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A Perspective Evolution Methodology of Energy Management in a Subcritical Regenerative Organic Rankine Cycles Operate at Two Temperature Levels

By Ali H. Tarrad[*]

The waste energy recovery and management philosophy represent a great challenge for scientists. This article outlines a scheme to utilize two different source temperature levels in the range of (160–200) °C. Two regenerative organic Rankine cycles (RORC) were implemented to construct a compound regenerative organic Rankine cycle (CRORC) to improve the energy management of the sources. The method of energy management for these cycles was accomplished by extracting a certain amount of energy from the high-temperature cycle and rejecting it to the working fluid in an economizer at the low-temperature level. R-123 was circulated in the high-temperature cycle due to its high critical temperature at evaporation and condensation temperatures of 150 °C and 50 °C respectively. R-123, R-245fa, R-1233zd-E, and the hydrocarbon R-600a were used as working fluids for the low-temperature cycle at evaporation and condensation temperatures of 130 °C and 35 °C respectively. This technique showed that the first law of thermodynamics efficiency was augmented by (3–5)% for the low-temperature mini-cycle of the (CRORC). The energy consumption at the low-temperature cycle was also reduced by (3–5)%. The latter reduction range accounts for 2% for the total extracted energy for the independent system where both high-temperature and low-temperature cycles were utilized separately. The data showed that increasing the superheat degree from 10 °C to 20°C has enhanced the thermal efficiency of the compound (CRORC) system by (2–4)%. The (CRORC) system of R-123/R600a, R-123/R-123, and R-123/R-245fa fluid pairs exhibited higher thermal efficiency than that of R-123/R-1233zd-E pair by (4.5–6)%, (4–6)% and (3–4)% respectively. The net thermal efficiency of the compound (CRORC) system fell in the range (12–13)% and the low-temperature mini-cycle of the (CRORC) system had a range of (12–14)% for all of the examined operating conditions.

Keywords: *compound cycle, regenerative, energy management, energy recovery*

Introduction

The basic and regenerative, sub-critical, and single pressure (ORC) systems have been adopted in the practical field due to their allowable working operating conditions range and compactness, Le et al. (2014) and Astolfi et al. (2017). Shengjun et al. (2011) investigated the utilization of several working fluids at 80–100 °C in an organic Rankine cycle (ORC). The results proved that isobutene demanded the lowest cost to produce electricity, and the R-152 unit is more compactable. Da Cunha and Souza (2020) simulated a regenerative organic

[*]Professor, CNRS, LEMTA, University of Lorraine, France.

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Rankine cycle with several extractions at the turbine circulated R-134a as a working fluid. The evaporation temperature was ranged between 60 °C and 100 °C with superheated temperatures of 120 °C, 200 °C, and 300 °C. They concluded that the maximum thermal efficiency and turbine output increase with the evaporation temperature. The turbine output power showed an augmentation with increasing in the superheat temperatures and the thermal efficiency exhibited a declination with superheat temperature increase.

Xi et al. (2013) investigated the performance of three different organic Rankine cycles systems to extract waste heat under the same condition. They found that the double-stage regenerative cycle produced the best thermal efficiency and exergy efficiency under the optimal operating conditions. It was followed by the single-stage regenerative system, and the simple organic Rankine cycle has the worst efficiencies. Javanshir et al. (2017) investigated the optimization of a regenerative Organic Rankine cycle (ORC) using dry working fluids. Butane, iso-Butane, and R113 offer the highest specific net of work output. They concluded that the higher cycle net of work output and thermal efficiency corresponds to the working fluids of higher specific heat and higher critical temperature respectively. Yuan and Zhang (2019) studied eight candidate working fluids R-123, R-245fa, R-114, R-236ea, R-236fa, RC318, R-227ea and R-1234yf with a low heat source grade of (100–150) °C. They concluded that under the given operating conditions, the heat source temperature and its allowable minimum temperature at outlet port influence the state for optimal turbine inlet condition. Further, the critical temperature of working fluid represents another factor which affects the optimal condition state.

Vankeirsbilck et al. (2011) compared the performance of the organic Rankine cycle with that of steam one. They concluded that the (ORC) can be operated on low-temperature heat sources grades with low to moderate evaporation pressure, and still achieve a better performance than that of a steam cycle. Molés et al. (2014) compared the performance of R-1233zd-E and R-1336mzz-Z, to R-245fa fluids in an (ORC). They concluded that R-1233zd-E requires 10.3% to 17.3% lower pump power and provides up to 10.6% higher cycle efficiency than R-245fa over the tested range of cycle conditions. They also postulated that the turbine size for R-1233zd-E would be about 7.5% to 10.2% larger than for R-245fa. More recently, Tarrad (2020) investigated the performance of a simple organic Rankine cycle (SORC) when circulated R-123, R-134a, R-290, R-245fa, R-1234ze-E, and R-1233zd-E fluids at low-temperature levels. He concluded that the thermal efficiencies of R-134a, R-123, R-245fa, R-1233zd-E, and R-1234ze-E were higher than that of R-290 by (10–14)%, (11–12)%, (9–12)%, (4–7)% and (1–3)% respectively. R-290 exhibited thermal efficiencies close to R-1233zd-E and R-1234ze-E in the superheat degree range of (5–15) °C. Hence, the hydrocarbon fluid R-290 is a suitable alternative candidate to the conventional fluids R-245fa and R-1233zd-E in the basic organic Rankine cycle (SORC) with a little more safety precautions.

In this work, the thermal performance of a compound regenerative organic Rankine cycle (CRORC) system was compared to that of the independent regenerative organic Rankine cycle (IRORC) system under the same operating conditions. Four organic fluids, R-123, R-1233zd-E, R-245fa, and R600a were studied as candidate working fluids. Four fluid pairs were utilized to evaluate the thermal performance of the postulated system. A hypothetical organic Rankine cycle of nominal heat recovery of 50 kW was implemented for the evaluation of the cycle performance. The low-temperature waste heat source was suggested to be available at the range between 160 °C and 200 °C. Superheat degrees of (10–20) °C were assumed for both temperature levels of the cycle and no subcooled was utilized at the discharge ports of condensers of both mini-cycles.

Methodology

Organic Fluids

The critical point characteristics, pressure, and temperature play a significant role in the working fluids' selection philosophy. Further, the fluid has to possess attractive global warming potential (GWP), Ozone depletion potential (ODP), and favourable thermal properties. Four organics were selected as working fluids to be circulated in the suggested compound regenerative organic Rankine cycles (CRORC). Table 1 shows some of the physical, safety, and environmental characteristics of the selected working fluids.

