SELECTION OF THE WORKING FLUID FOR A HIGH TEMPERATURE ORC HOT-SOURCE TO BE APPLIED IN THE BRAZILIAN SEMI-ARID

by

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Original scientific paper
https://doi.org/10.2298/TSCI220718201S

This paper aims to select the most suitable working fluid to be applied in a high temperature regenerative hot-source ORC, such as those driven by biomass, for climatic conditions measured from real data in Bom Jesus da Lapa in northeastern Brazil. To this end, the most commonly used working fluids in these systems were selected among numerous authors, discarding those with high GWP and ozone depletion potential and those classified as wet according to the slope of their temperature-entropy diagram. Then, from the model developed in the software EES, the simulation and performance analysis of the proposed system was performed based on thermal efficiency. It was conducted a fluid selection from the adaptation and expanding the parameters of the qualitative spinal point method, considering the thermodynamic performance, environmental preservation criteria, safety, and fluid characteristics. As a result, it was obtained that hydrocarbons present the best thermodynamic and qualitative performances, with benzene and cyclohexane being the most attractive to be used as fluids in the proposed Rankine cycle, followed by n-hexane.

Keywords*: organic fluids, power generation, alternative thermal sources*

Introduction

The gradual change of the energy matrices due to the finiteness of petroleum-derived fuels and the environmental impacts from their burning was responsible for the recent search for new thermal energy sources to be used in power generation [1, 2]. In this context, RES for power generation have spread, which are characterized by low pollution potential and are abundantly [3]. These sources are commonly found at low temperatures, making their utilization difficult. One of the technologies used to harness these thermal sources is ORC. This system is similar to the conventional Rankine cycle, differed by using organic fluids instead of water. Organic fluids have lower critical pressures and lower evaporation temperatures, allowing lower temperature thermal sources [4, 5].

A working fluid for an ORC should have a low specific volume, low toxicity, low potential for environmental degradation, low viscosity, be chemically stable, non-corrosive,

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and preferably non-flammable [3, 6] and the performance of ORC is related to the organic fluid [7, 8]. As a result, studies dealing with methodologies for selecting the most suitable working fluid for ORC have been developed.

Freeman *et al*. [9], performed the selection of working fluid for a solar-driven ORC to be applied as a domestic power generation system in the UK, finding higher performances using HFC-245fa. Zhu *et al*. [10] identified 19 possible fluids for ORC, selecting among them 10 that fit as dry or isentropic and evaluated the system's performance from variations in its operating parameters. Rayegan and Tao [6] proposed a procedure for selecting working fluids for ORC with solar energy as heat source from, first, environmental preservation criteria and, then, evaluation of the system's energy performance. With the same intention, Saloux *et al*. [11] proposed the reconstruction of procedure to select the most appropriate fluid for ORC taking into account mass-flows and thermal properties of fluids. Yu *et al*. [12] performed working fluid selection for ORC rejecting heat to liquefied natural gas and driven, by residual heat from industry in Condition 1 and, in Condition 2, by seawater, evaluating a total of 22 candidate fluids.

Huster *et al*. [13] developed a methodology for optimized selection of the best ORC working fluid, using the software CoolProp library as a basis of the thermodynamic properties of the evaluated fluids. Imre *et al*. [14], used the new classification of working fluids, which takes into account the phase change points in the fluid expansion in the turbine from the slope of the temperature-entropy diagram, to evaluate their performances when applied in ORC. Liang and Yu [15] conducted the selection of the working fluid for a combined ORC system coupled to a heat pump, obtaining better performance of fluids with higher decomposition temperatures.

In the different methodologies used for the selection of ORC fluids, it is observed that the analysis of environmental, safety, and thermodynamic performance criteria still lack a practical approach that defines the degree of importance of each parameter. Therefore, this study aims to realize the selection of the working fluid, using environmental impacts and performance analysis as evaluation parameters, for a subcritical regenerative ORC, using heat sources high temperature renewable energies, such as biomass, considering climatic conditions of the city of Bom Jesus da Lapa – BA, located in northeastern Brazil, using adaptation and expansion of the spinal point method. In addition the innovation in the criteria used in the spinal point method, this work differs from the literature by incorporating real meteorological data to define the climatic conditions for the condensation process and by considering the self-ignition temperature of the fluids as a limiting factor for the maximum evaporation pressure.

Description of the subcritical regenerative organic Rankine cycle

The ORC is basically composed of four components: a pump, an evaporator, a turbine, and a condenser. Its greater simplicity, due to the lower working pressures, reduces the costs of maintenance, operation and acquisition of the system [10]. An alternative used to raise the efficiency of a convetional ORC is to add an intermediate heat exchanger, so that the superheated fluid leaving the turbine energy for the liquid going to the evaporator. This reduces the amount of heat required for the cycle [16].

In ORC that use biomass, the biomass combustion process leads high temperatures, which makes the passage of the organic fluid in the furnace unfeasible, since its chemical stability can be affected under these conditions or its autoignition temperature can be reached. Thus, a thermal oil is used to receive the heat from the direct burning of the biomass and transfer it to the organic fluid [17, 18].

Procedure for selection of the working fluid

Another factor that must be considered for working fluids of ORC is the isentropic volume flow (VFR). This factor, eq. (1), is related to the variation of the specific mass of the fluid during the expansion process. Excessive specific mass variation raises the cost of the turbine, makes its operation difficult, and reduces its efficiency [19-21]. The VFR values less than 50 are indicated to achieve turbine isentropic efficiency of at least 80% for single-stage expansion turbine models, while double-stage turbines allow the same isentropic efficiency of 80% for VFR values up to 300:

$$VFR = \frac{\rho_{\text{out}}}{\rho_{\text{int}}} \quad (1)$$

The fluids that were evaluated in the optimal selection for the proposed ORC were taken from the literature, according to Dresher and Bruggemann [18], Invernizzi *et al.* [21], Dai *et al*. [22], Yu and Gundersen [12], Bao and Zhao [23], Han *et al.* [19], and Qiu [24].

Preliminary selection of ORC working fluid

All CFC and HCFC fluids, because they have high ozone depletion potential (ODP), and HFC fluids or compounds with higher GWP were discarded on a preliminary basis. In addition, since burning biomass results in high furnace temperatures, fluids with critical or thermal stability temperatures lower than 150 ºC were rejected.

When evaluating the temperature-entropy diagram curve of fluids, they can be classified as dry, wet, or isentropic. Dry and isentropic fluids are most commonly used in ORC, because in isentropic expansion in the turbine, these fluids will remain as superheated steam. This contributes to increasing the efficiency of the turbine and ensuring its integrity. Furthermore, this condition allows the use of a heat recovery unit to preheat the organic fluid before it enters the system evaporator [2]. Thus, the wetted fluids were previously discarded in this study.

However, even for dry or isentropic fluids, at pressures near the critical pressure there may be a region where expansion in the turbine would occur with a portion of liquid being formed. Therefore, the adjustment indicated by Reygan and Tao [6] was performed. From the fig. 1, Point A is considered to be the point of maximum pressure, P_{max}, where the slope of the temperature-entropy curve is infinite, and thus there would be no liquid phase in the isentropic expansion. The adjustment made consists of allowing the maximum pressure to increase up to P_{co}, where the isentropic expansion occurs by-passing in BCD. The Point C is where the vapor quality is smaller in this process, limited to a tolerable maximum of 1% of saturated liquid. This adjustment tends to increase the amount of work available in the turbine.

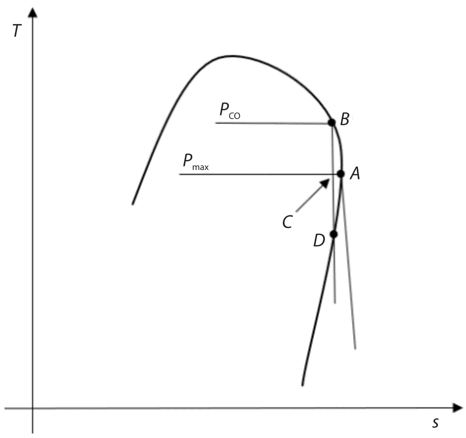

Figure 1. Adjustment in the *T-s* for maximum pressure with a vapor quality of 1%

Final selection of the ORC working fluid

After rejecting part of the fluids in the pre-selection performed, the subcritical regenerative ORC was simulated aiming to obtain the thermal efficiency of the cycle, in search of optimal operation. Then, the eight fluids that obtained the highest thermodynamic efficiencies were selected to proceed in the search for the most appropriate one. To select the best among these eight fluids, we used an adaptation of the methodology indicated by Qiu [24], called method of spinal points, which consists of evaluating how well the fluid meets specific criteria, based on the application of values from 1-5 for each criterion, where five indicates optimal performance and 1 indicates poor performance. The chosen one is that with the highest final sum of all values. The criteria evaluated are those listed as most suitable for high temperature ORC fluids in the evaporator [7, 3, 11, 18, 22, 23, 25], clarified:

– Higher thermal efficiency and net work.
– Higher condensing temperature – Indicates that there is more energy available in the condenser that can be used to drive other systems from the insertion of cogeneration or polygeneration.
– Lower evaporating pressure – Lower pressures reduce the complexity and costs of system.
– Higher latent heat of vaporization – Resulting in the use of smaller heat exchangers.
– Low GWP and ODP.
– Low viscosity when liquid – Makes the pressure losses in the pipes and heat exchangers smaller.
– Low flammability and toxicity.
– Lower VFR values.

Energy modelling of the ORC

The ORC was modeled in the Academic EES software [26] environment by applying the first law of thermodynamics to all system components to determine each fluid's efficiency. In addition, the properties and the necessary adjustments for each fluid were obtained through the EES. The thermodynamic simplifying hypotheses considered for the model were: disregard of heat loss, friction, and variations in kinetic and potential energies. All processes in the cycle are in permanent regime, constant pressures in the heat exchangers, working fluid as saturated liquid at the pump inlet, and working fluid as saturated vapor at the turbine inlet.

Given the assumptions and considerations made, the energy balance, eqs. (2)-(6) were applied to all components of the regenerative ORC, fig. 2:

$$\dot{Q}_{\text{evap}} = \dot{m}\left(h_3 - h_{2a}\right) \tag{2}$$

$$\dot{Q}_{\text{cond}} = \dot{m}\left(h_1 - h_{4a}\right) \tag{3}$$

$$\dot{W}_{\text{pump}} = \dot{m}\left(h_1 - h_2\right) \tag{4}$$

$$\dot{W}_{\text{turb}} = \dot{m}\left(h_3 - h_4\right) \tag{5}$$

$$h_4 - h_{4a} = h_{2a} - h_2 \tag{6}$$

The thermal efficiency of the cycle is determined by the eq. (7) and the effectiveness of the regenerator is determined by the eq. (8):

$$\eta = \frac{\dot{W}_t - \dot{W}_b}{\dot{Q}_{\text{eva}}} \tag{7}$$

$$\eta_{\text{reg}} = \frac{T_4 - T_{4a}}{T_4 - T_2} \tag{8}$$

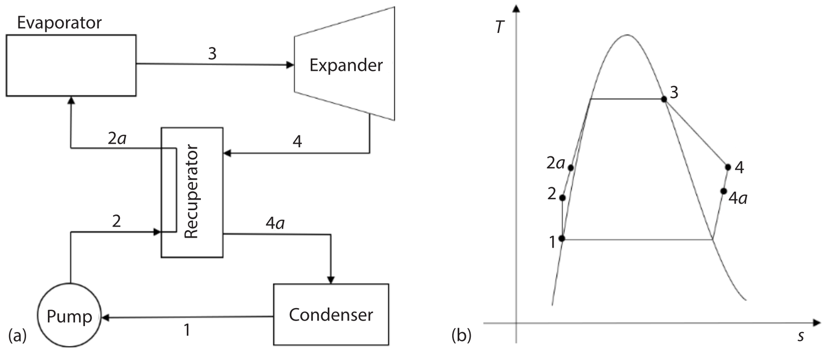

Figure 2. (a) Regenerative ORC and (b) temperature-entropy diagram for the proposed ORC

Operating conditions

The following conditions were adopted for the simulation of the proposed subcritical ORC model:

- The maximum possible pressure of the cycle for the system evaporator was 90% of the critical working fluid pressure [8], to be adjusted to maximum mass rate of 1% in the expansion [6].
- The maximum possible evaporation temperature was 5 ºC lower than the auto-ignition temperature of the fluid, setting the maximum pressure when necessary.
- The quality was set to 1% at the evaporator outlet [8, 17].
- The isentropic efficiency of the turbine was 80%.
- The isentropic efficiency of the pump was 75%.
- The effectiveness of the cycle regenerator was equal to 80%.

Condensing temperature and condensing pressure

To define the condensation temperature, considering the operation of the ORC in Bom Jesus da Lapa-Bahia-Brazil, climatic data on dry bulb temperature and relative air humidity were obtained from the National Institute of Meteorology (INMET) of the Brazilian government, of the municipal meteorological station, between the years 2015 and 2020.

