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A comparative study for the organic Rankine cycle coupled with low-temperature grade waste energy source

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Abstract: The present work presents an evaluation comparison between a regenerative organic Rankine cycle (RORC) and a simple organic Rankine cycle (SORC) at two low evaporator temperature levels. The low-temperature waste heat source is to be available from an industrial sector at a temperature range of (160-200) °C. R-123, R-1233zd-E, R-245fa and R600a were studied as candidate working fluids at a boiling temperature of (130) °C superheated by (5-15) °C and condensed at (45) °C sub-cooled by (5) °C. A hypothetical organic Rankine cycle of nominal heat recovery of (10) kW was implemented for the evaluation of the cycle performance. The results indicated that all of the examined fluids gave close values of the expander power output and waste energy extraction. The R-600a and R-245fa exhibited the highest and lowest values of extracted waste energy and expander power output respectively. R-600a absorbed higher energy and produced a power output of (3) % higher than the values of R-245fa at (15) °C superheat degree. The regenerative organic Rankine cycle (RORC) showed higher thermal efficiency than that of the simple one by the range of (8-15) % for the test fluids and operating conditions. The attained maximum and minimum cycle thermal efficiencies were (12) % and (10.7) % for R-600a and R-1233zd-E respectively at (15) °C superheat degree. Increasing of the expander volumetric efficiency by (10) % has improved the thermal efficiency by the range of (10-11) % for the test fluids, it was as high as (13.5) %. The net cycle thermal efficiency of (SORC) showed an augmentation by (34-40) % when the evaporation temperature of the test fluids was increased from (90) °C to (130) °C at fixed superheat and subcooled degree conditions.

Keywords: Organic Rankine Cycle, Regenerative, Hydrocarbons, Thermal Analysis

I. Introduction

There is a lot of waste heat available, often on low-temperature levels and on small to moderate thermal power scale. Energy losses from industrial activities compose about (25-55) % of total energy use. The work of [1], [2], and [3] postulated that for low-temperature grade heat energy conversion systems, the organic Rankine cycle is the optimal choice. There is a variety of organic Rankine cycle configurations; they include sub-critical, trans-critical, or super-critical, basic or regenerative, single pressure or dual-pressure cycles, [4] and [5]. The basic and regenerative, sub-critical, and single pressure ORC systems were intensively simulated and optimized. They were adopted in the practical field due to their allowable working pressure range and sizing, [6] and [7].

The performance of three different organic Rankine cycles systems using six different working fluids under the same waste heat condition was studied, [8]. The results showed that the double-stage regenerative cycle always gives 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. The technical and economic feasibility of converting waste heat from a stream of liquid kerosene was investigated [9]. The performance of the (ORC) system with eight potential refrigerants such as R123, R134a, R245fa, iso-Butane, Butane, Pentane, and some of the hydrocarbon mixtures was examined. The results showed that Isobutene yields the best plant efficiency of 6.8%, and the efficiency can be increased to 7.6% using the Butane/Pentane mixture.

The thermal efficiency and specific investment cost of basic (ORC), single stage-regenerative, and double-stage regenerative (ORC) were analyzed [10]. The optimization procedure showed that R245fa is the best working fluid under-considered conditions and basic (ORC) has low specific investment cost and thermal efficiency compared to regenerative (ORC). The average increase in thermal efficiency from basic (ORC) to single-stage and double-stage regenerative (ORC) was (1.01) % and (1.45) % respectively. They also concluded that evaporation pressure has a promising effect on thermal efficiency and specific investment cost. Reference [11] studied the effect of turbine bleeding pressure on the performance of the organic Rankine cycle. Under the conditions of the critical fraction of turbine bleeding, the simulation results showed that the exergy efficiency decreases with increasing bleeding fraction and it also decreases with increasing bleeding pressure. The optimization of a regenerative organic Rankine cycle (ORC) using dry working fluids. Butane, iso-Butane, and R113 offer the highest specific net work output that has been investigated [12]. They concluded that working

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fluids with higher specific heat produce higher specific net work output while working fluids with higher critical temperatures produce higher thermal efficiency. It was also concluded that regeneration could decrease the difference in thermal efficiencies for different working fluids.

Reference [13] analyzed the performance of several pure organic working fluids in an organic Rankine cycle (ORC). The outcomes indicated that R11, R141b, R113, and R123 manifest slightly higher thermodynamic performances than the other examined fluids. R245fa and R245ca are the most environment-friendly working fluids for engine waste heat-recovery applications. The performance of the organic Rankine cycle when circulated 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 was studied [14]. They concluded that 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 the working fluid represents an important factor that affects the optimal condition state. Reference [15] conducted an experimental investigation to study R-245fa, R-123, and their mixture with different ratios in a laboratory (ORC) with a heat source at (110) °C and (120) °C. The results revealed that the (ORC) system has better thermodynamic performance at (120) °C heat source than that obtained from (110) °C one. R123 fluid achieved the highest (ORC) efficiency with values between (9.4) % and (13.5) % for the examined operating conditions.

