eta_{Collector} \cdot F_c \cdot DNI \tag{16}$$

Equation (16) highlights that the selection parameter considered in this study is a function of the Rankine cycle efficiency (secondary circuit), the heat exchanger efficiency (common to both subsystems), the efficiency and concentration factor of the solar collector (primary circuit), and the DNI, characteristic of the CSP site. This demonstrates that, due to CSP systems having series circuits, all components directly affect their performance and sizing. Similarly, by rearranging Eq. 16, one obtains:

$$\eta_{CSP} = \eta_{Rankine} \cdot \eta_{HE} \cdot \eta_{Collector} \tag{17}$$

Equation (17) shows that the efficiency of CSP depends on the contribution of the efficiency of each of its subsystems.

Thus, among the fluids analyzed in this study, according to the criterion of Eq. (17), O-Xylene stood out as the best organic fluid for operation in a CSP, achieving a CSP efficiency of 12.45% and a net work per collector area of 516.64 W/m². In the following, the next five organic fluids are: n-Decane, n-Nonane, Toluene, n-Octane, and Cyclohexane, all with CSP efficiencies above 10.20% (Tab. 3). The remaining fluids have CSP efficiencies ranging from 10.20% to 3.80%. Considering that the parameters of heat exchanger efficiency, collector efficiency, concentration factor, and DNI were kept constant in the simulation, it can be stated that the differences highlighted by Eq. (17) stem from the characteristic Rankine cycle efficiency of each fluid. It is important to note that this analysis was limited to assessing the thermodynamic effects of fluids on the performance of CSP plants, without considering other aspects such as availability, toxicity, or environmental safety of the organic fluids evaluated.

4. CONCLUSIONS

The main motivation for using organic fluids in CSP Rankine cycles is their low boiling temperature, which enables evaporation and condensation with lower thermal load compared to water in conventional Rankine cycles. In this study, a CSP plant was simulated operating with Therminol VP-1 as the primary fluid in the solar field and 23 secondary organic fluids in the energy conversion cycle, forming a real Rankine cycle with a recuperator. The system operates at a maximum pressure of 2 MPa at the turbine inlet, with a temperature of 25°C and quality values of 0 and 1 at the pump and condenser inlets, respectively. The mass flow rate of the ORC was fixed at 0.03 kg/s for all organic fluids and 1 kg/s for Therminol VP-1. The parabolic trough collector has an efficiency of 45% and a concentration factor of 5. Efficiencies considered were 100% for the heat exchanger and 80% for both the pump and turbine. The CSP plant was located in a region with a Direct Normal Irradiance (DNI) of 830 W/m². Based on these settings, the performance of the CSP plant was simulated using an algorithm developed in EES software, and the 23 selected organic fluids were chosen from its database.

A equation was established that correlates the efficiency of each subsystem with the overall efficiency of a CSP. It was found that this parameter depends on the Rankine cycle efficiency, the heat exchanger, and the solar collector.

According to this criterion, the six best organic fluids for operating a CSP are: O-Xylene, n-Decane, n-Nonane, Toluene, n-Octane, and Cyclohexane. This study evaluated only the thermodynamic behavior of a CSP using Therminol VP-1 in the solar field circuit and various organic fluids in the energy conversion cycle. The analysis focused on the thermodynamic effects of the fluids on the CSP plant performance, without considering other aspects such as availability, toxicity, flammability, costs, or environmental safety of the organic fluids evaluated.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE