17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0770
ENERGY AND ECONOMIC ANALYSIS OF GAS TURBINE WITH ORGANIC RANKINE CYCLE

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Abstract. This work presents the modeling of a system combining a gas turbine and an organic Rankine cycle by means of a single pressure heat recovery steam generator and an evaporator. A thermodynamic analysis is done in the system in order to evaluate its parameters and determine the energy efficiency of the system considering R123 and R1234yf as work fluids. In addition, an economic analysis of the project is made to determine its financial viability. Through these results, they are compared with the results available in the literature and it evaluates, for this system, which working fluid is most effective considering the environmental, economic and thermodynamic aspects.

Keywords: organic Rankine cycle, Brayton cycle, economic analysis

1. INTRODUCTION

When energy is produced it is important to consider the environmental, social and economic aspects. A survey conducted by the World Energy Balance, 1984, estimated that rapid industry growth, power shortages and blackouts are meeting ever-higher energy demands, accounting for about 25% in 1978 to 33% in 2000. And the forecast is that this value increases to 35-40% in the year 2020. Based on these aspects, new resources, mechanisms and innovative systems have been studied aiming at a socioeconomic sustainability in the production of energy.

The Rankine steam cycle uses water as a working fluid (Pethurajan, *et al*., 2018), as it has good thermodynamic properties, as well as being easily found, cheap, non-toxic and ideal for working in medium temperature ranges in generation cycles power. (Tchanche, *et al*., 2011).

The system studied in this work approaches the combination of a Brayton cycle so that the thermal energy of the exhaust gases can be harnessed in a heat exchanger for a Rankine cycle. Since the temperature of these exhaust gases can reach considerably high temperatures, a certain amount of energy is wasted (Deng and Tang, Li, 2017). One way to solve this problem of low-temperature heat sources would be to increase the boiler area or heat exchanger in this case. However, this option is economically unfeasible, because, with the increase of the dimensions of the heat exchanger, the system is expensive. Therefore, other means arise in order to maintain a system cost stability.

The Organic Rankine cycle uses the same operating principle of a conventional cycle, except for the exchange of water by an organic fluid as a working fluid (Pethurajan, *et al.*, 2018). This contributes to the favorable production of shaft work at temperatures around 300°C (Vescovo and Spagnoli, 2017), since organic fluid becomes key to the plant's performance and economy (Tchanche, *et al*., 2011).

This work aims to evaluate the thermodynamic and economic feasibility of a combined power and cogeneration system between a Brayton cycle and a Rankine cycle. In the Rankine cycle, the influence of different organic fluids on the efficiency of the system according to the first law of thermodynamics is analyzed. All analyzes were performed using Engineering Equation Solver (EES) software.

2. METHODOLOGY

2.1 System description

The power cycle combines a gas turbine with an organic Rankine cycle (ORC) through a single pressure steam generator, as can be seen in Fig. 1. Air, under ambient pressure and temperature conditions, being compressed in the compressor flows into the regenerator, where it is preheated, and then enters the combustion chamber, where the fuel is injected into the hot air, thus occurring, combustion. After that, these flue gases are expanded in the turbine, resulting in the production of power. Part of the exhaust gas energy is recovered as it passes through the regenerator. Subsequently, these gases are introduced into a heat recovery vapor generator, where there is inlet of water exits as saturated vapor at the same pressure. The organic Rankine cycle is related to the gas turbine cycle through an evaporator. The exhaust gases from the power cycle enter this evaporator and exchange heat with the working fluid present in the Rankine cycle. The fluid, in the state of saturated liquid, is pumped at high pressure, and then heated in an internal heat exchanger and upon entering the evaporator becomes saturated vapor. The superheated fluid after passing through the internal heat exchanger goes to the condenser, where it is condensed to the saturated liquid phase.