The performance of a regenerative organic Rankine cycle circulates R-134a as a working fluid with turbine extractions at an evaporation temperature range of (60-100) °C was analyzed [16]. They concluded that the turbine output power increases with an increase in the evaporation and superheat temperatures, but decreases with the increase in extractions. They concluded that the maximum thermal efficiency increases with the increase of the evaporation temperature and the number of extractions and decreases with the increase of the superheat temperature. More recently, [17] analyzed the thermal performance of a basic organic Rankine cycle at evaporation and superheat degree temperatures of (90) °C and (5-15) °C respectively. The maximum thermal efficiency was attained when circulating R-134a, R-123, and R-245fa, it was within the range of (7.5-7.7) % at (15) °C superheat. 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.

In this work, the thermal performance of a simple organic Rankine cycle (SORC) was compared to that of the regenerative organic Rankine cycle (RORC). The term simple was used to refer to the basic organic Rankine cycle without a regenerative component. Four organic fluids, R-123, R-1233zd-E, R-245fa and R600a were studied as candidate working fluids at a boiling temperature of (130) °C superheated by (5-15) °C, and condensed at (45) °C subcooled by (5) °C. A hypothetical organic Rankine cycle of nominal heat recovery of (10) kW was implemented for the evaluation of the cycle performance. The simple cycle version was also studied at (90) °C evaporation temperature and compared to the thermal performance of that obtained at (130) °C. The low-temperature waste heat source was ranged between (160) °C and (200) °C, lower than this range may be used for the (90) °C cycle. The present research also studied the effect of the volumetric efficiency of the expander on the performance of the organic Rankine cycle.

II. Methodology

The characteristics of the working fluid are shown in Table 1.

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	CHCl2CF3	183.68	36.618	152.93	27.82	0.02	77	B1
R-1233zd-E	CF3CH=CHCl	166.45	36.237	130.496	18.26	0.00034	7	A1
R-245fa	CHF2CH2CF3	153.86	36.51	134.048	15.05	0	1030	B1
R-600a	CH(CH3)2CH3	135.0	36.50	58.12	-12	0	3	A3

* ANSI/ASHRAE Standard 34, [18]

Table 2 illustrates some physical properties of the selected working fluids.

Table 2. Thermodynamics properties of candidate working fluids

Refrigerant	Pressure (bar)		Liquid Density (kg/m3)		Liquid Enthalpy (kJ/kg)		Vapor Enthalpy (kJ/kg)		$\dot{m}$ (kg/s)
	45 °C	130 °C	45 °C	130 °C	45 °C	130 °C	45 °C	130 °C	10 kW
R-123	1.824	14.578	1411.43	1133.6	243.63	341.32	406.92	454.07	0.0470
R-1233zd-E	2.521	19.08	1213	927.0	255.99	372.878	436.542	484.764	0.0431
R-245fa	2.945	23.442	1282.05	940.0	259.397	390.39	437.33	487.699	0.0436
R-600a	6.102	33.665	527.93	279.37	307.86	602.31	616.53	691.89	0.0253

2.1 Regenerative Organic Rankine Cycle (RORC)

Figure 1 illustrates a schematic diagram for a regenerative organic Rankine cycle. It composes of the principal components such as the evaporator, condenser, expander actuator, and pump. A heat exchanger is installed before passing the fluid to the condenser. It works as a regenerator to extract heat from the working and improves the thermal efficiency of the cycle. A generator is connected to the expander to convert the work output to electrical power.