Table 1. *Characteristics of Test Candidate Fluids*

Refrigerant	Chemical Formula	T_c (°C)	p_c (bar)	M_w (gr/mol)	$T_{n,b}$ (°C)	Depletion		Safety Group*
						ODP	GWP	
R-123	$CHCl_2CF_3$	183.68	36.618	152.93	27.82	0.02	77	B1
R-1233zd-E	$CF_3CH{=}CHCl$	166.45	36.237	130.496	18.26	0.00034	7	A1
R-245fa	$CHF_2CH_2CF_3$	153.86	36.51	134.048	15.05	0	1030	B1
R-600a	$CH(CH_3)_2CH_3$	135.0	36.50	58.12	-12	0	3	A3

*ANSI/ASHRAE Standard 34 2016.

Selected thermodynamics properties of the test fluids are listed in Table 2 for both of the high-temperature and low-temperature cycles fluids.

Table 2a. *Thermodynamics Properties of the Candidate Working Fluid R-123 for the Higher Temperature Level Cycle*

Refrigerant	Pressure (bar)		Liquid Density (kg/m^3)		Liquid Enthalpy (kJ/kg)		Vapor Enthalpy (kJ/kg)	
	50 °C	150 °C	50 °C	150 °C	50 °C	150 °C	50 °C	150 °C
R-123	2.1246	20.987	1397.8	1036.8	251.06	367.1	411.50	461.05

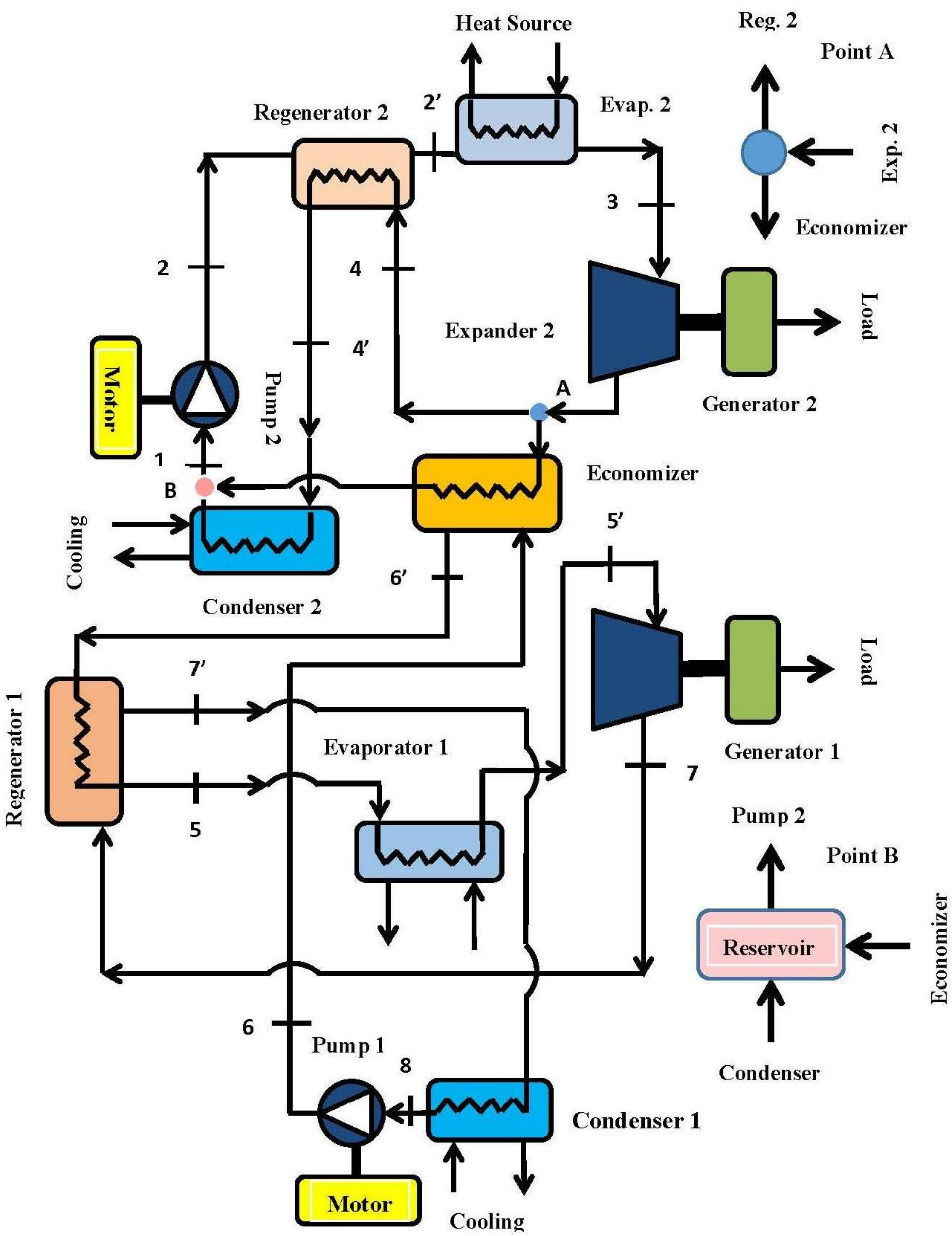
Table 2b. *Thermodynamics Properties of Working Fluids for the Low-Temperature Level Cycle*

Refrigerant	Pressure (bar)		Liquid Density (kg/m^3)		Liquid Enthalpy (kJ/kg)		Vapor Enthalpy (kJ/kg)	
	35 °C	130 °C	35 °C	130 °C	35 °C	130 °C	35 °C	130 °C
R-123	1.305	14.6	1437.7	1133	233.5	340	401	452.70
R-1233zd-E	1.831	19.081	1238	927	243.37	372.878	429.635	484.764
R-245fa	2.117	23.442	1311	940	245.81	390.39	430.08	487.699
R-600a	4.686	33.665	541.42	279.37	282.68	602.31	603.09	691.89

These fluids were selected according to their excellent thermal performance in organic Rankine cycles (ORC), Yuan and Zhang (2019), Vankeirsbilck et al. (2011), Molés et al. (2014), and Tarrad (2020).