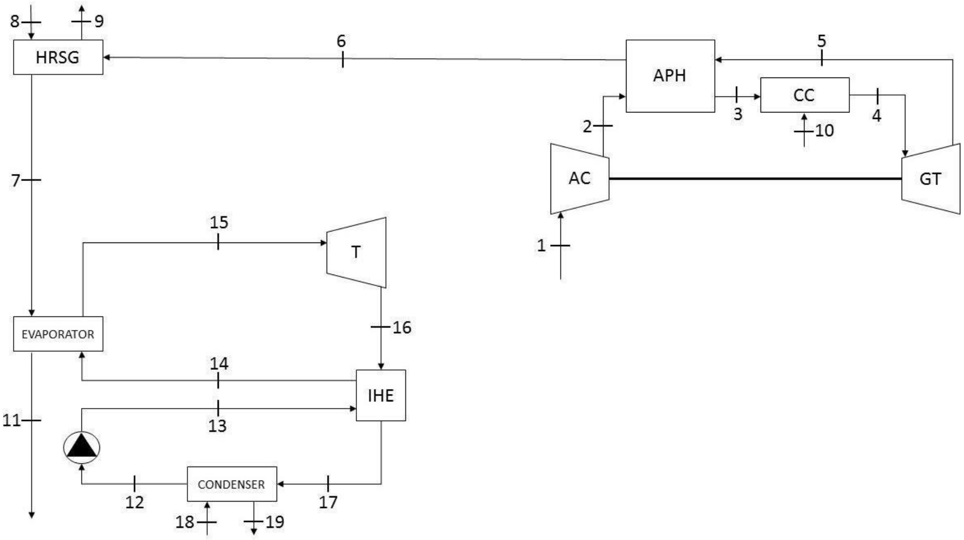

Figure 1. Schematic diagram of the combined heat and power system between the Brayton and Rankine cycles

2.2 Thermodynamic analysis

The thermodynamic analysis was made from the following considerations (Khaljani, 2015):

1. All processes of the cycle are in steady state;
2. Air compressor and gas turbine are assumed adiabatic;
3. Lower heating value of the fuel (methane) is 802661 kJ/kmol;
4. The principles of ideal gas mixtures are used for air and combustion products;
5. Heat transfer from combustion chamber is 2% of lower heating value of the fuel;
6. The organic working fluid enters the turbine as saturated vapor.

The thermodynamic modeling was made based on the temperature and pressure data provided by Khaljani (2015) and for its analysis the software Engineering Equation Solver (EES) was used. The energy balance of each component of the cycle can be seen in Tab. 1.

Table 1. Energy balances for the combined cycle

Components	Energy balances
Air compressor (AC)	$\eta_{AC} = (h_{2s} - h_1)/(h_2 - h_1)$, $W_{AC} = \dot{m}_{air}(h_2 - h_1)$
Air preheater (APH)	$(h_3 - h_2) = (1 + \lambda)(h_5 - h_6)$
Combustion chamber (CC)	$-0.02\lambda LHV_{CH_4} + h_3 + \lambda h_{10} - (1 + \lambda)h_4 = 0$
Gas turbine (GT)	$\eta_{GT} = (h_4 - h_5)/(h_4 - h_{5s})$, $W_{GT} = (\dot{m}_{air} + \dot{m}_{fuel})(h_4 - h_5)$
Heat Recovery Steam Generator (HRSG)	$(\dot{m}_{air} + \dot{m}_{fuel})(h_6 - h_7) = \dot{m}_{water}(h_9 - h_8)$
Pump	$\eta_{AC} = (h_{13s} - h_{12})/(h_{13} - h_{12})$, $W_P = \dot{m}_{ORC}(h_{13} - h_{12})$
Internal Heat Exchanger (IHE)	$(h_{14} - h_{13}) = (h_{16} - h_{17})$, $\varepsilon_{IHE} = (T_{16} - T_{17})/(T_{16} - T_{13})$
Evaporator	$(\dot{m}_{air} + \dot{m}_{fuel})(h_7 - h_{11}) = \dot{m}_{ORC}(h_{15} - h_{14})$
Turbine (T)	$\eta_T = (h_{15} - h_{16})/(h_{15s} - h_{16})$, $W_T = \dot{m}_{ORC}(h_{15} - h_{16})$
Condenser	$\dot{m}_{ORC}(h_{17} - h_{12}) = \dot{m}_{water}(h_{19} - h_{18})$, $Q_{cond} = \dot{m}_{ORC}(h_{17} - h_{12})$