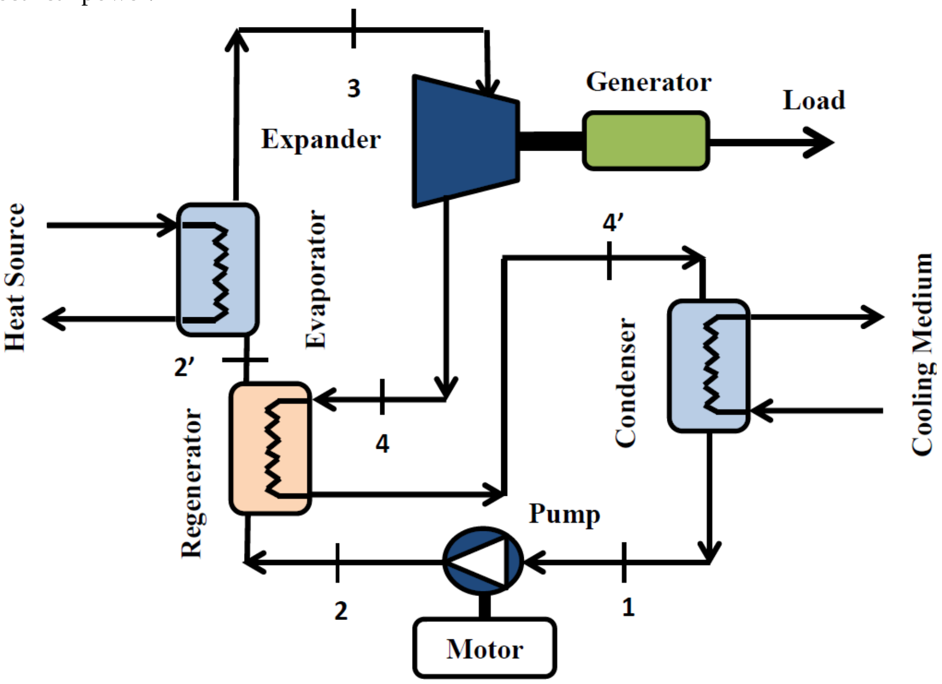

Figure 1: A schematic diagram for a regenerative organic Rankine cycle (RORC)

A typical *T-s* diagram of the regenerative organic Rankine cycle (RORC) is shown schematically in Fig. 2.

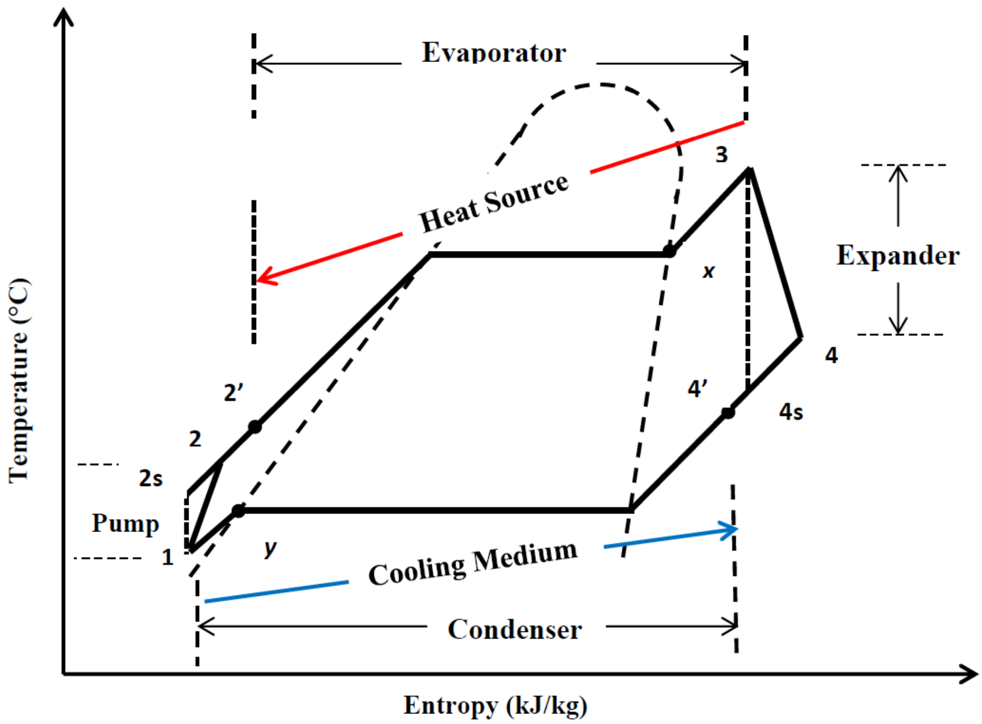

Figure 2: The T-s diagram for a regenerative organic Rankine cycle (RORC)

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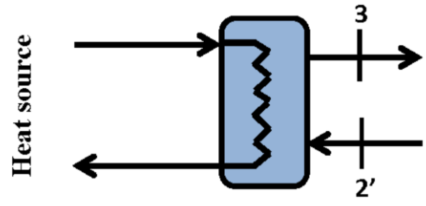
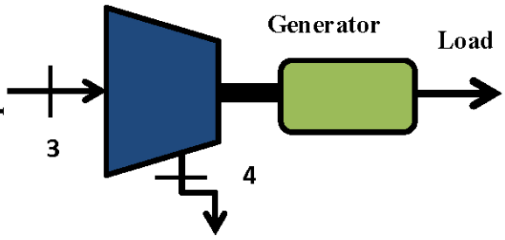
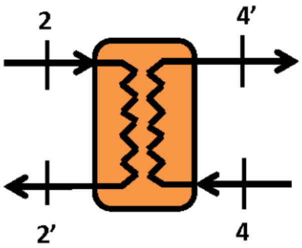
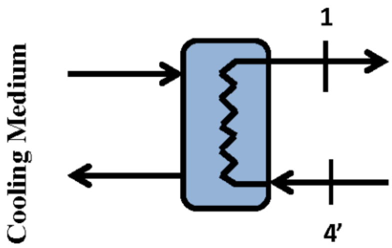
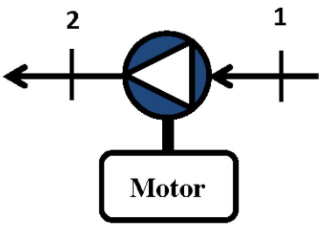
2.2 Thermal Analysis

The thermal analysis of each component of the regenerative organic Rankine cycle (RORC) is illustrated in Table 3. These equations were derived from the first law of thermodynamics for steady-state operating conditions.