With the data, hourly averages of these parameters were obtained for the 6 years evaluated and the wet bulb temperature was calculated as proposed by Stull [27]. The behavior of the average temperatures of dry and wet bulb for the municipality, in the evaluated period, are indicated in fig. 3.

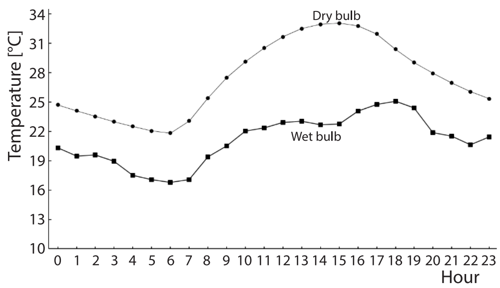

Figure 3. Average hourly temperatures in the city of Bom Jesus da Lapa between 2015 and 2020

As can be seen from fig. 3, the city has high temperatures throughout the day, with an average wet bulb maximum of approximately 25 °C and an average dry bulb maximum of approximately 33 °C.

Thus, considering a minimum difference of approximately 5 °C between the water that would leave the cooling tower (at 30 °C) and the average wet bulb temperature, it was defined for the ORC:

- The minimum condensing temperature of the system was 40 °C [28] to ensure that there is at least 10 °C difference in the temperature of the water entering the condenser and coming from the cooling tower.
- The minimum condensing pressure was 100 kPa [27] to avoid pressures below atmospheric and the increased likelihood of infiltration into the system.

Results and discussion

Results of the preliminary selection of the ORC working fluid

After an initial analysis of the fluids, the options of chlorinated compounds and high GWP HFCs were discarded, as well as excluded wet fluids. Finally, after this filtering, depending on the selected parameters and considerations, the selected fluids were: toluene, ethylbenzene, *n*-butane (R-600), *n*-pentane (R-601), *n*-hexane, cyclopentane, *n*-octane, MDM, 1.1.1.3.3-Pentafluoropropane (R245fa), HFE7100, HFE7500, R1233zd(E), benzene, hexamethyldisiloxane (MM), octamethylcyclotetrasiloxane (D4), decamethylcyclopentasiloxane (D5), neopentane, isopentane (R601a), isohexane, *n*-heptane, cyclohexane, *n*-non-ane, *n*-decane, pentafluorobutane(R365mfc), and diethylether (R610).

Energy analysis of the ORC system

Validation of the ORC energy model

The model validation was performed simulating conditions proposed by Khaljani *et al*. [29] for the R-123. The input data implemented in the model were: condensing and evaporating temperatures of 30 ºC and 137 ºC, respectively, superheat of 0 ºC, regenerator effectiveness of 0.90, and isentropic efficiencies of the pump and turbine of 0.85 and 0.80, respectively. The results obtained are shown in tab. 1. As shown in tab. 1, it is observed that all the values of the thermodynamic properties of the ORC obtained from the model of this study were identical to the values presented in [28].

Table 1. Comparison between developed with the authors

Point	T [°C]		P [kPa]		h [kJkg^{-1}]		s [kJkg^{-1}K^{-1}]	
	Simulated	[28]	Simulated	[28]	Simulated	[28]	Simulated	[28]
1	30.00	30	109.7	109.7	231.4	231.4	1.109	1.109
2	30.74	30.74	1666	1666	232.6	232.6	1.109	1.109
2a	49.17	49.17	1666	1666	252.1	252.1	1.171	1.171
3	137	137	1666	1666	460.8	460.8	1.708	1.708
4	60.09	60.09	109.7	109.7	423.1	423.1	1.737	1.737
4a	33.67	33.67	109.7	109.7	403.7	403.7	1.677	1.677

Energy study of the model for each fluid

Based on the condensing pressure data, according to tab. 1, the evaporating pressure of the system was varied from 500 kPa to the maximum pressure indicated for each fluid, in order to evaluate the thermodynamic behavior of the cycle. The figs. 4 and 5 shows the influence of varying the evaporation pressure on the energy efficiency and the net work, respectively.

It is worth noting that the *n*-non-ane and *n*-decane fluids when having their evaporation temperatures corrected for the autoignition temperature, had maximum evaporation pressures of 318.83 kPa and 208.8 kPa, respectively, and thus do not appear in figs. 4 and 5.