2.3 Economic analysis of the system

Energy conversion systems can be optimized through economic considerations, providing a crucial knowledge for the project, and several methods are developed for this analysis. This work was based on the studies developed by Ahmadi (2011), Sayyaadi (2011) and Khaljani (2015). The capital investment into cost per time unit can be seen in Eq.(1):

$$Z_k = PEC_k \cdot CRF \cdot \varphi/(N) \tag{1}$$

where PEC_k is the purchase equipments cost in U.S. factor dollar, CRF is the capital recovery factor, φ is maintenance factor and N is annual number of operating hours of the system. The Capital Recovery Factor, CRF, depends on the interest rate, as well as the estimated useful life of the equipment, and is determined using Eq. (2) (Ahmadi, 2011):

$$CRF= \frac{i(1+i)^n}{i(1+i)^n - 1} \tag{2}$$

where i is the interest rate, adopted as 12%, and n is the system lifetime, estimated at 20 years (Khaljani, 2015). The cost of equipment acquisition (PEC) of each component of the system is evaluated through the equations given in Table 2 (Khaljani, 2015).

Table 2. Purchase equipments cost

Equipment	Purchase equipments cost (PEC) US$
Air compressor	$PEC_{AC} = ((71.10\dot{m}_a)/(0.9-\eta_{SC})(P_2/P_1)ln(P_2/P_1)$
Air preheater	$PEC_{APH} = 4122(\dot{m}_a(h_5-h_6)/U\Delta T_{lm,aph})^{0.6}, U = 18\ W/(\dot{m}^2K)$
Combustion chamber	$PEC_{CC} = (46.08\dot{m}_a/(0.995-P_4/P_3))(1+e^{(0.018T_4-26.4)})$
Gas turbine	$PEC_{GT} = (479.3\dot{m}_g/(0.92-\eta_{SC}))lnP_4/P_5(1+e^{(0.036T_4-54.4)})$
Heat recovery steam generator	$PEC_{HRSG} = 6570[(Q_{ec}/\Delta T_{lm,ec})^{0.8}+(Q_{ev}/\Delta T_{lm,ev})^{0.8}]+21276\dot{m}_w+1184.4\dot{m}_g^{1.2}$
Pump	$PEC_P = 3540W_p^{0.71}$
Evaporator	$PEC_{EVA} = 309.143A_{EVA}+231.915$
Turbine	$PEC_T = 6000W_p^{0.7}$
Condenser	$PEC_P = 1773\dot{m}_{steam}$
Internal heat exchanger	$PEC_{IHE} = 1.3(190+310A_{IHE})$

3. RESULTS

3.1 Using R123 as the working fluid for the ORC

3.1.1 Thermodynamic results

The thermodynamic properties of work fluids of the gas turbine cycle and ORC are validated based on the results reported by Khaljani (2015). The Tables 3, 4 and 5 present the results of the energy analysis of this author for the components for the studied system.

Table 3. Validation of the data in the ESS and comparison with other works by Khaljani (2015).

Points	Working fluid	T (K)		P (bar)		$\dot{E}^{PH}$ (MW)		$\dot{E}^{CH}$ (MW)		$\dot{E}$ (MW)	
		[16]	This work	[16]	This work	[16]	This work	[16]	This work	[16]	This work
1	Air	298.15	298.15	1.013	1.013	0	0	0	0	0	0
2	Air	603.73	603.5	10.13	10.13	27.53	27.533	0	0	27.53	27.533
3	Air	850	850	9.623	9.624	41.93	41.949	0	0	41.93	41.949
4	Comb.gas	1520	1520	9.142	9.142	101.0	101.897	0.3665	0.3666	101.45	102.26
5	Comb.gas	1006.1	1006.3	1.09	1.1	38.41	39.231	0.3665	0.3666	38.78	39.598
6	Comb.gas	779.78	779.7	1.066	1.067	21.38	22.180	0.3665	0.3666	21.75	22.547
10	Fuel	298.15	298.15	12	12	0.627	0.6305	84.36	84.397	84.99	85.010

Points	Working fluid	T (°C)		P (kPa)		h (kJ/kg)		s (kJ/kg K)		$\dot{E}$ kW		$\dot{m}$ (kg/s)	
		[11]	This work	[11]	This work	[11]	This work	[11]	This work	[11]	This work	[11]	This work
12	R123	30	30	109.7	109.7	231.4	231.4	1.109	1.109	88.68	88.71	1324	1324
13	R123	30.67	30.74	1666	1666	232.6	232.6	1.109	1.109	1513	1515	1324	1324
14	R123	48.15	49.17	1666	1666	251	252.1	1.168	1.171	2718	2831	1324	1324
15	R123	137	137	1666	1666	460.8	460.8	1.708	1.708	66969	66994	1324	1324
16	R123	60.09	60.09	109.7	109.7	423.1	423.1	1.737	1.737	5791	5794	1324	1324
17	R123	35.08	33.67	109.7	109.7	404.7	403.7	1.68	1.677	3952	3906	1324	1324
18	Water	25	25	100	100	104.8	104.8	0.367	0.367	0	0	1324	1324
19	Water	35	35	100	100	146.6	146.6	0.505	0.505	3776	3776	1324	1324

Table 4. Thermodynamic properties of the cycle by Khaljani (2015).