Compound Cycle

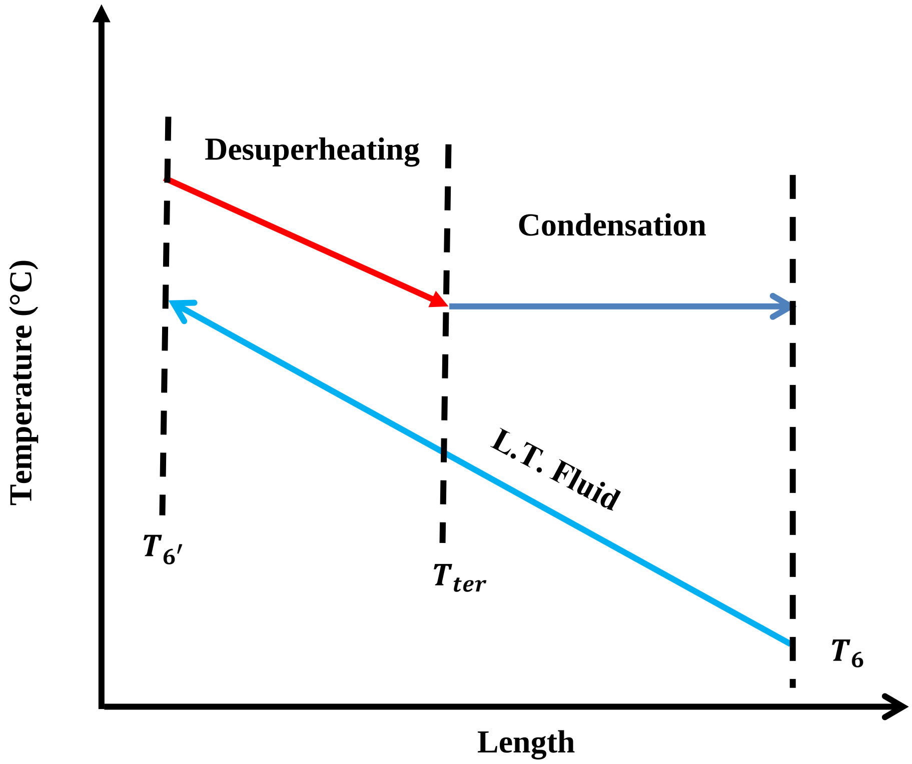
Figure 1. *Compound Cycle with Economizer Condenser*



The arrangement of the postulated cycle is shown schematically in Figure 1, it consists of two regenerative cycles. The upper part of the system represents the high-temperature cycle which circulates R-123 at 150 °C and 50 °C evaporation and condensation temperatures respectively. It utilizes a regenerator to capture the energy before leaving to the condensation unit and improves the thermal performance. The lower part of the compound cycle represents the low-temperature cycle where one of the R-123, R-245fa, R-1233zd-E, or R-600a fluid was circulated in the low-temperature level of 130 °C and 35°C evaporation and condensation temperatures respectively.

The two cycles are combined through the economizer which extracts the energy from R-123 vapor at the exit of the expander port (4) and heats the low-temperature fluid before passing through the regenerator at the lower part of the system. The suggested technology improves the thermal management of the cycle, it raises the temperature of low-temperature cycle fluid and minimizing the required heat absorbed at the lower part of the cycle. An 8% of R-123 mass flow rate of the high-temperature cycle fluid was extracted at point (A) and passed through the economizer. This amount of fluid bypass was inferred from keeping a constant terminal temperature difference between condensate and the low-temperature fluid at the exit side of the condensation zone of the condenser. This is shown schematically in Figure 2.

Figure 2. *Fluid Temperature Variation in the Economizer*



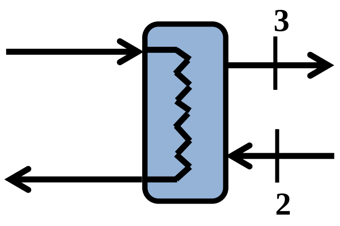
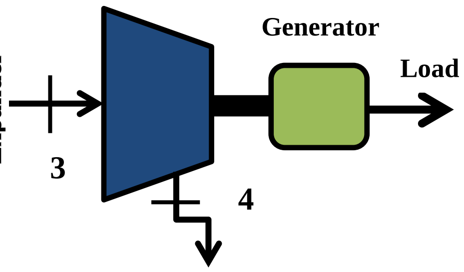
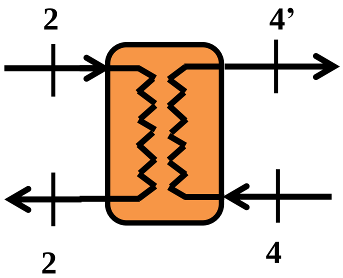
In the present work, a value of 2 °C was considered as a maximum terminal temperature difference (ΔT_{ter}) to ensure a complete condensation of the bypassed fluid amount in the economizer. Although using a lower (ΔT_{ter}) raises the low-temperature fluid to a higher energy level but it is not preferable since this will increase the surface area of the economizer which could lead to an economic issue problem.

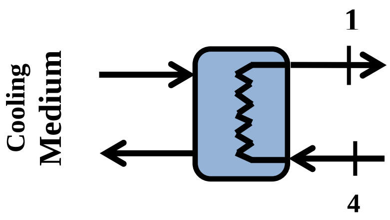
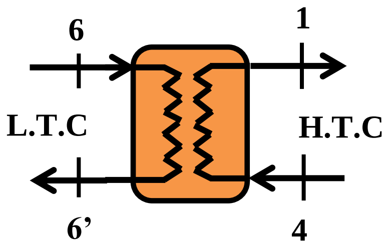
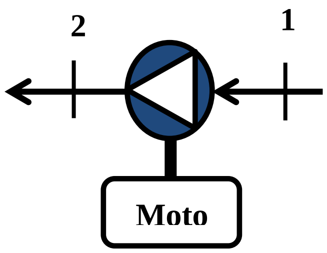
The remainder amount of flow rate accounts for 92% of total circulating fluid was passed through the regenerator (2) where it heats the R-123 fluid before entering the evaporator (2). The bypassed R-123 fluid was condensed in the economizer and discharged to the reservoir at point (B) and mixed with the condensed flow from the condenser (2) as shown in Figure 1. This technique allows for consuming energy at a low-temperature level and converts it to a useful one for electricity production.

Thermal Analysis

The thermal analysis of the compound cycle is presented in Table 3 for each of the cycle components in the high and low-temperature levels.