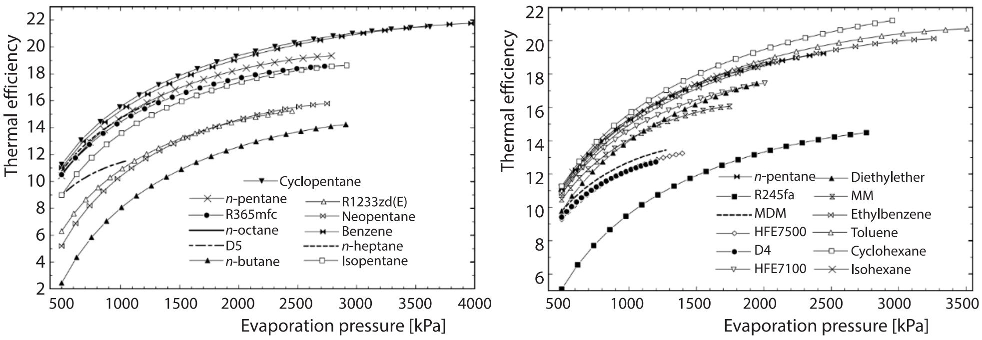

Figure 4. Thermal efficiency of ORC as a function of evaporating pressure variation

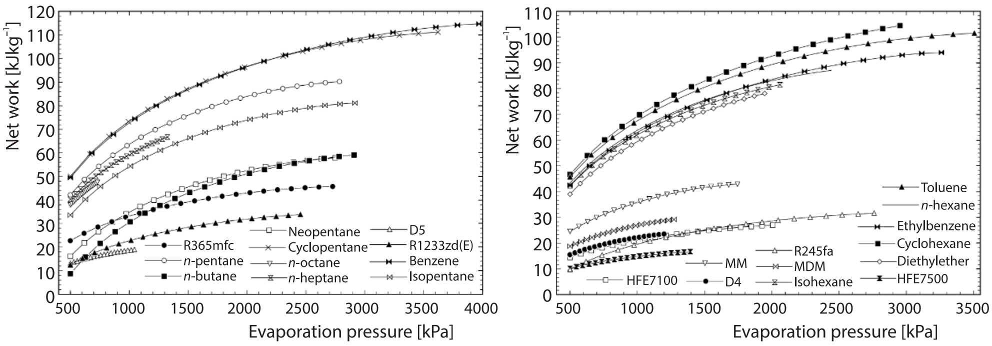

Figure 5. Net work of ORC as a function of evaporating pressure variation

When analyzing figs. 4 and 5, it is observed that increasing the evaporating pressure of the cycle, has raised along with the system's thermal efficiency for all the fluids implemented in the model raising net work produced. The net work is related to the amount of fluid mass required to generate the desired power and, thus, the higher its value, the less mass will be required to obtain the power.

Raising the evaporating pressure increases the pressure ratio in the turbine and the enthalpy of fluid input, which raises its available work. Since the increase in work occurred more intensely than the increase in heat input to the system's evaporator, the thermal efficiency also rose. The behavior of the efficiencies and net work obtained in this study were similar to those found by Moharamian *et al.* [3].

Hydrocarbons, which are natural fluids, were the best-performing fluid species. The use of benzene provided a maximum efficiency of approximately 21.7%, while cyclopentane provided the system with a maximum efficiency of approximately 21.5%. For the net work, benzene presented the highest value of 114.7 kJ/kg, followed by cyclopentane, which maximum net work was 111.2 kJ/kg.

Natural fluids, have been evaluated for use in ORC and are showing satisfactory results [21]. Hydrocarbons are formed by hydrogen and carbon chains. They are notable not only for their performance and thermodynamic properties but also for having ODP equal to zero and for their GWP that are equally low. However, they are flammable, with low auto-ignition temperature [23, 25].

The evaporation temperature is generally limited by the temperature of the heat source that will provide the energy required to the ORC. Other limiting factors for the evaporation temperature are the auto-ignition temperature of the fluids and the thermal stability temperature. Flammable fluids with low auto-ignition temperatures must be applied under specific conditions [25].

Similarly, to what was done for the evaporation pressure, the ORC condensation temperature was varied from the minimum value for each fluid to the value equivalent to –40 °C of the cycle evaporation temperature, keeping the evaporation pressure constant and equal to the maximum value and also keeping constant the other system parameters. Figure 6 shows the influence of this variation on the thermal efficiency of the ORC and fig. 7 shows the behavior of the net work as a function of this same variation.