Table 3. Thermal analysis of the regenerative organic Rankine cycle (RORC)

Component		Analysis
Evaporator		$\dot{Q}_{evap,R} = \dot{m}\,(h_3 - h_{2'})$ (1.a) $\dot{Q}_{evap,S} = \dot{m}\,(h_3 - h_2)$ (1.b)
Expander		$\eta_{is,exp} = \frac{h_3 - h_4}{h_3 - h_{4,is}}$ (2) $\dot{W}_{exp} = \eta_{m,exp}\,\eta_{vol,exp}\,\dot{m}\,(h_3 - h_4)$ (3)
Regenerator		$\varepsilon = \frac{T_4 - T_{4'}}{T_4 - T_2}$ (4) $h_{2'} = h_2 + h_4 - h_{4'}$ (5)
Condenser		$\dot{Q}_{cond,R} = \dot{m}\,(h_{4'} - h_1)$ (6.a) $\dot{Q}_{cond,S} = \dot{m}\,(h_4 - h_1)$ (6.b)
Pump		$\eta_{is,pump} = \frac{h_{2,is} - h_1}{h_2 - h_1}$ (7) $\dot{W}_{pump} = \dot{m}\,(h_1 - h_2)/\eta_{m,p}$ (8)

The implemented efficiencies of the expander and pump and the effectiveness of the regenerator are depicted in Table 4.

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Table 4: The numerical values of performance parameters utilized at the present work

Parameter	Magnitude
Expander isentropic efficiency, $\eta is,exp$	85 %
Expander volumetric efficiency, $\eta v,exp$	85 %
Expander mechanical efficiency, $\eta m,exp$	90 %
Pump isentropic efficiency, $\eta is,pump$	85 %
Pump mechanical efficiency, $\eta m,pump$	80 %
Regenerator effectiveness, ε	80 %

2.3 Regenerator

The regenerator is added to the basic or simple organic Rankine cycle (SORC) to provide energy from the fluid itself before heat rejection in the condenser. This technique is used to enhance the thermal performance of the cycle. The effectiveness of the heat exchanger is defined as:

$$\varepsilon = \frac{(\dot{m}\,cp)_h\,(T_{h,i} - T_{h,o})}{(\dot{m}\,cp)_{min}\,(T_{h,i} - T_{c,i})} \tag{9}$$

The fluid is flowing at the same mass flow rate on both sides of the regenerator and the specific heat capacity of the hot gas side is less than that of the liquid side, therefore,

$$(\dot{m}\,cp)_h < (\dot{m}\,cp)_c \tag{10.a}$$

Hence

$$(\dot{m}\,cp)_{min} = (\dot{m}\,cp)_h \tag{10.b}$$

Then, to calculate the exit temperature of the hot side fluid, use the following equation.

$$\varepsilon = \frac{T_{h,i} - T_{h,o}}{T_{h,i} - T_{c,i}} \tag{11.a}$$

The cold side exit temperature, the liquid temperature before entering the evaporator could be estimated from the heat transfer balance on both sides of the heat exchanger or by using the following relation:

$$\varepsilon = \frac{(\dot{m}\,cp)_c\,(T_{c,o} - T_{c,i})}{(\dot{m}\,cp)_{min}\,(T_{h,i} - T_{c,i})} \tag{11.b}$$

The net cycle thermal efficiency (η_{net}) is calculated for both (RORC) and (SORC) by using the appropriate evaporator heat load from Table 3 as:

$$\eta_{net} = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{\dot{Q}_{evap}} \tag{12}$$

The mass flow rate of the circulated fluid was calculated for the hypothetical simple cycle of (10) kW from the following expression:

$$\dot{m} = \frac{10}{(h_{g,evap} - h_2)} \tag{13}$$

Where ($hg_{,p}$) refers to the vapor enthalpy at the operating evaporator saturation temperature, Table 2. The same mass flow rate was used for the (RORC) system as well.

$$\dot{Q}_{evap,t} = \dot{Q}_{waste} + \dot{Q}_{sup} \tag{14}$$

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

$$\beta = \frac{\phi_n - \phi_{ref}}{\phi_n} \times 100 \tag{15}$$

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 W_{pump}, W_{exp}, Q_{eavp}, and η_{net}. This expression is valid for comparison of the performance of the same fluid at different operating conditions such as

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volumetric efficiency or evaporation temperature change. The comparison of the (SORC) and (RORC) performance parameters was deduced from:

$$\zeta = \frac{\phi_{Reg} - \phi_{Sim}}{\phi_{Reg}} \times 100 \tag{16}$$

The parameter (ϕ) has the same definitions as those in (15).