Table 3. *Thermal Analysis of the Compound Regenerative Organic Rankine Cycle (CRORC)*

Component	Analysis
Evaporator **Heat source** 	$\dot{Q}_{evap,H.T} = \dot{m}_{H.T}\,(h_3 - h_{2'})$ (1.a) $\dot{Q}_{evap,L.T} = \dot{m}_{L.T}\,(h_{5'} - h_5)$ (1.b)
Expander 	$\eta_{is,ex,H.T} = \frac{h_3 - h_4}{h_3 - h_{4,is}}$ (2.a) $\eta_{is,ex,L.T} = \frac{h_{5'} - h_7}{h_{5'} - h_{7,is}}$ (2.b) $\dot{W}_{ex,H.T} = \eta_{m,ex}\,\eta_{v,ex}\,\dot{m}_{H.T}\,(h_3 - h_4)$ (3.a) $\dot{W}_{ex,L.T} = \eta_{m,ex}\,\eta_{v,ex}\,\dot{m}_{L.T}\,(h_{5'} - h_7)$ (3.b)
Regenerator 	$\varepsilon = \frac{T_4 - T_{4'}}{T_4 - T_2}$ (4.a) $\varepsilon = \frac{T_7 - T_{7'}}{T_7 - T_{6'}}$ (4.b) $h_{2'} = h_2 + h_4 - h_{4'}$ (5.a) $h_5 = h_{6'} + h_7 - h_{7'}$ (5.b)

Component		Analysis
Condenser		$\dot{Q}_{cond,H.T} = 0.92\,\dot{m}_{H.T}\,(h_{4'} - h_1)$ (6.a) $\dot{Q}_{cond,L.T} = \dot{m}_{L.T}\,(h_{7'} - h_8)$ (6.b)
Economizer		$\dot{Q}_{Econ} = 0.08\,\dot{m}_{H.T}\,(h_4 - h_1)$ (7) $h_{6'} = h_6 + \frac{\dot{Q}_{Econ}}{\dot{m}_{L.T}}$ (8)
Pump		$\eta_{is,p,H.T} = \frac{h_{2,is}-h_1}{h_2-h_1}$ (9.a) $\eta_{is,p,L.T} = \frac{h_{6,is}-h_8}{h_6-h_8}$ (9.b) $\dot{W}_{p,H.T} = \dot{m}_{H.T}(h_1 - h_2)/\eta_{m,p}$ (10.a) $\dot{W}_{p,L.T} = \dot{m}_{L.T}\,(h_6 - h_8)/\eta_{m,p}$ (10.b)

The first law of thermodynamics efficiency is defined as:

$$\eta_{net} = \frac{\dot{W}_{ex} - \dot{W}_p}{\dot{Q}_{evap}} \quad (11)$$

Hence, the compound cycle net thermal efficiency is estimated from:

$$\eta_{net,com} = \frac{(\dot{W}_{ex,H.T}+\dot{W}_{ex,L.T})-(\dot{W}_{p,H.T}+_{p,L.T})}{\dot{Q}_{evap,H.T}+\dot{Q}_{evap,L.T}} \quad (12)$$

The corresponding net thermal efficiency for the two independent cycles is calculated by:

$$\eta_{net,ind} = \frac{(\dot{W}_{ex,H.T}+\dot{W}_{ex,f})-(\dot{W}_{p,H.T}+\dot{W}_{p,f})}{\dot{Q}_{evap,H.T}+\dot{Q}_{evap,f}} \quad (13)$$

The subscription (*f*) refers to the working fluid which is circulating in the lower temperature cycle. This includes R-123, R-245fa, R-1233zd-E, and R-600a at evaporation and condensation temperatures of 130 °C and 35 °C respectively. The high-temperature cycle corresponds to the R-123 working fluid at evaporation and condensation temperatures of 150 °C and 50 °C respectively. The parameter

$\eta_{net,ind}$ is the mean value of the net thermal efficiency when these cycles operate independently at the two temperature levels.

The mass flow rate of the circulated fluid was calculated for the hypothetical cycles of the total 50 kW nominal evaporation load, for a mini-cycle of the (CRORC) and independent systems, it corresponds to:

$$\dot{m} = \frac{25}{(h_{g,evap} - h_x)} \tag{14}$$

In this expression, it has been assumed that each mini-cycle of the (CRORC) and independent systems possesses half of the total nominal heat load. The ($h_{g,evap}$) refers to the vapor enthalpy at the operating evaporator saturation temperature, Table 2. The enthalpy (h_x) corresponds to that at the pump discharge side, it is equal to (h_2) and (h_6) for the high and low-temperature mini-cycles respectively for the compound system. The same mass flow rates were circulated in both of the (CRORC) and (IRORC) systems.

$$\dot{Q}_{evap,t} = \dot{Q}_{evap} + \dot{Q}_{sup} \tag{15}$$

Table 4 illustrates the numerical values of the efficiencies of the expander and pump and the effectiveness of the regenerators.

Table 4. *The Numerical Values of Performance Parameters Utilized at the Present Work*

Parameter	Magnitude
Expander isentropic efficiency, $\eta_{is,ex}$	85%
Expander volumetric efficiency, $\eta_{v,ex}$	85%
Expander mechanical efficiency, $\eta_{m,ex}$	90%
Pump isentropic efficiency, $\eta_{is,p}$	85%
Pump mechanical efficiency, $\eta_{m,p}$	80%
Regenerator effectiveness, ε	80%

The evaluation of the performance comparison between different test fluids under similar operating conditions was based on the discrepancy percentage defined as:

$$\beta_{\phi} = \frac{\phi_n - \phi_{ref}}{\phi_n} \times 100 \tag{16}$$

Here, the subscriptions (*n*) and (*ref*) refer to the compared fluid and reference fluid respectively. The parameter (ϕ) refers to the required characteristic variable for comparison such as $\dot{W}_{pump}$, $\dot{W}_{exp}$, $\dot{Q}_{eavp}$, and η_{net}. This expression is valid for comparison of the performance of the same fluid at different operating conditions such as volumetric efficiency or evaporation temperature change. The comparison of the compound regenerative organic Rankine cycle (CRORC) system and the independent regenerative organic Rankine cycle (IRORC) system performance parameters were deduced from:

$$\zeta_{\phi} = \frac{\phi_{com} - \phi_{ind}}{\phi_{com}} \times 100 \qquad (17)$$

The parameter (ϕ) has the same definitions as those in Eq. (16). Equation (17) is valid for all of the compared parameters, $\dot{W}_{pump}$, $\dot{W}_{exp}$, and η_{net} except for the consumed energy one ($\dot{Q}_{eavp}$) which was inverted as:

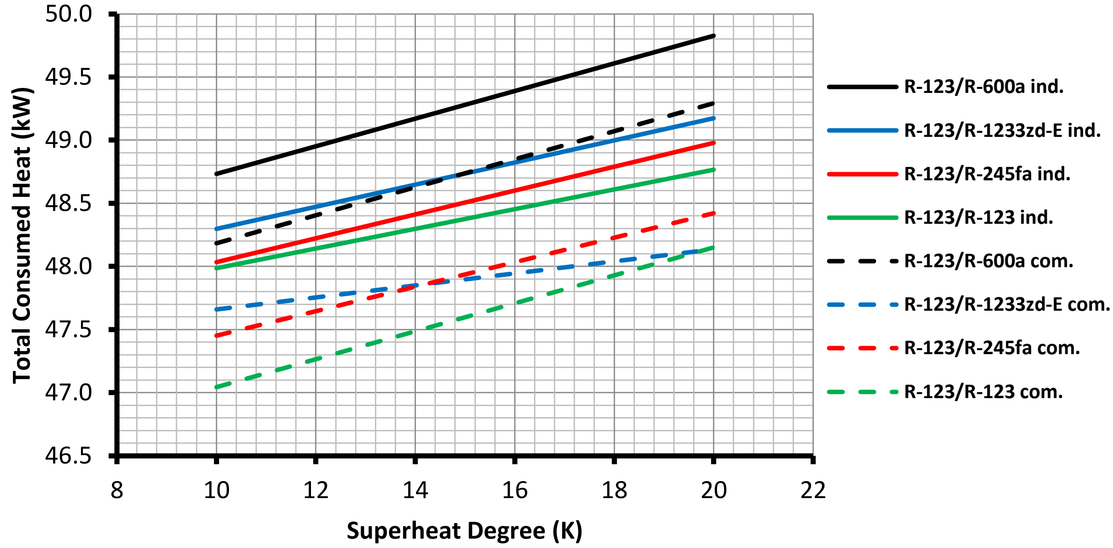
$$\zeta_{\dot{Q}_{evap}} = \frac{\dot{Q}_{evap,ind} - \dot{Q}_{evap,com}}{\dot{Q}_{evap,ind}} \times 100 \qquad (18)$$

Results and Discussion

Consumed Energy

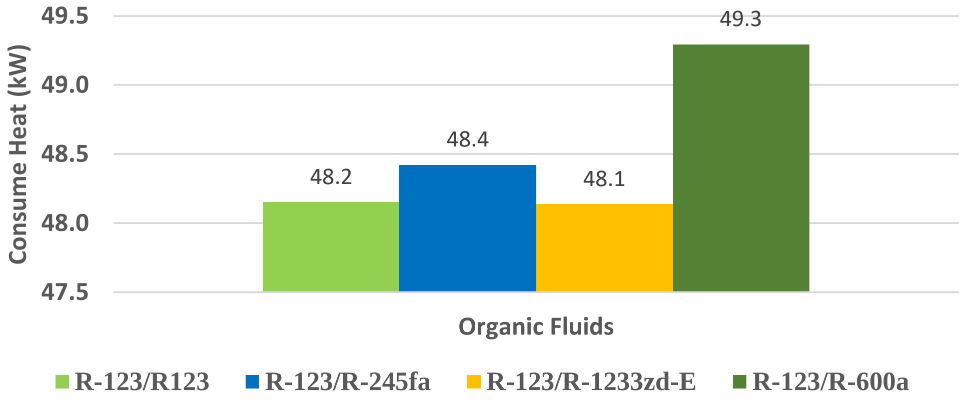
Figure 3 illustrates a comparison of the total consumed heat rate between the compound and independent cycle systems.

Figure 3. *A Comparison of Consumed Heat Load for the (CRORC) and (IRORC) Systems*



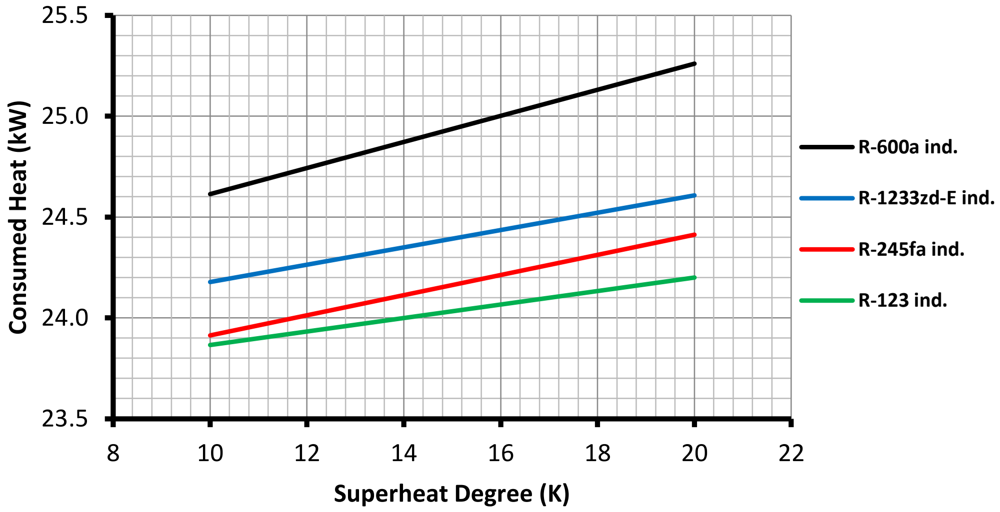
The results indicated that the (IRORC) independent cycle system needed more energy consumption than that of the compound system for all fluid combinations, the high and low-temperature cycles. The R-123/R-600a and R-123/R-123 systems consumed the higher and lower energy respectively than other fluid combinations for both compound and independent cycle systems. For the independent system, the R-123/R-600a, R-123/R-245fa, and R-123/R-1233zd-E systems showed higher energy extractions than that of R-123/R-123 by (1.5–2)%, 1% and 0.5% respectively. The corresponding numerical values of energy consumption discrepancy from that of the R-123/R-123 system for the R-123/R-600a, R-123/R-245fa, and R-123/R-1233zd-E systems were 2.5%, 1%, and 1% respectively. Figure 4 depicts a comparison of the total consumed energy for both of the high and low-temperature levels of the compound system at a superheat degree of 20 °C.

Figure 4. *A Comparison of the Consumed Heat of the Compound System for Different Fluid Combinations at a Superheat Degree of (20) °C*



The consumed energy for the independent system was higher than that of the compound system by the range of (1–2)% for the test fluid combinations and operating conditions.

Figure 5. *Comparison of Consumed Heat Load at the Simple Independent Low-Temperature Cycle Version*



At the low-temperature cycle of (IRORC) operating conditions, the R-600a and R-123 cycles showed higher and lower consumed energy respectively than other examined fluids, Figure 5. R-600a, R-1233zd-E and R-245fa energy consumptions were higher than that of the R-123 value by (3–4)%, (1.3–1.7)% and within 0.5% respectively. The corresponding values of the consumed energy for the low-temperature cycles were 5%, (2–2.5)% and about 2% higher than that of the R-123 fluid for the R-600a, R-1233zd-E and R-245fa respectively.