Stream	Working fluid	T (K)	P (bar)	$\dot{m}$ (kg/s)	$\dot{E}^{PH}$ (MW)	$\dot{E}^{CH}$ (MW)	$\dot{E}$ (MW)
1	Air	298.15	1.013	94.75	0	0	0
2	Air	603.5	10.13	94.75	28.577	0	28.577
3	Air	850	9.624	94.75	43.540	0	43.540
4	Comb.gases	1520	9.142	96.454	105.761	0.3805	106.142
5	Comb.gases	1016	1.157	96.454	41.947	0.3805	42.328
6	Comb.gases	789.6	1.122	96.454	24.153	0.3805	24.533
7	Comb.gases	422.1	1.066	96.454	3.604	0.3805	3.985
8	Water	298.15	35	15.12	0.051	0.0377	0.0892
9	Water	515.7	35	15.12	14.833	0.0377	14.871
10	Fuel	298.15	12	1.704	0.654	87.579	88.234
11	Comb.gases	381.5	1.013	96.454	2.067	0.3805	2.448
12	R123	303.2	1.097	21.61	0.0014	–	0.0014
13	R123	303.5	8.199	21.61	0.0120	–	0.0120
14	R123	316.2	8.199	21.61	0.0239	–	0.0239
15	R123	375	8.199	21.61	0.810	–	0.810
16	R123	323.8	1.097	21.61	0.079	–	0.079
17	R123	305.5	1.097	21.61	0.063	–	0.063
18	Water	298.15	1	177.1	0	–	0
19	Water	303.2	1	177.1	0.024	–	0.024

Table 5. Thermodynamic analysis results by Khaljani (2015).

Parameters	Value
$\eta_{I,GT-HRSG}$(%)	53.61
$\eta_{I,GT-HRSG/ORC}$ (%)	54.3
$\dot{Q}_{SG}$ (MW)	40.732
$\dot{Q}_{CC}$ (MW)	83.539
$\dot{W}_{ORC}$ (kW)	580.3
$\dot{W}_{Net,GT}$ (MW)	30

A number of modifications are required in order to make the system compatible and feasible for possible installation and operation. The new modifications generate the results seen in Tables 6, 7 and 8.

Table 6. Thermodynamic properties obtained from the modeling in EES.

	Working fluid	h[kJ/kg]	h_s[kJ/kg]	P[kPa]	s[kJ/kg·K]	T[°C]	$\dot{m}$ [kg/s]
1	Air	289,4	-	101,3	6,86	25	94,75
2	Air	610,6	576,8	1013	-	330,6	94,75
3	Air	877,4	-	962,3	-	576,9	94,75
4	Combustion gases	1661	-	914,2	7,995	1247	96,45
5	Combustion gases	1054	935	109	-	733	96,45
6	Combustion gases	800,3	-	106,6	-	506,6	96,45
7	Combustion gases	423,7	-	106,6	-	149	96,45
8	Water	108	-	3500	-	25	12,13
9	Vapor	2803	-	3500	-	242,6	12,13
10	Steam	-	-	-	-	-	1,704
11	Combustion gases	382,5	-	101,3	-	108,4	96,45
12	R123	231,4	-	109,7	1,109	30	17,00
13	R123	232,6	232,4	1666	1,109	30,67	17,00
14	R123	251	-	1666	1,168	48,15	17,00
15	R123	460,8	-	1666	1,708	137	17,00
16	R123	423,1	413,6	109,1	1,737	60,09	17,00
17	R123	404,7	-	109,1	1,68	35,08	17,00
18	Water	104,8	-	100	0,3669	25	70,44
19	Water	146,7	-	100	0,5049	35	70,44

Table 7. Energy results for each component.

