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COMPARATIVE ANALYSIS OF ORC FOR WHR IN CEMENT INDUSTRY

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Abstract. *The cement industry demonstrates one of the greatest electricity consumption levels among industrial sectors. The waste heat recovery (WHR) technology offered by the organic Rankine cycle (ORC) is capable of generating electric energy from waste heat sources originated in the cement production process without consuming additional fuel. This paper aims to investigate and compare the thermodynamic performance of a simple and a regenerative ORC working under subcritical operating condition with 8 distinct organic fluids. After selecting the most adequate working fluids to perform on this study based on their environmental and safety aspects, thermodynamic characteristics and saturated vapor curves, both of the cycles were designed and optimized using the genetic algorithm methodology in the Equation Engineering Solver (EES) software. Results revealed that the regenerative arrangement is superior to the simple one from the context of net power output produced, thermal and exergy efficiencies. Additionally, the isentropic fluid R141b reached the best effectiveness during the simulations of the proposed cycles. Furthermore, it was verified that regenerative components increase the average temperature of heat addition and reduce the exergy destruction within the system.*

Keywords: *ORC, waste heat recovery, cement kiln, cogeneration*

1. INTRODUCTION

The cement industry is one of the largest electricity consumers among industrial segments. As explained by IFC (2014), the expenses with electric energy constitute around 25% of all operational costs in a cement factory and waste heat recovery (WHR) technologies, such as cogeneration systems, are able to provide low-grade heat or supply up to 30% of the global electricity needs of a cement plant. With the purpose of reducing the energy expenditure in cement industry by producing electric energy with no additional fuel utilization and decreasing CO_2 emissions, the energy cogeneration system supplied by the organic Rankine cycle (ORC) has been highlighted as an interesting alternative. The ORC is able to generate electricity from waste heat sources originated in the preheater exhaust and clinker cooler exhaust gases with low-medium temperature between 80 and 400º C, which would be released into the atmosphere.

The principal difference between ORC and the conventional steam Rankine cycle (SRC) is that the ORC operates with organic fluids with low boiling points such as refrigerants, alcohols, ethers, etc. instead of water. Based on the organic working fluid's characteristics, the ORC presents significant benefits compared to the SRC when working with temperatures from 80 to 400ºC, for instance: good efficiency, low operational and maintenance costs, simpler construction, good commercial availability, good adaptability to different heat sources (Eyidogan *et al*, 2016; Lecompte *et al*, 2015a; Li, G., 2016; Tchanche *et al*, 2014; Wang, X. *et al*, 2015). Another important advantage of the ORC is that dry and isentropic working fluids do not require superheating as water does and this avoids the risk of erosion on the turbine blades (Tchanche *et al*, 2011).

The organic fluids can be classified in according to their chemical composition in pure or zeotropic fluids. Pure fluids have a fixed chemical composition throughout, whereas zeotropic fluids are comprised of a mixture of pure substances. In addition, these fluids can also be identified by their environmental and safety properties. The environmental aspects are related to the impact on the environment of a substance, which are ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) indexes and must be carefully assessed according to Javanshir and Sarunac (2017). Lastly, as reported by Li, C. and Wang, H. (2016), the organic working fluids can be evaluated in consonance with their saturation vapor curves in (i) dry, with positive slopes; (ii) wet, with negative slopes; and (iii) isentropic, with nearly vertical saturation vapor curve.

Moreover, it is essential to evaluate the ORC based on its operating condition, which can be illustrated in the temperature–entropy (T-s) diagram, as: (i) subcritical, in which the working fluid crosses the biphasic region at a constant pressure lower than the pressure at the critical point; (ii) subcritical with superheating, which is similar to the subcritical condition, however the organic fluid is superheated before entering the turbine; and (iii) supercritical, where the working fluid achieves a pressure and temperature superior to those ones at the critical point, in other words, it passes from the liquid state directly to superheated vapor before the turbine inlet.

Furthermore, Lecompte *et al* (2015b) clarify that it is possible to increase the ORC performance by modifying its configuration. The most applied alterations are the inclusion of regenerators, extraction of steam from the turbine, installation of reheaters, etc. In order to contrast the first and second law efficiencies demonstrated by two different ORC arrangements, Mago *et al* (2008) designed a simple ORC and a regenerative ORC with extraction of steam from the turbine. Both of the cycles worked with wet organic fluids and operating parameters at the turbine inlet as temperature and pressure were varied under subcritical and subcritical with superheating conditions. It was verified by the authors that the regenerative ORC performed better than the simple ORC in terms of thermal and exergy efficiencies during the simulations due to the decline in exergy destruction within the system provided by the regenerative components. Following this logic, Desai and Bandyopadhyay (2009) investigated the variation of thermal efficiency presented by a simple ORC, a regenerative ORC, a simple ORC with extraction of steam from the turbine and a direct contact heater, and a regenerative ORC with extraction of steam from the turbine and a direct contact heater. After changing the pressure at the turbine inlet for the sixteen dry and isentropic working fluids under subcritical condition, results revealed that the fourth composition reached the highest level of first law efficiency, although operating with sub atmospheric condensation pressures for certain fluids raised the risk of air infiltration into the system.

The main objective of this study is to analyze and compare the thermodynamic effectiveness of a simple and a regenerative ORC working under subcritical operating condition with eight different organic fluids. The cycles were designed and optimized using the genetic algorithm method in the Equation Engineering Solver (EES) software. The models operated as a typical Brazilian cement factory with a clinker productive capacity of 3,500 ton/day.

2. METHODOLOGY

The criteria established for working fluid selection, as well as the ORC systems specifications and their thermodynamic modeling are described as follows.

2.1 Working fluid selection

Since there is a wide range of organic working fluids available to perform on the ORC, the working fluid selection for this study was based on four criteria: (i) availability on EES database; (ii) safety and environmental characteristics; (iii) thermodynamic properties and (iv) saturation vapor curves classification.

In accordance with the bibliography examined, refrigerants are, in general, the most environmental friendly among other types of organic fluids eligible to work in the ORC. In agreement with this premise and with the first selection criterion, 25 out of 42 pure refrigerant fluids obtained from ASHRAE (2009) were initially selected for this work, for their thermodynamic characteristics were available on EES database.

Afterwards, the working fluids were classified according to their safety and environmental aspects. From the safety perspective, all organic fluids were considered suitable for this application because beyond showing null or low toxicity and flammability indexes, they do not offer risk of explosion during operation as stated by Embraco (1996). From the environmental point of view, in spite of all of working fluids possess very low or even zero ODP levels and varied indexes of GWP, 7 organic fluids were excluded (R13, R23, R114, R116, R218, R236fa and RC318), for they presented atmospheric lifetime greater than 100 years.

Subsequently, the chosen working fluids up to this step were assessed in consonance with their properties and thermodynamic states achieved in a simulation of an ideal simple ORC. The principal attributes observed in this stage were critical temperature (T_{cr}), critical pressure (P_{cr}) and saturation pressure at the condenser outlet ($P_{sat\ cond}$). After this analysis, the fluid R113 was eliminated from the following procedure due to its saturation pressure at the condenser outlet has been lower than the atmospheric pressure of 0.101 MPa and this study does not propose to work with sub atmospheric pressures in the system.

Finally, all organic fluids were categorized in accordance with their quality at the turbine outlet in the ideal ORC aiming to evaluate their saturation vapor curves. Examining the minimum and maximum quality values demonstrated by the working fluids during the simulation, it was possible to identify them based on the shape of their saturation vapor curves in wet, dry and isentropic fluids. With the purpose of preventing erosion on the turbine blades, the organic fluids with quality inferior to 85% at the turbine outlet were removed, that is the wet fluids R12, R22, R32, R125, R134a, R143a, R152a and R290. Additionally, the dry fluid R227ea was also disqualified due to be considered a "cold" fluid, it means that its critical temperature is close to 100°C, so that the cycle operation with this fluid demands high pressure and temperature at the turbine inlet, making it impracticable for this utilization.

Table 1 shows the working fluids elected to be used in this work with their respective characteristics observed during this selection process. The working fluid selection carried out in this work employed the methodology proposed by Moreira *et al* (2017) in their study.

Table 1. Organic working fluids selected for application in this work

Fluid	Safety group	ODP	GWP_{100*}	Atmospheric lifetime [years]	T_{cr} [°C]	P_{cr} [MPa]	$P_{sat\ cond}$ [MPa]	Quality at the turbine outlet min - max[-]	Classification
R11	A1	1	4,750	45	198.00	4.41	0.130	0.852 – 0.989	Isentropic
R124	A1	0.022	609	5.8	122.28	3.62	0.470	0.959 – 1.000	
R141b	-	0.11	725	9.3	204.20	4.25	0.101	0.962 – 1.000	
R142b	A2	0.065	2,310	17.9	137.11	4.06	0.420	0.929 – 0.999	
R600	A3	0	~20	0.018	151.98	3.80	0.300	0.951 – 1.000	
R600a	A3	0	~20	0.019	134.67	3.64	0.430	0.926 – 1.000	
R123	B1	0.02	77	1.3	183.68	3.67	0.120	0.984 – 1.000	Dry
R245fa	B1	0	1,030	7.6	154.01	3.65	0.190	0.977 – 1.000	

After finishing the analysis for selecting the most appropriate working fluids for this study, the operating parameters of the ideal ORC were analyzed. During the temperature variation at the turbine inlet, it was verified which pressure led the cycle to reach the best performance in terms of specific net power output for each organic fluid. This was made in order to align the results of the optimization performed afterwards with the working fluid selection in this section. Thus, this pressure at the turbine inlet, referred as optimum operating pressure, was utilized as inlet data in the design of the real ORCs proposed in this work.

2.2 Systems specifications and thermodynamic modeling

Thermal energy from the suspension preheater exhaust gas and the hot air derived from the clinker cooler discharge were used simultaneously to generate electric energy. The first configuration conceived, a simple ORC, was composed of a turbine (TURB), a condenser (COND), a pump (BB 01) and an evaporation unit, which consists of an economizer (ECO), evaporator 01 (EVP 01), evaporator 02 (EVP 02) and a superheater (SAQ). Supplementary equipment are the electric generator (GER), electrical substation (SEE) and electric motor (M). The simple ORC for WHR in a cement industry considered in this study is represented in Fig. 1.

The operation of the presented simple ORC can be described as: the working fluid receives heat in the evaporation unit at constant pressure from process 4 to 1; it is expanded isentropically in the turbine from process 1 to 2; the organic fluid transfers heat to the cooling water at constant pressure in the condenser from process 2 to 3; and then, it is pumped back to the evaporation unit from process 3 to 4 to initiate the cycle again.

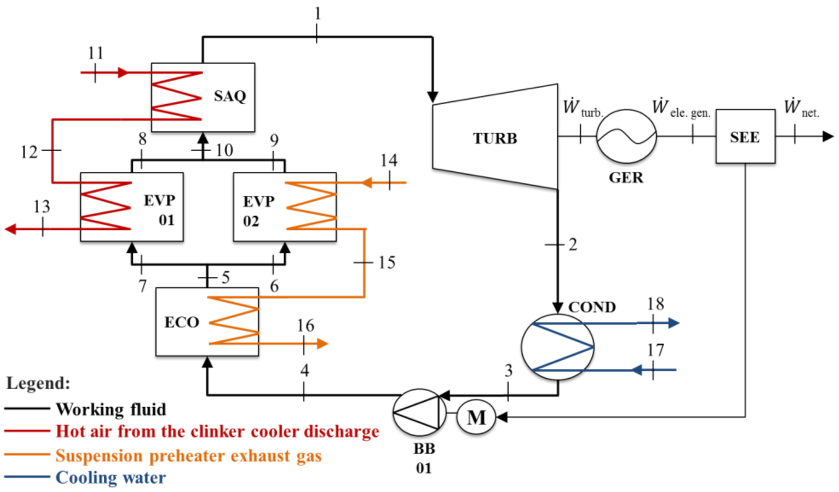

Figure 1. Diagram of the simple ORC for WHR in a cement factory

In agreement with the first and second laws of thermodynamics, the main operational parameters of the developed simple ORC were calculated as follow:

The heat received by the organic working fluid in the evaporation unit is given by Eq. (1):

$$\dot{Q}_{in\ cycle} = \dot{m}(h_1 - h_4)\dot{\mathrm{W}}_{\mathrm{turb}} = \dot{\mathrm{m}}_{12}(\mathrm{h}_1\text{-}\mathrm{h}_2) \quad (1)$$

where h_1 and h_4 are the specific enthalpies of the working fluid at the evaporation unit outlet and inlet, subsequently; and $\dot{m}$ is the mass flow rate of organic fluid.

The power produced by the turbine can be expressed as Eq. (2):

$$\dot{W}_{TURB} = \dot{m}(h_1 - h_2)\dot{\mathrm{W}}_{\mathrm{turb}} = \dot{\mathrm{m}}_{12}(\mathrm{h}_1\text{-}\mathrm{h}_2) \quad (2)$$

where h_1 and h_2 are the specific enthalpies of the working fluid at the turbine inlet and outlet, in this order.

The power consumed by the pump is given by Eq. (3):

$$\dot{W}_{BB,01} = \dot{m}(h_4 - h_3)\dot{\mathrm{W}}_{\mathrm{turb}} = \dot{\mathrm{m}}_{12}(\mathrm{h}_1\text{-}\mathrm{h}_2) \quad (3)$$

where h_4 and h_3 are the specific enthalpies of the organic fluid at the pump outlet and inlet, respectively.

The net power output generated by the ORC can be expressed as Eq. (4):

$$\dot{W}_{net} = \eta_{GEN}\dot{W}_{TURB} - \dot{W}_{BB,01}\dot{\mathrm{W}}_{\mathrm{turb}} = \dot{\mathrm{m}}_{12}(\mathrm{h}_1\text{-}\mathrm{h}_2) \quad (4)$$

where η_{GEN} is the efficiency of the electric generator.

The thermal efficiency of the ORC is given by Eq. (5):

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in\ cycle}}\dot{\mathrm{W}}_{\mathrm{turb}} = \dot{\mathrm{m}}_{12}(\mathrm{h}_1\text{-}\mathrm{h}_2) \quad (5)$$

The physical exergy of each thermodynamic state can be expressed as Eq. (6):

$$ex = h - h_0 - T_0(s - s_0)\dot{\mathrm{W}}_{\mathrm{turb}} = \dot{\mathrm{m}}_{12}(\mathrm{h}_1\text{-}\mathrm{h}_2) \quad (6)$$

where h is the specific enthalpy of the stream; h_0 is the specific enthalpy of the stream evaluated in the pressure and temperature of the dead state; T_0 is the temperature of the dead state (see Tab. 3); s is the specific entropy of the stream; and s_0 is the specific entropy of the stream assessed in the pressure and temperature of the dead state.

The exergy destruction within the control volume by action of irreversibilities is given by Eq. (7):

$$\dot{E}_d = T_0\dot{\sigma}_{cv}\dot{\mathrm{W}}_{\mathrm{turb}} = \dot{\mathrm{m}}_{12}(\mathrm{h}_1\text{-}\mathrm{h}_2) \quad (7)$$

where $\dot{\sigma}_{cv}$ is the entropy generation inside the control volume.