III. Results and Discussion

3.1 Extracted Waste Energy

Figure 3 depicts a comparison for extracted heat from a low-temperature grade waste energy source.

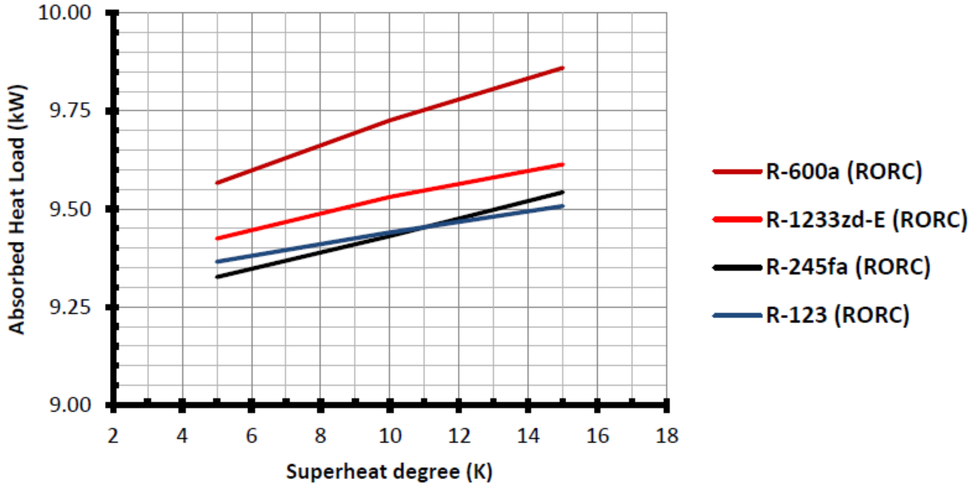

Figure 3.a: (RORC) unit

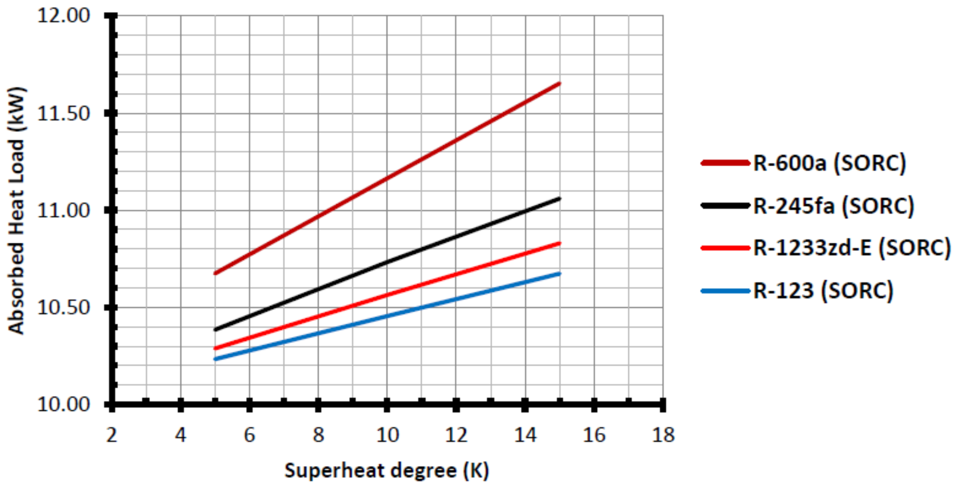

Figure 3.b: (SORC) unit

Figure 3: A comparison of the extracted heat load of test fluids in (SORC) and (RORC) at different superheat degrees and nominal evaporator heat load of 10 (kW)

The simple cycle (SORC) requires a higher heat load to produce power than that of the regenerative (RORC) one. The comparison of these cycles showed that R-600a, R-245fa, R-123, and R-1233zd-E simple cycles require higher values of heat load than those of the regenerative ones by (10-15) %, (10-14) %, (9-11) % and (8-11) % respectively. This is because of the installation of the regenerator in the cycle where it economizes

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the use of heat load. The general trend of the data shows that the R-600a cycle requires higher loads than those of R-123, R-245fa, and R-1233zd-E fluids for both of (SORC) and (RORC). This is mainly due to the discrepancy in the thermal properties and the critical temperature of the operating fluids. R-600a and R-123 possess the minimum and maximum critical temperatures respectively among other examined fluids. The (RORC) needs lower energy extraction to produce useful power than that of the (SORC), all of the examined fluids possessed close values of heat loads. R-245fa and R-123 fluids showed a similar heat extraction load and the discrepancies were within (± 0.4) %. Whereas, R-600a and R-1233zd-E extracted heat loads as (2.5-3) % and (1) % higher than that of R-245fa for the (RORC) case. In the simple cycle, R-600a, R245fa, and R-1233zd-E required more energy extractions than that of R-123 by (4-8) %, (2-3.5), and (1) % respectively. Figure 4 shows a comparison of the extracted heat load at (15) °C superheat degree for (RORC) and (SORC).