The gradients of the consumed energy to the superheat degree for the R-123 and R-1233zd-E cycles were the lower among other working fluids. Hence, the superheat degree has less influence on the consumed energy for R-123 and R-1233zd-E, whereas R-600a showed the higher gradient and R-245fa exhibited a moderate one.

Thermal Efficiency

Figure 6 illustrates the net thermal efficiency comparison for both of the compound and independent systems when circulating different combinations of working fluids. The general trend of the results revealed that the compound cycle system achieved higher thermal efficiencies than those of the independent one. The compound system provided a thermal efficiency enhancement when compared to the independent system within the range of 2%. The R-123/R-1233zd-E pair showed lower thermal efficiency among the other examined fluid pairs and operating conditions.

Figure 6. *A Comparison of the Net Cycle Thermal Efficiency for the Two-Cycle Systems*
Figure 6a. *R-600a and R-1233zd-E Low-Temperature Cycle Fluids*

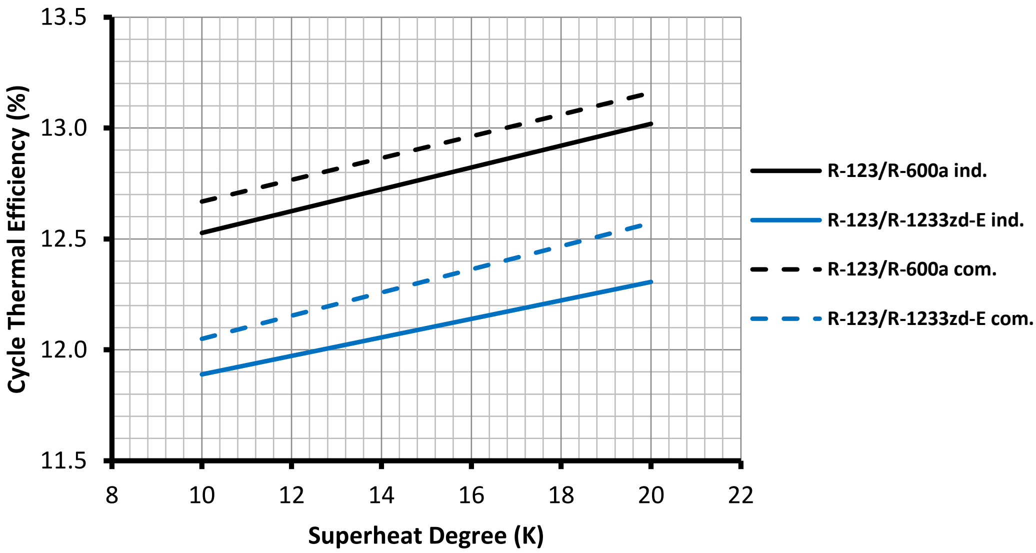
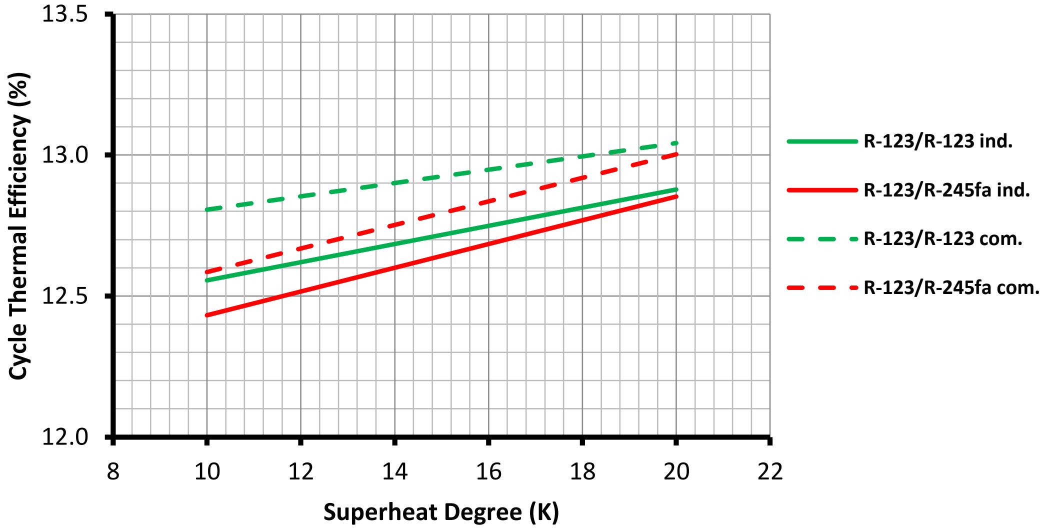


Figure 6b. *R-245fa and R-123 Low-Temperature Cycle Fluids*



The (CRORC) system of R-123/R600a, R-123/R-123, and R-123/R-245fa fluid pairs exhibited higher thermal efficiency than that of R-123/R-1233zd-E pair by (4.5–6)%, (4–6)% and (3–4)% respectively. The corresponding discrepancies for these pairs in the independent system were higher than that of the R-123/R-1233zd-E pair by (5–5.5)%, (4–5)%, and (4–5)% respectively.

Figure 7 illustrates the net thermal efficiency of the compound system at the examined operating conditions and superheat degrees. The net thermal efficiency of the compound (CRORC) system fell in the range between 12% and 13% for all of the examined operating conditions.

Figure 7. *A Comparison of the Cycle Net Thermal Efficiency for the Compound (CRORC) System Arrangement*
Figure 7a. $\Delta T_{sup} = 10\ °C$