The exergy efficiency of the ORC can be expressed as Eq. (8):

$$\eta_{ex} = \frac{\dot{P}}{\dot{F}}\dot{\mathrm{W}}_{\mathrm{turb}} = \dot{\mathrm{m}}_{12}(\mathrm{h}_1\text{-}\mathrm{h}_2) \quad (8)$$

where $\dot{P}$ is the exergy product; and $\dot{F}$ is the exergy fuel.

The second configuration, exhibited in Fig. 2, is a regenerative ORC. It contains the same components as the first arrangement and other equipment, for example, a direct contact heater (AAA), a regenerator (AAF), a liquid drain trap (PURG) and a second pump (BB 02) were incorporated into this system. In addition, the simple turbine was replaced by a three stage turbine with two steam extractions.

As in the previous composition, the working fluid is heated in the evaporation unit at constant pressure (process 9-1); it experiences isentropic expansion in the turbine (process 1-4), however, before finishing the expansion, there are two steam extractions (processes 1-2 and 1-3). These steam extractions are sent to the direct contact heater and to the regenerator, subsequently. After the complete expansion process in the turbine, the organic fluid transfers heat to the cooling water at constant pressure in the condenser (process 4-5) and it is pumped to the regenerator (process 5-6), where it absorbs heat from the second steam extraction (process 3-16) at constant pressure. After crossing the regenerator (process 6-7), the working fluid is mixed with the first steam extraction from the turbine. Meanwhile, the condensed organic fluid (process 16-17) is sent back to the condenser. Lastly, the organic working fluid leaves the direct contact heater and returns to the evaporation unit (process 8-9) to start a new cycle.

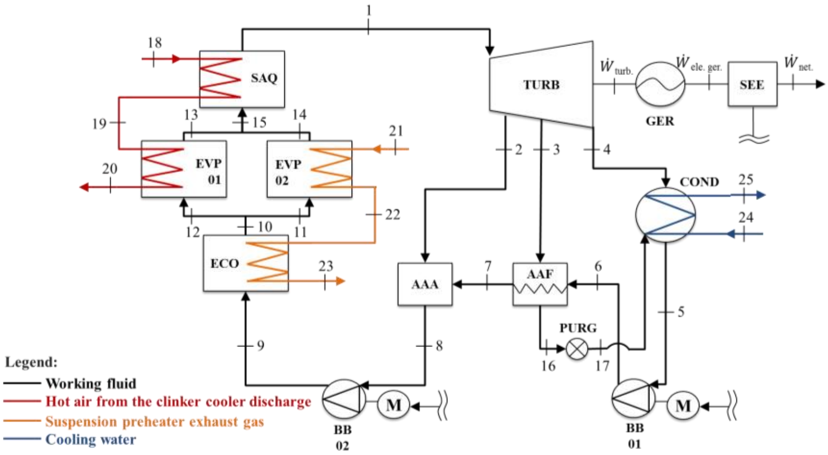

Figure 2. Diagram of the regenerative ORC for WHR in a cement plant

Analogously to the simple ORC, the principal operational parameters of the regenerative ORC were acquired applying Eq. (1), Eq. (2), Eq. (3), Eq. (4), Eq. (5), Eq. (6), Eq. (7) and Eq. (8) presented previously according to the first and second laws of thermodynamics.

The cycles worked under subcritical operating conditions, in other words, the operating pressure for all working fluids was inferior to P_{cr}. The chemical composition of the exhaust gases from cement productive process as well as their outlet temperature from the evaporation unit were obtained from Cimento Apodi (2015) and are summarized in Tab. 2. This is a real cement plant located in Quixeré, CE, Brazil capable to produce 3,500 tons of clinker per day.