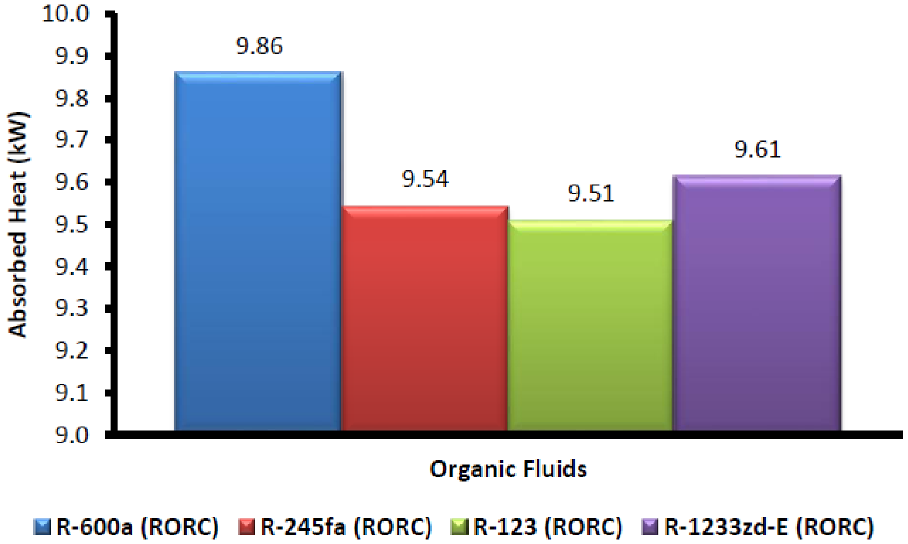

Figure 4.a: (RORC) unit at (15) °C superheat

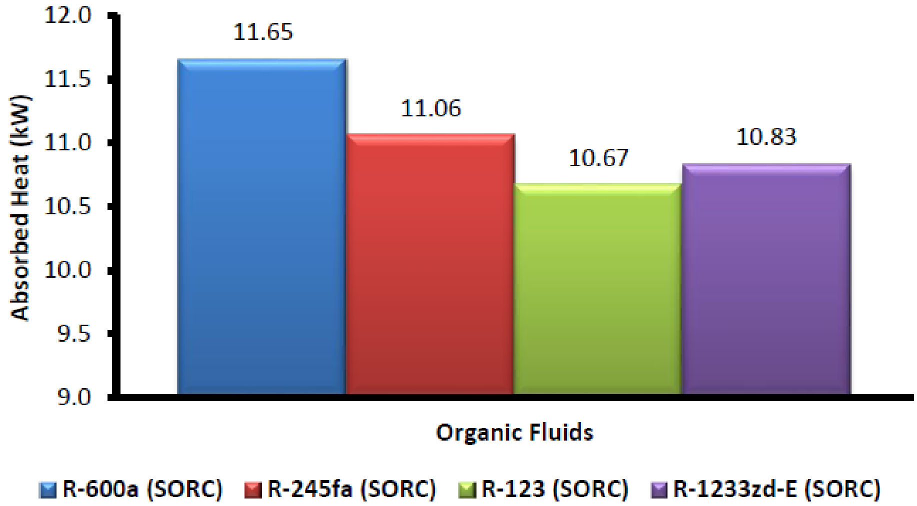

Figure 4.b: (SORC) unit at (15) °C superheat

Figure 4: A comparison of the extracted heat load of test fluids for (RORC) and (SORC) at (15) °C superheat degree

The maximum absorbed heat loads reached values of (11.7) kW and (10.7) kW for R-600a and R-123 respectively for the (SORC) case. The corresponding values of the extracted load in (RORC) were (9.9) kW and (9.5) kW for R-600a and R-123 respectively.

3.2 Net Power Output

A comparison for the cycle net power output at different superheat degrees.is illustrated in Fig. 5.