	W [kW]	Q [kW]
Air compressor	29582	-
Air preheater 2-3	-	25281
Air preheater 5-6	-	24432
Combustion chamber	-	85241
Gas turbine	58583	-
Heat recovery steam generator 6-7	-	36328
Heat recovery steam generator 8-9	-	32695
Evaporator 7-11	-	3972
Evaporator 14-15	-	3566
Turbine	640,4	-
Internal heat exchanger 16-17	-	312,8
Internal heat exchanger 13-14	-	312,8
Condenser 17-12	-	2946
Condenser 18-19	-	2946
Pump	20,33	-

Table 8. Cycle efficiency results.

	η
Air compressor	0,8919
Gas turbine	0,8367
Pump (ORC)	0,8974
Turbine (ORC)	0,7981
Organic Rankine Cycle	0,1739
Brayton Cycle	0,3402
Full Cycle	0,5393

From these modifications, the system becomes thermodynamically feasible, since no law is broken during its analysis. In addition, the values are close to reality and consistent with the study developed by Khaljani (2015).

3.1.2 Economic results

The value of the purchase cost in US dollar of each equipment with R123 as working fluid in the ORC can be seen in Tab. 9. The calculations were made in the EES Software based on the equations given in Tab. 2.

Table 9. Value of the purchase cost of each equipment for the system.

Equipment	Purchase equipments cost (PEC) US$
Air compressor	5.017.000
Air preheater	1.190.000
Combustion chamber	452.847
Gas turbine	4.893.000
Heat recovery steam generato	2.032.000
Pump	28.915
Evaporator	65.270
Turbine	521.628
Condenser	120.189
Internal heat exchanger	81.344

The initial investment can be determined by the cost of purchasing of all the equipments in the system. It is estimated that the system operates for 7,000 hours throughout the year, stopping for maintenance. According to National Electric Energy Agency (ANEEL), the cost of the average energy tariff in Brazil calculated by the market in 2017 was US$ 0,14. From this information, as well as the net work value of the combined cycle, it is possible to determine the gross revenue. According to *Comgás* the cost of the fuel was estimated from the knowledge of the cost of methane (US$ 0.26/m^3), the mass flow of the fuel in the combustion chamber, the operating hours of the system, and its density, assumed as 0.653 kg/m³. The social contribution on net income is estimated at 9%, as established by Brazilian Law 7,689/1988. The income tax can be determined considering the National Simple as a form of its collection. According to the Federal Government of Brazil, by the current criterion, they can choose to collect by the National Simple Companies that invoice up to R$ 3.6 million per year and the rates vary between 4% and 17.42%, according to the activity performed. Therefore, an income tax of 15% was estimated. Proportional taxes can be estimated at 3.65%. Whereas the cost of maintenance to system was estimated in about 6% of investment initial (Khaljani, *et al.*, 2015). From all this information, an initial investment of US$ 14,430,000.00 is obtained with a gross revenue of U$ 29,030,000.00 and a net profit of US$ 7,605,323.80. It is very important to highlight that the cost determined in this article is considerably high, since some others cost, like manpower, buy of land, installation and etc., not being considered.

This work used three deterministic methods of evaluating investments. The first one was the Net Present Value (NPV), which is calculated by bringing all project cash flows to the date zero and adds them to the initial investment using the Minimum Acceptable Rate of Return (MARR), adopted as 12% (Khaljani, 2015), such as the project discount rate. The second was the Internal Rate of Return (IRR) method defined as the percentage of profitability of the project analyzed and the third method was the payback defined as the time that a project takes to profit in a way that can pay its initial investment. The value found for the NPV was US$ 42.417.537 a 12% MARR. The IRR obtained a value of 52.84%. The simple payback was obtained after 1.89 years and the discounted payback from 2.28 years.

From the results found, it is evaluated that the project is economically viable to invest. Since the NPV has a positive value, the IRR is larger than the MARR and the payback is less than the economic life of the system, which is 20 years.

3.2 Using R1234yf as working fluid for the ORC

3.2.1 Thermodynamic results

According to Francisco Molés et al. (2017), due to its low Global Warning Potential, the working fluid R1234yf has been used as a replacement alternative for R134-a in ORC systems for low temperature heat sources. This work evaluated the influence of this fluid, replacing R123, in the combined system, considering that no change is made in the gas turbine cycle and in the steam generator. In addition, the pressure values remain the same in the ORC cycle, changing only the temperatures to suit those pressures. From the EES Software a thermodynamic analysis is done with this new working fluid and the results are exposed in the Tables 10, 11 and 12.