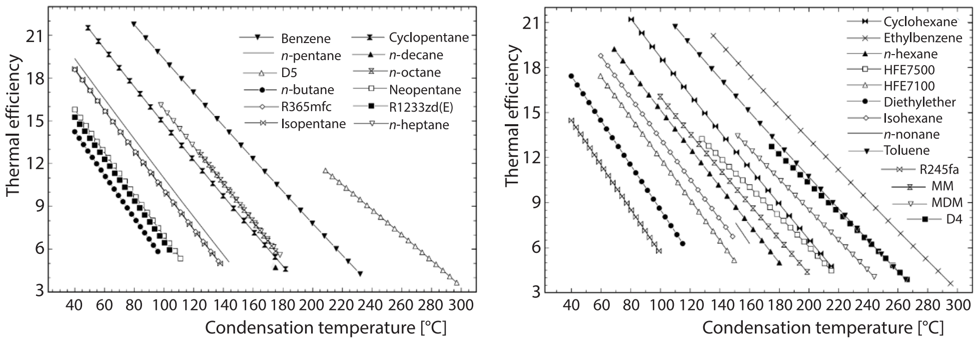

Figure 6. Thermal efficiency of ORC as a function of condensing temperature variation

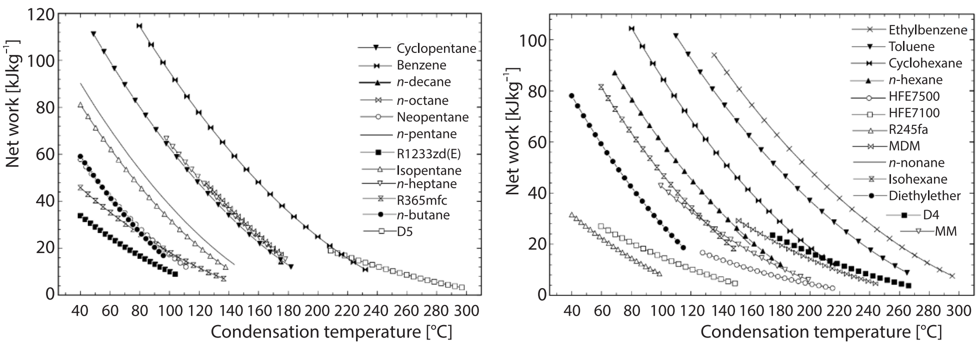

Figure 7. Net work of ORC as a function of condensing temperature variation

Figures 6 and 7 show that the increase of the condensation temperature leads to the reduction of the thermodynamic efficiency and the system's net work. Despite this, increasing the condensation temperature can be interesting when it is desired to use the ORC in a cogeneration or polygeneration system and thus take advantage of the heat rejected by its condenser, optimizing the overall efficiency of this new system.

In addition the parametric analyses performed and shown previously, the model was simulated from the defined values of operating conditions. Also, the maximum pressure limits in the evaporator and condensing pressure, after the corrections for the tolerance of liquid presence in the expander, autoignition temperature, and condensation limits, were considered for each fluid to determine the highest possible thermodynamic efficiency for the proposed regenerative ORC. Table 2 shows the results obtained for all fluids implemented in the cycle.