Table 2. Exhaust gases from cement production process inlet data

Variable	Unit	Value
Hot air from the clinker cooler discharge data:		
Molar composition: N_2	%	79.00
O_2	%	21.00
Inlet / Outlet temperature	ºC	440 / 114
Mass flow rate	kg/s	48.15
Suspension preheater exhaust gas data:		
Molar composition: CO_2	%	26.30
N_2	%	64.58
O_2	%	4.94
H_2O	%	4.18
Inlet / Outlet temperature	ºC	310 / 228
Mass flow rate	kg/s	88.03

The isentropic efficiencies of the pump and turbine were provided by Wang, J. *et al* (2009) and the main assumptions for the calculations of cogeneration systems usually adopted in the analyzed literature to execute the simulations are demonstrated in Tab. 3.

Table 3. Further inlet data considered in the modeling

Variable	Unit	Value
Isentropic efficiency of the pump	%	70.00
Isentropic efficiency of the turbine	%	85.00
Efficiency of the electric generator	%	98.50
Efficiency of the electric motor	%	99.00
Pressure of the exhaust gases from cement production process	MPa	0.101
Environment pressure (P_0)	MPa	0.101
Environment temperature (T_0)	ºC	22.00

Moreover, during the modeling of the ORCs it was established that: (i) the cycles were at steady state; (ii) the variations of kinetic and potential energies were neglected; and (iii) all processes were adiabatic. Furthermore, the simulations were performed using the EES Professional V.10.092 software.

2.3 Optimization

As mentioned by Rao (2009), the optimization supplied by the genetic algorithm is adequate for solving complex problems which involve either multiple variables or non-linear and discrete functions. This method works based on principles of genetic and natural selection from the evolutionary theory proposed by Charles Darwin (1809-1882).

The optimization of the operating parameters of the cycles under subcritical condition in this work aimed to find the largest amount of net power output for all working fluids chosen. For this reason, net power output was defined as the objective function. The range of variation for the operating parameters considered in the optimization procedure is exposed in Tab. 4. The temperature difference at the economizer ($\Delta T_{sub\text{-}cooling}$) and evaporator 02 ($\Delta T_{EVP\ 02}$) were the variables diversified in both configurations. Additionally, the genetic algorithm method from EES library was set with 32 individuals, 64 generations and a mutation rate of 0.2625.

Table 4. Range of variation of the variables during the optimization

Fluid	$\Delta T_{sub\text{-}cooling}$ min – máx [°C]	$\Delta T_{EVP\ 02}$ min – máx [°C]
R11	71 - 139	100 - 200
R123	111 - 130	
R124	74 - 78	
R141b	97 - 139	
R142b	84 - 91	
R245fa	96 - 103	
R600	91 - 100	
R600a	50 - 62	

3. RESULTS AND DISCUSSION

Applying the first and second laws of thermodynamics, continuity equation and utilizing the indicated inlet data, the simple ORC was designed and optimized under subcritical operating condition. The most important results reached in this arrangement, such as the heat required by the cycle, mass flow rate at the turbine inlet, net power output, exergy destruction, thermal and exergy efficiencies are shown in Tab. 5. An accurate analysis of the results revealed that the isentropic fluids R141b, R11 and the dry fluid R123, in this order, demonstrated superiority over other organic fluids from the perspective of net power output, first and second law efficiencies.

Table 5. Results for the simple ORC under subcritical operating condition

Fluid	Classification	$\dot{Q}_{in}$ [kW]	$\dot{m}$ [kg/s]	$\dot{W}_{net}$ [kW]	η_{th} [%]	η_{ex} [%]	$\dot{E}_d$ [kW]
R11	Isentropic	24,260	111.39	4,537	18.70	41.52	6,391
R124		24,261	151.70	2,876	11.85	26.31	8,053
R141b		24,261	82.11	4,564	18.81	41.76	6,365
R142b		24,261	109.56	3,303	13.62	30.23	7,625
R600		24,260	52.99	3,552	14.64	32.50	7,377
R600a		24,260	61.20	3,107	12.81	28.43	7,822
R123	Dry	24,261	105.81	4,316	17.79	39.49	6,613
R245fa		24,261	100.82	3,605	14.86	32.99	7,324