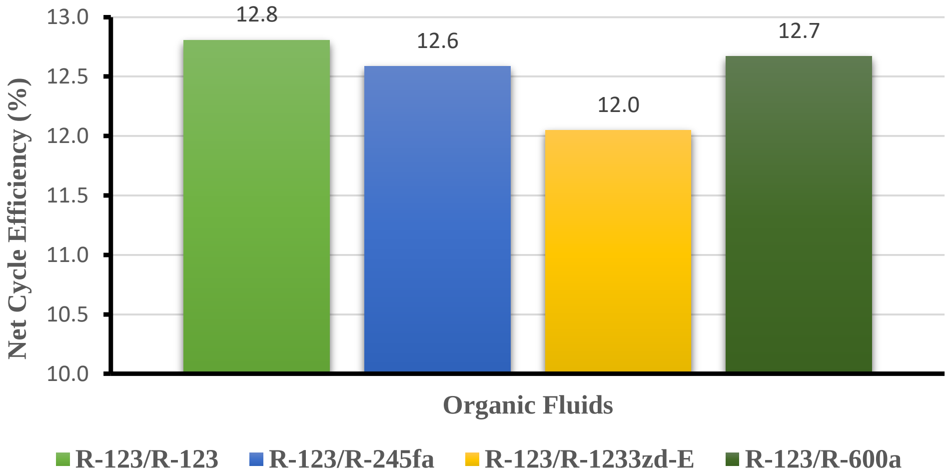
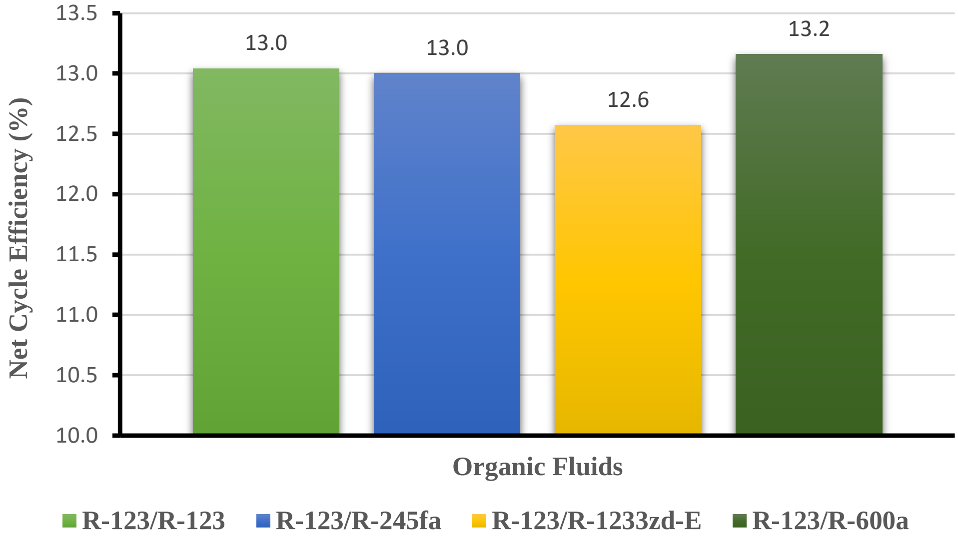


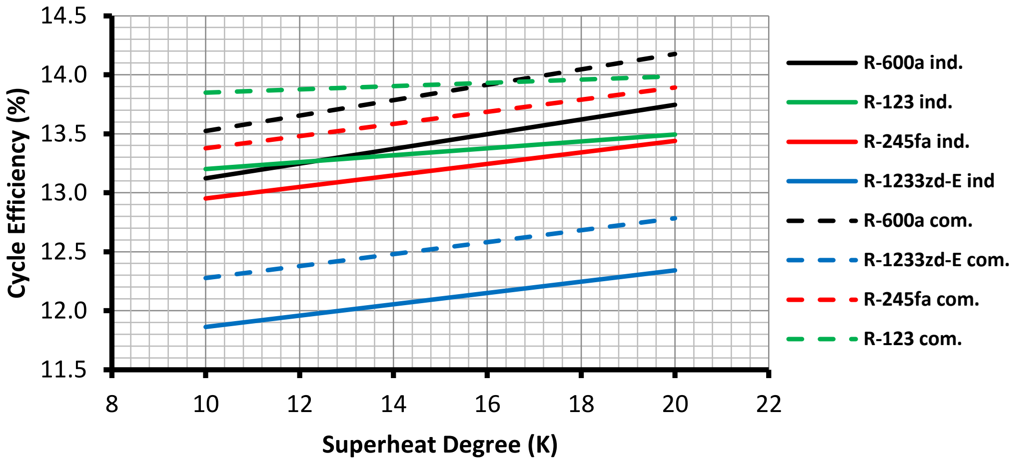
Figure 7b. $\Delta T_{sup} = 20\ °C$



The fluid pairs of R-123/R600a, R-123/R-123, and R-123/R-245fa exhibited close figures of the thermal efficiency, the maximum discrepancy between them fell within 1.5%. The data showed that increasing the superheat degree from 10 °C to 20 °C has enhanced the thermal efficiency of the compound (CRORC) system by (2–4)%. The corresponding figures for the 20 °C of the independent (IRORC) system fell within the range of (2.5–4)% as they were compared to the results at 10 °C.

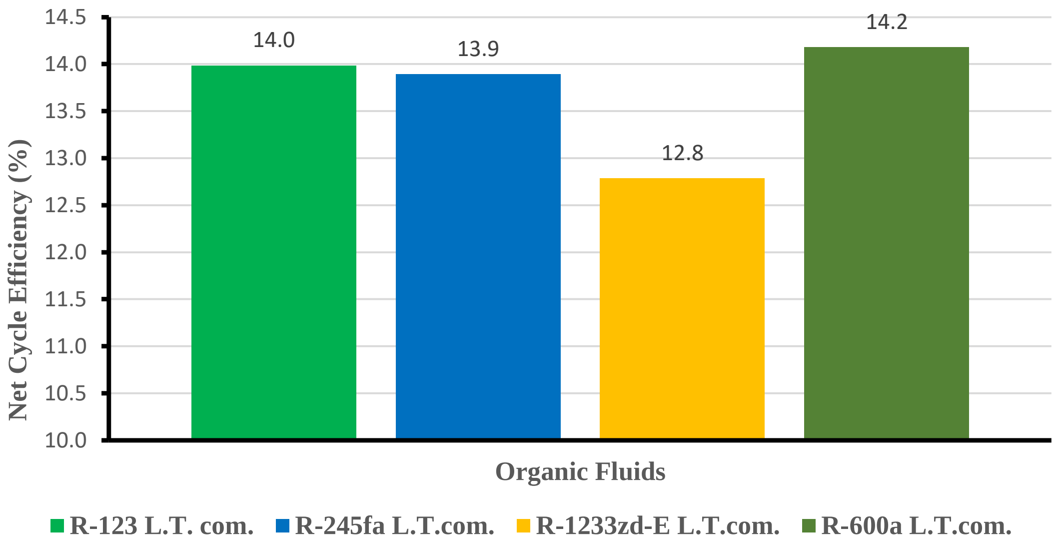
The utilization of the economizer has improved the thermal performance of the low-temperature cycle by minimizing the amount of energy required to run the evaporator. The energy consumption at the low-temperature cycle was reduced by (3–5)%. The thermal efficiency of the low-temperature cycle as compared to that of the independent system is shown in Figure 8.