Table 2. Thermal efficiency for all fluids implemented in the ORC

Fluid	P_{cr} [kPa]	P_{con} [kPa]	P_{eva} [kPa]	T_{con} [ºC]	T_{eva} [ºC]	W_{net} [kJkg^{-1}]	η	VFR	Type
Benzene	4894	100.0	3969.5	79.6	271.9	114.7	0.2176	58.6	dry
Cyclopentane	4571	100.0	3621.0	48.9	221.8	111.2	0.2151	54.7	dry
Cyclohexane	4081	100.0	2953.2	80.3	255.0	104.4	0.2122	43.3	dry
Toluene	4216	100.0	3506.0	109.9	305.1	101.5	0.2072	61.9	dry
Ethylbenzene	3622	100.0	3260.2	135.7	335.4	94.0	0.2012	62.5	dry
n-Pentane	3364	100.0	2786.1	35.5	183.7	95.1	0.2000	44.6	dry
Isopentane	3370	128.8	2914.8	35.0	177.9	86.2	0.1938	37.8	dry
n-Hexane	3058	100.0	2441.6	68.9	220.0	87.1	0.1923	39.5	dry
Isohexane	3040	100.0	2061.0	59.8	198.6	81.5	0.1879	30.5	dry
R365mfc	3266	100.0	2727.8	39.8	176.5	45.9	0.1860	43.9	dry
Diethylether	3644	103.4	1946.6	35.0	155.0	83.3	0.1818	23.2	dry
HFE7100	2229	100.0	2006.4	59.6	189.6	27.0	0.1745	36.5	dry
Neopentane	3196	233.3	2749.2	35.0	151.1	62.2	0.1656	19.3	dry
n-Heptane	2727	100.0	1323.8	97.9	218.0	66.7	0.1610	17.3	dry
MM	1939	100.0	1745.1	99.8	238.8	42.9	0.1606	34.9	dry
R1233zd(E)	3573	183.0	2452.1	35.0	143.8	36.3	0.1598	17.5	isentropic
R245fa	3651	211.0	2761.0	35.0	138.9	34.1	0.1523	18.2	isentropic
n-Butane	3796	329.0	2908.3	35.0	135.9	63.9	0.1500	12.3	dry
MDM	1415	100.0	1273.5	152.7	284.0	29.2	0.1344	25.3	dry
HFE7500	1550	100.0	1394.6	127.9	255.1	16.7	0.1325	27.3	dry
D4	1332	100.0	1198.8	174.9	306.1	23.6	0.1273	24.6	dry
n-octane	2497	100.0	728.1	125.0	215.0	47.5	0.1262	8.4	dry
D5	1160	100.0	1044.0	208.7	336.9	19.0	0.1152	20.1	dry
n-non-ane	2281	100.0	318.8	150.6	200.0	25.2	0.0766	3.4	dry
n-Decane	2103	100.0	208.8	173.8	205.0	14.8	0.0500	2.2	dry

From the data in tab. 2 it is observed that all eight working fluids of which the ORC showed the highest thermodynamic efficiencies under the set conditions were hydrocarbons. The MDM, D4, D5, and MM had their efficiencies limited by the minimum condensing pressure allowed, that was 100 kPa, and thus remained with very high condensing temperatures. Reducing the condensing pressure would lead to an increase in the specific volume ratio of the fluid in the turbine, causing an increase in the VFR, which would reduce the isentropic efficiency of this equipment increase its size and complexity [21].

Final fluid selection

With the eight fluids that resulted in higher thermodynamic efficiencies in the ORC, a qualitative analysis was performed considering the desirable characteristics and assigning values from 1-5 according to how the fluid meets the requirements, where five indicates the best possible. The values assigned for each criterion are shown in tabs. 3 and 4 (values highlighted in parentheses). The latent heat of vaporization considered was that obtained for a vaporization temperature of 100 °C [19], and the viscosity of liquid considered was the average of the viscosity at the beginning and end of the condensation process. Table 5 indicates the final result of the qualitative analysis.

Table 3. Spinal point analysis

Fluid	η	W_{liq} [kJkg^{-1}]	P_{eva} [kPa]	T_{con} [ºC]	Q_{lat} [kJkg^{-1}]
Benzene	0.2176 (5)	114.7 (5)	3969.5 (1)	79.6 (3)	378.5 (5)
Cyclopentane	0.2151 (5)	111.2 (5)	3621.0 (2)	48.9 (1)	347.5 (4)
Cyclohexane	0.2121 (4)	104.4 (4)	2953.2 (3)	80.3 (3)	342.8 (4)
Toluene	0.2072 (4)	101.5 (4)	3506.0 (2)	109.9 (4)	368.1 (5)
Ethylbenzene	0.2012 (3)	94.0 (3)	3260.2 (3)	135.7 (5)	356.5 (4)
n-Pentane (R-601)	0.1935 (2)	90.3 (3)	2785.8 (4)	40 (1)	296.6 (2)
n-Hexane	0.1923 (2)	87.1 (2)	2441.6 (4)	68.9 (2)	310.2 (3)
Isohexane	0.1879 (1)	81.5 (1)	2061.0 (5)	59.8 (2)	291.2 (1)