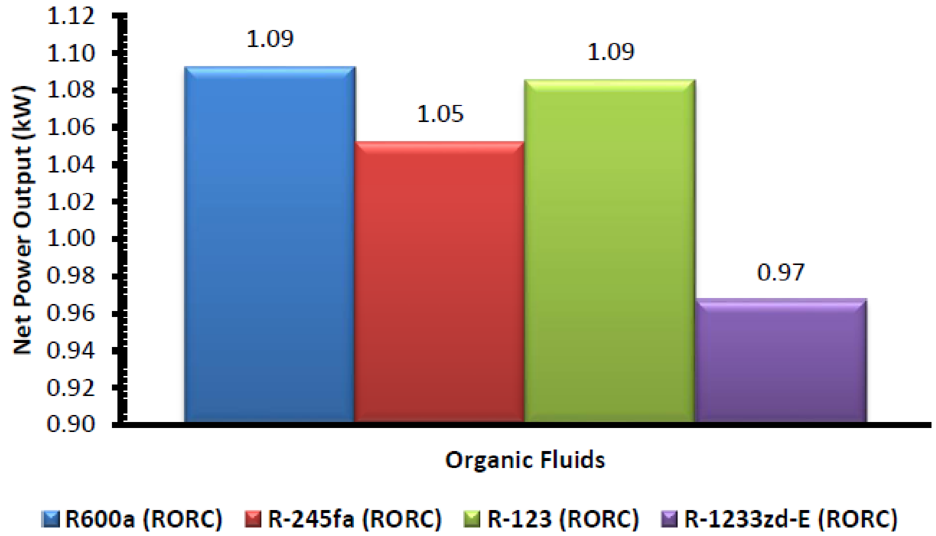

Figure 5.a: Cycle net power output at (5) °C superheat degree

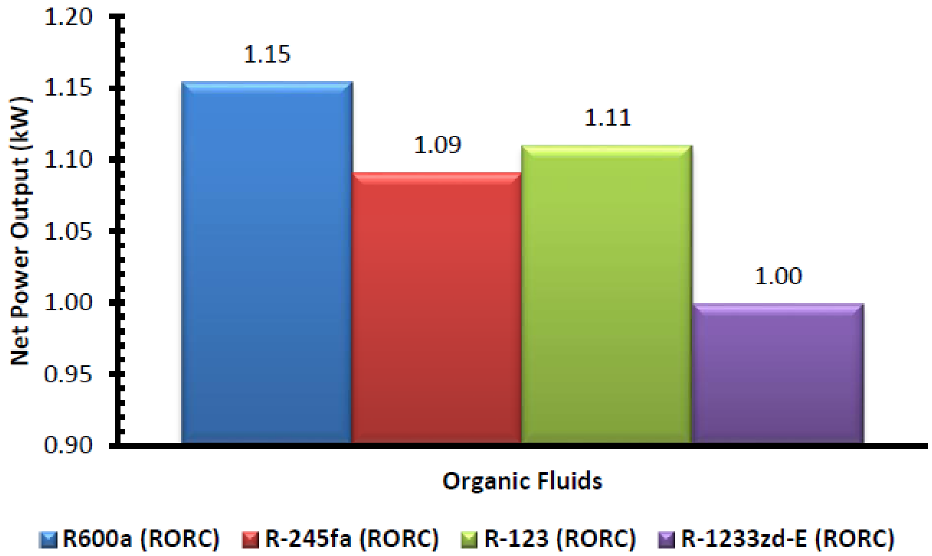

Figure 5.b: Cycle net power output at (10) °C superheat degree

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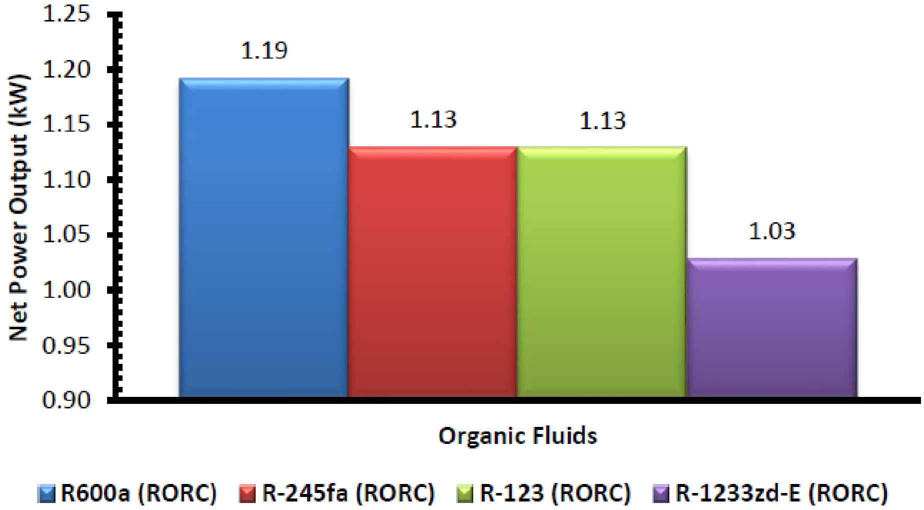

Figure 5.c: Cycle net power output at (15) °C superheat degree

Figure 5: A comparison of regenerative cycle power output of test fluids for (RORC) at a nominal heat load of (10) kW and temperature of (130) °C in the evaporator

R-600a and R-1233zd-E revealed the highest and lowest net power of the cycle regardless of the superheat degree respectively. However, the maximum values were experienced at (15) °C superheat degree, they were ranged between (1.0) kW and (1.2) kW achieved when circulating R-1233zd-E and R-600a respectively. R-600a, R-245fa, and R-123 showed higher cycle net power output than that of R-1233zd-E by (10-12) %, (8-9) %, and (9-11) for the examined range of fluid superheat degrees.