Figure 8. *A Comparison of Net Cycle Efficiency of the Independent and Compound Systems for the Low-Temperature Part*



The thermal efficiency of the low-temperature cycle of the (CRORC) showed an enhancement of about (3–5)% as compared to the low-temperature of the independent cycle of the (IRORC) system. The R-1233zd-E fluid exhibited the lower value of the thermal efficiency among the other examined fluids at the low-temperature mini-cycle whereas the R-600a cycle produced the highest thermal efficiency. The numerical values of the thermal efficiency discrepancies for the R-600a, R-245fa, and R-123 were (9–11)%, 8%, and (8–11)% respectively when compared to that of the R-1233zd-E low-temperature mini-cycle of the (CRORC) efficiency. The thermal efficiency of the low-temperature mini-cycle of the (CRORC) system approached a value of 14% at 20 °C superheat degree, Figure 9, whereas the R-1233zd-E cycle achieved (12.8)% at the same operating conditions.

Figure 9. *Cycle Net Thermal Efficiency for the Low-Temperature Mini-Cycle of the Compound System at (20) °C Superheat Degree*



Conclusions

A compound cycle was suggested and thermally analyzed to improve the energy management for the case where different temperature levels of waste energy are available in the industrial site. This technique of the (CRORC) has minimized the total energy consumption by (3–5)% for the low-temperature level. This accounts for 2% reduction of total consumed energy when compared to independent cycles (IRORC) operation. This technique showed that the first law of thermodynamics efficiency was improved by (3–5)% for the low-temperature mini-cycle. The numerical values of the mini-cycle low-temperature of the (CRORC) thermal efficiency for the R-600a, R-245fa, and R-123 working fluids were (9–11)%, 8%, and (8–11)% respectively higher than that of the R-1233zd-E one.

The (CRORC) system of R-123/R600a, R-123/R-123, and R-123/R-245fa fluid pairs exhibited higher thermal efficiency than that of R-123/R-1233zd-E pair by (4.5–6)%, (4–6)% and (3–4)% respectively. The corresponding discrepancies for these pairs in the independent system were higher than that of the R-123/R-1233zd-E pair by (5–5.5)%, (4–5)%, and (4–5)% respectively. The net thermal efficiency of the compound (CRORC) system fell in the range (12–13)% and the low-temperature mini-cycle had a range of (12-14)% for all of the examined operating conditions. Increasing the superheat degree from 10 °C to 20 °C has enhanced the thermal efficiency of the compound (CRORC) system by (2–4)%. The corresponding figures for the 20 °C of the independent (IRORC) system fell within the range of (2.5–4)% as they were compared to the results at 10 °C.

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Nomenclature

Parameter	**Definition**
h	Fluid specific enthalpy, (kJ/kg)
M_w	Fluid molecular weight, kg/kmol
$\dot{m}$	Fluid mass flow rate, (kg/s)
P	Fluid working pressure, (bar)
$\dot{Q}$	Heat transfer rate, (kW)
s	Fluid specific entropy, (kJ/kg)
T	Fluid temperature, (°C)
$\dot{W}$	Power, (kW)

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Parameter	**Definition**
c	Critical point
com	Compound
cond	Condenser
evap	Evaporator
ex	Expander
g	Gas condition
H.T	High-temperature side
i	Inlet side
ind	Independent
is	Isentropic
L.T	Low-temperature side
n	Fluid, normal point

net	Net value
p	Feed pump
ref	Reference fluid
sup	Superheated vapor
t	Total
ter	Terminal
v	Volumetric

Greek Letter

β	Deviation percentage, (%)
ε	Heat exchanger effectiveness, (%)
ζ	Deviation, (%)
η	Cycle thermal efficiency, (%)
ϕ	Characteristic parameter

Abbreviations

Parameter	**Definition**
CRORC	Compound Regenerative Organic Rankine Cycle
GWP	Global Warming Potential
IRORC	Independent Regenerative Organic Rankine Cycle
ODP	Ozone Depletion Potential
ORC	Organic Rankine Cycle

References

ANSI/ASHRAE Standard 34 (2016) *Designation and safety classification of refrigerants*. ASHRAE.

Astolfi M, Diega LN, Romano MC, Merlo U, Filippini S, Macchi E (2017) Application of the novel "emeritus" air cooled condenser in geothermal ORC. *Energy Procedia* 129(Sep): 479–86.

Da Cunha AFV, Souza SLS (2020) Analysis of R134a organic regenerative cycle. *Journal of Power and Energy Engineering* 8(5): 32–45.

Javanshir A, Sarunac N, Razzaghpanah Z (2017) Thermodynamic analysis of a regenerative organic Rankine cycle using dry fluids. *Applied Thermal Engineering* 123(Aug): 852–864.

Le VL, Kheiri A, Feidt M, Pelloux-Prayer S (2014) Thermodynamic and economic optimizations of a waste heat to power plant driven by a subcritical ORC (Organic Rankine Cycle) using pure or zeotropic working fluid. *Energy* 78(Dec): 622–638.

Molés F, Navarro-Esbrí J, Peris B, Mota-Babiloni A, Barragán-Cervera Á, Kontomaris KK (2014) Low GWP alternatives to HFC-245fa in organic Rankine cycles for low-temperature heat recovery: HCFO-1233zd-E and HFO-1336mzz-Z. *Applied Thermal Engineering* 71(1): 204–212.

Shengjun Z, Huaixin W, Tao G (2011) Performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. *Applied Energy* 88(8): 2740–2754.

Tarrad AH (2020) A steady-state evaluation of simple Organic Rankine Cycle (SORC) with low-temperature grade waste heat source. *Journal of Power and Energy Engineering* 8(7): 15–31.

Vankeirsbilck I, Vanslambrouck B, Gusev S, De Paepe M (2011) Organic Rankine cycle as efficient alternative to steam cycle for small scale power generation. In *8th International Conference on Heat Transfer, Fluid Mechanics, and Thermodynamics (HEFAT2011), Pointe Aux Piments, Mauritius, 11-13 July 2011*, 785–792.

Xi H, Ming-Jia L, Chao X, Ya-Ling H (2013) Parametric optimization of regenerative organic Rankine cycle (ORC). *Energy* 58(Sep): 473–482.

Yuan P, Zhang C (2019) Comparison on thermodynamic performances between basic and regenerative sub-critical organic Rankine cycles coupled with low-grade heat source. In *IOP Conference Series: Materials Science and Engineering* 473: 012031.