Analogously to the simple ORC, a similar approach was carried out for the regenerative composition for simulating and optimizing the variables of the ORC. Table 6 presents the most relevant results for the regenerative ORC working under subcritical condition, for instance, the heat demanded by the cycle, mass flow rate at the turbine inlet, net power output, exergy destruction, thermal and exergy efficiencies. In consonance with the acquired results, all of the investigated working fluids produced higher quantities of net power output, as well as an increment in the first and second law efficiencies compared to the simple ORC. Similarly to the simple configuration, the most benefited organic fluids from the point of view of net power output, thermal and exergy efficiencies were the isentropic fluids R141b and R11 and the dry fluid R123, correspondingly.

Table 6. Results for the regenerative ORC under subcritical operating condition

Fluid	Classification	$\dot{Q}_{in}$ [kW]	$\dot{m}$ [kg/s]	$\dot{W}_{net}$ [kW]	η_{th} [%]	η_{ex} [%]	$\dot{E}_d$ [kW]
R11	Isentropic	24,255	158.65	5,535	21.72	48.22	5,658
R124		24,259	171.99	3,186	13.10	29.08	7,750
R141b		24,168	118.08	5,541	22.40	49.70	5,478
R142b		24,259	127.49	3,703	15.03	33.35	7,283
R600		24,258	63.33	4,001	16.32	36.23	6,969
R600a		24,253	69.18	3,434	14.01	31.09	7,529
R123	Dry	24,257	151.28	4,964	20.46	45.42	5,964
R245fa		24,261	127.90	4,090	16.82	37.34	6,848

Contrasting the results presented by of both arrangements, it was verified that the regenerative ORC performed more effectively than the simple ORC in terms of net power output generated, first and second law efficiencies, which in average, corresponds to improvements of 12.73%, 11.55% and 11.54%, respectively. This results comparison can be better evaluated in Fig. 3, which contrasts the net power output produced by the cycles for all working fluids. On the other hand, Fig. 4 and Fig. 5 compare the thermal and exergy efficiencies between the simple and the regenerative ORC for the studied organic fluids.

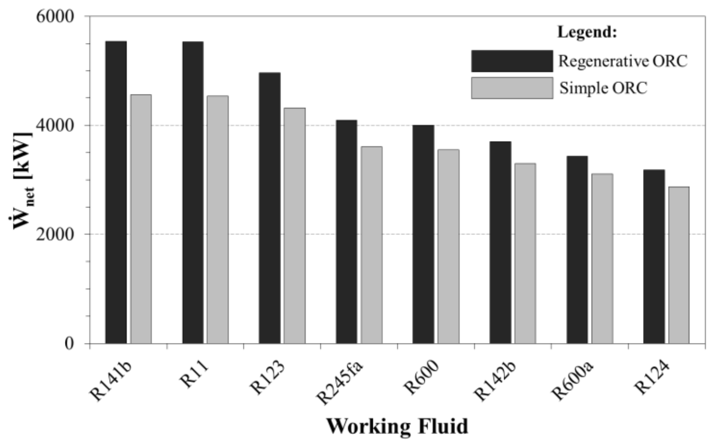

Figure 3. Comparison of the net power output generated by the simple and the regenerative ORCs for all working fluids

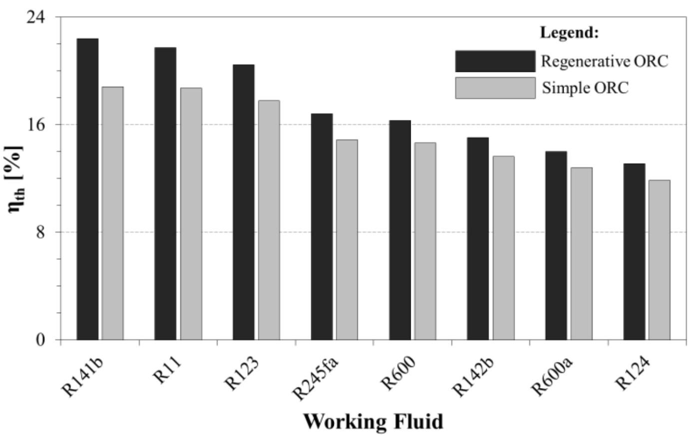

Figure 4. Comparison of the thermal efficiency demonstrated by the simple and the regenerative ORCs for all working fluids