Table 10. Thermodynamic properties obtained from the modeling in EES.

	Working fluid	h[kJ/kg]	h_s[kJ/kg]	P[kPa]	s[kJ/kg·K]	T[°C]	$\dot{m}$ [kg/s]
12	R1234yf	165,3		109,7	0,8683	-27,67	16,64
13	R1234yf	168	167,2	1666	0,8714	-27	16,64
14	R1234yf	181,3		1666	0,9242	-15,95	16,64
15	R1234yf	396,2		1666	1,609	60,65	16,64
16	R1234yf	361,3	347,6	109,7	1,663	-8	16,64
17	R1234yf	347,9		109,7	1,61	-24	16,64
18	Water	104,8		100	0,3669	25	72,64
19	Water	146,7		100	0,5049	35	72,64

Table 11. Energy results for each component.

	W [kW]	Q [kW]
Evaporator 7→11	-	3973
Evaporator 14→15	-	3576
Turbine	580	-
Internal heat exchanger 16→17	-	223
Internal heat exchanger 13→14	-	221
Condenser 17→12	-	3038
Condenser 18→19	-	3038
Pump	44,76	-

Table 12. Cycle efficiency results.

	η
Air compressor	0,8899
Gas turbine	0,8373
Pump (ORC)	0,7093
Turbine (ORC)	0,718
Organic Rankine Cycle	0,1497
Brayton Cycle	0,3402
Full Cycle	0,5382

3.2.2 Economic results

The value of the purchase cost in US dollar of each equipment with R1234yf as working fluid in the ORC can be seen in Tab. 13. The calculations were made in the EES Software based on the equations given in Tab. 2.

Table 13. Value of the purchase cost of each equipment for the system.

Equipment	Purchase equipments cost (PEC) US$
Air compressor	5.017.000
Air preheater	1.190.000
Combustion chamber	452.847
Gas turbine	4.893.000
Heat recovery steam generato	2.032.000
Pump	50.637
Evaporator	65.270
Turbine	486.682
Condenser	123.942
Internal heat exchanger	81.344

The same cost considerations made for the R123 fluid are also valid for the R1234yf fluid, hence from this information an initial investment of US$ 14,390,000.00 is obtained with a gross revenue of US$ 28,940,000.00 and a net profit of US$ $7,539,420.40. One more time, other costs, like manpower, buy of land, installation and etc., not being considered. Because these costs are essentially the same to the region which would use, hypothetically, the working fluid as R123.

Using the three deterministic methods of investment assessment, the NPV is found, with a value of US$ 41.925.276 for a 12% MARR. Whereas the IRR obtained a value of 52.38%. The simple payback was obtained after 1.91 years and the discounted payback from 2.31 years.

The obtained results allow to affirm that both working fluids are viable for the ORC of the studied cycle, since the thermodynamic and economic results are similar. However, the thermal efficiency of the ORC with R1234yf was lower when compared to R123 and this influences, even if only slightly, the overall efficiency of the system. In addition, the working temperature of R1234yf is lower, which is good because the ORC is a cycle characterized by having a lower boiling temperature than water, allowing heat to be recovered at warmer temperatures (Wenzel, 2015).

4. CONCLUSION

This work analyzed the thermodynamic and economic results of a cogeneration combined cycle to determine its energy efficiency, as well as to evaluate the influence of the working fluid in the system. From the necessary adaptations, for a congruent thermodynamic analysis, as well as from the evaluations of equipment cost, energy cost per kWh, fuel cost, tax revenue discounts and using NPV, IRR and payback as methods deterministic evaluation of investments, it is concluded that the project studied is economically feasible for an investment and thermodynamically possible for both fluids. However, the R1234yf fluid influences the system with a slightly lower thermal efficiency when compared to R123, yet both remain profitable and able to be chosen as working fluids for the cycle, as the results for thermal efficiency as well as financial investment were close and both fluids have low GWP and are environmentally appropriate.

5. ACKNOWLEDGEMENTS

This work was supported by the team of Thermal Systems and Alternative Energies Laboratory of the Federal University of Rio Grande do Norte (LSTEA/UFRN).

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