Table 4. Continuation of spinal point analysis

Fluid	ODP	GWP	Flammability	Toxicity	μ [Nsm^{-2}]	VFR
Benzene	0 (5)	Baixo (5)	2 (3)	B (3)	0.0001607 (3)	58.56 (2)
Cyclopentane	0 (5)	<0,1 (5)	3 (1)	A (5)	0.0001557 (3)	54.71 (2)
Cyclohexane	0 (5)	NA (5)	3 (1)	A (5)	0.0002081 (2)	43.28 (4)
Toluene	0 (5)	Low (5)	3 (1)	B (3)	0.0001352 (4)	61.94 (1)
Ethylbenzene	0 (5)	NA (5)	3 (1)	B (3)	0.0001322 (4)	62.5 (1)
n-Pentane (R-601)	0 (5)	~20 (4)	3 (1)	A (5)	0.0000867 (5)	38.49 (4)
n-Hexane	NA (5)	NA (5)	3 (1)	A (5)	0.0000948 (5)	39.54 (4)
Isohexane	NA (5)	NA (5)	3 (1)	NA (5)	0.0001059 (5)	30.47 (5)

* ODP values [17, 25]; GWP values [17]; flammability values [16], toxicity values [16, 25].

Table 5. The final result of the qualitative analysis

Fluid	Benzene	Cyclopentane	Cyclohexane	Toluene	Ethylbenzene	n-pentane	n-hexane	isohexane
Score obtained	40	38	40	38	37	36	39	36

Benzene and cyclohexane were the fluids that presented the best characteristics to be employed in the proposed ORC. Both have low ODP and do not significantly GWP, but they are flammable, cyclohexane being the most flammable. The condensing temperature was quite similar for the ORC using the two fluids, approximately 80.0 °C, demonstrating the potential of the fluids to be implemented in polygeneration systems to take advantage of the energy still available after power generation.

The use of benzene resulted in a thermodynamic efficiency of only 0.55% higher and with a net work generated in the ORC 10.18% higher than the application of cyclohexane, showing that the fluids have similar thermodynamic performances. However, benzene requires less mass-flow for the same power production. It has a higher toxicity than cyclohexane, and for the thermodynamic conditions implemented, the VFR obtained was 58.56 for the former and 43.28 for the latter. The maximum evaporation pressure was 25.6% lower when using cyclohexane.

The lower evaporation pressure and the lower VFR value result in a more simplified construction and operation of the system when using cyclohexane since high pressures require greater robustness and safety, and the VFR value of 43.28 allows the use of a single-stage turbine for power generation.

Conclusions

The hydrocarbons presented more satisfactory thermodynamic performances, besides showing good results in the qualitative analysis. The highest thermodynamic efficiencies of the cycle were found using benzene, with values of approximately 21.8%, followed by cyclopentane and cyclohexane, with 21.5% and 21.2%, respectively. The net work produced was also higher with benzene, with a maximum of 114.7 kJ/kg, followed by cyclopentane, for which the maximum value was 111.2 kJ/kg.

However, after qualitative analysis, benzene and cyclohexane proved to be the most attractive working fluids for the operating conditions of the proposed ORC. Among them, benzene presented better thermodynamic performance, and cyclohexane was distinguished by lower working pressures and allowing the use of single-stage expanders, ensuring, consequently, less complexity of the system.

Despite their low thermodynamic performance, the siloxanes MDM, D4, D5, and MM remained with relatively high condensing temperatures, indicating a possible potential of these fluids when employed in polygeneration systems that allow the use of this available energy.

Acknowledgment

The first author thanks the PPGEM/UFPE and the UFOB for the support of the Doctorate. The third author thanks the CNPq for the Productivity Grant No. 3303417/2022-6 and also the FACEPE/Cnpq for financial support for research project APQ-0151-3.05/14.

Nomenclature

h – specific enthalpy, [kJkg^{-1}]
$\dot{m}$ – mass-flow, [kgs^{-1}]
P – pressure, [kPa]
$\dot{Q}$ – rate of heat transfer, [kW]
T – temperature, [°C]
VFR – isentropic volume flow, (ρ_{out}/ρ_{in}), [–]
$\dot{W}$ – Power generated or consumed, [kW]

Greek symbols

η – efficiency or effectiveness, [–]
ρ – specific mass, [kgm^{-3}]
μ – viscosity of the fluid

Subscripts

cr – critical
net – net
lat – latent
liq – liquid
out – going out
con – condensing
eva – evaporating
evap – evaporator
cond – condenser
pump – pump
turb – turbine
reg – regenerator
int – entering

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Paper submitted: July 18, 2022
Paper revised: December 1, 2022
Paper accepted: December 3, 2022