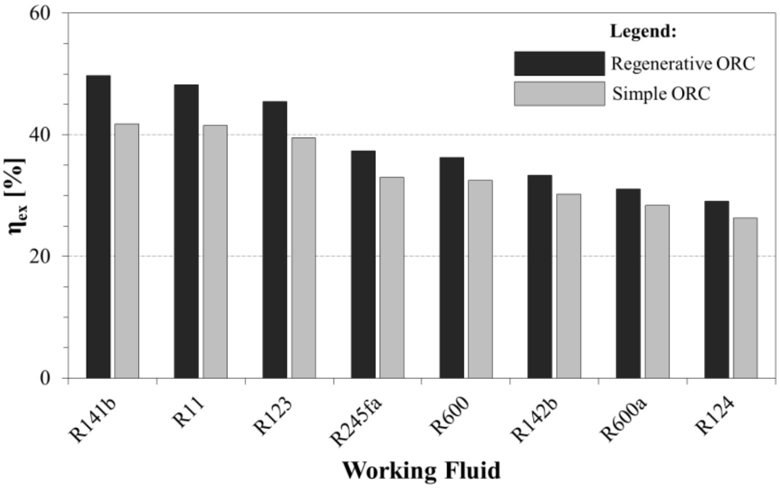

Figure 5. Comparison of the exergy efficiency demonstrated by the simple and the regenerative ORCs for all working fluids

The evident advantage of the regenerative ORC over the simple ORC from the context of overall performance was already expected. After a more detailed analysis, it was found out that it occurred due to the increase in the thermodynamic average temperature during the heat addition process in the evaporation unit explained by the presence of the regenerative components in this cycle, for example, the regenerator, the direct contact heater and the three stage turbine with steam extractions. Hence, the working fluids in the regenerative composition operated with a modest temperature difference between the temperature at the turbine inlet and the temperature at the evaporation unit inlet. That is, the organic fluids entered more warmed in the evaporation steps, allowing this cycle to work with greater mass flow rate and, consequently, to generate larger amount of net power output.

Also, another effect of enhancing the average temperature in the heat admission process was that the regenerative configuration required less thermal energy from the heat source for evaporating the working fluid compared to the simple ORC. This led the regenerative arrangement to be superior from the perspective of thermal efficiency. In addition, another aspect that deserves to be emphasized is the reduction in entropy generation in most equipment of the regenerative ORC justified by the decrease in exergy destruction within the cycle components, which is the motive for the growth of exergy efficiency. These results agree on what was stated by Mago *et al* (2008) and Moran *et al* (2013) that, in summary, the effectiveness of the regenerative configuration is higher than the simple one, by reason of its more elevated average temperature of heat addition.

4. CONCLUSIONS

The main conclusions of the comparative analysis of ORC for WHR in cement industry are:

- Operating parameters such as heat supplied to the cycle, temperature, pressure and mass flow rate at the turbine inlet play a key role in the system performance;
- The regenerative ORC takes advantage over the simple one, for it produces more net power output and it is also more thermally end exergetically efficient;
- Expanding the thermodynamic average temperature along the heat admission process, beyond improving the system's efficiency, it diminishes the exergy destruction within the cycle equipment. It means that less entropy is generated and irreversibility losses are minimized;
- The best organic fluid to perform on the proposed ORCs, from the point of view of net power output, first and second laws of thermodynamics, was the isentropic fluid R141b.

5. ACKNOWLEDGEMENTS

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