3.3 Pumping Fluid Flow Rate

Figure 6 shows a comparison of the circulated volumetric flow rate of the examined fluids. It was estimated at the intake pump condition for the simple organic Rankine cycle (SORC) of a nominal heat load of (10) kW.

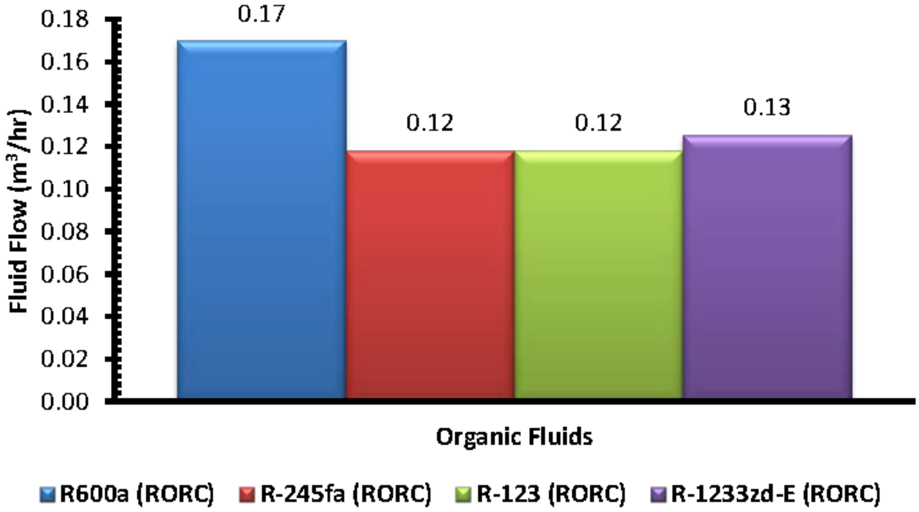

Figure 6: A comparison of the pumping flow rate of test fluids for (RORC) and (SORC) at a nominal heat load of (10) kW and temperature of (130) °C in the evaporator.

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The results showed that the volumetric flow rate of R-245fa, R-123, and R-1233zd-E exhibited close values and the R-600a circulated the highest rate as (0.17) m^3/hr. The consumed pump power was quite low values due to the low volumetric that circulated through the unit.

3.4 Net Cycle Thermal Efficiency

The thermal efficiency of the (RORC) and (SORC) is compared in Fig. 7 for examined working fluids at the superheat degree range of (5-15) °C and at nominal extracted heat load of (10) kW in the evaporator.

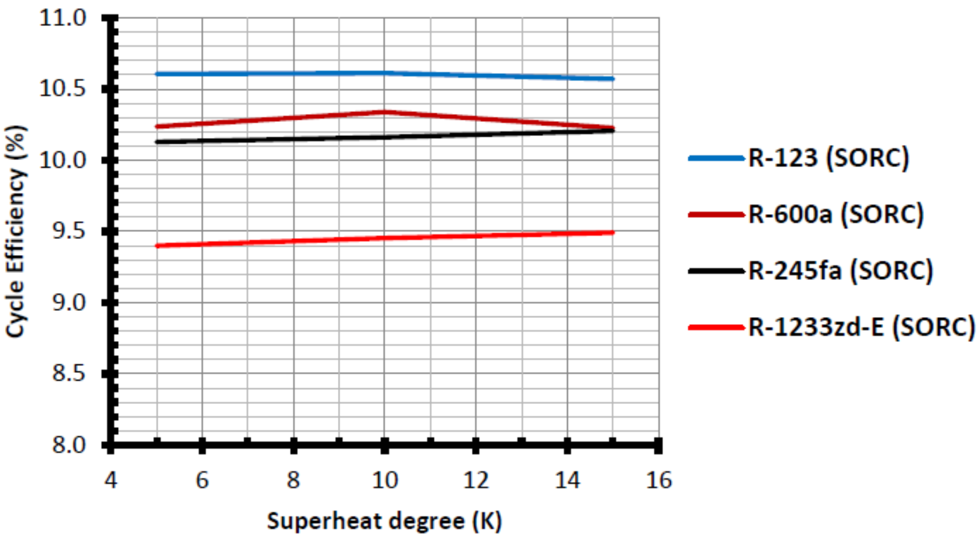

Figure 7.a: (SORC) unit

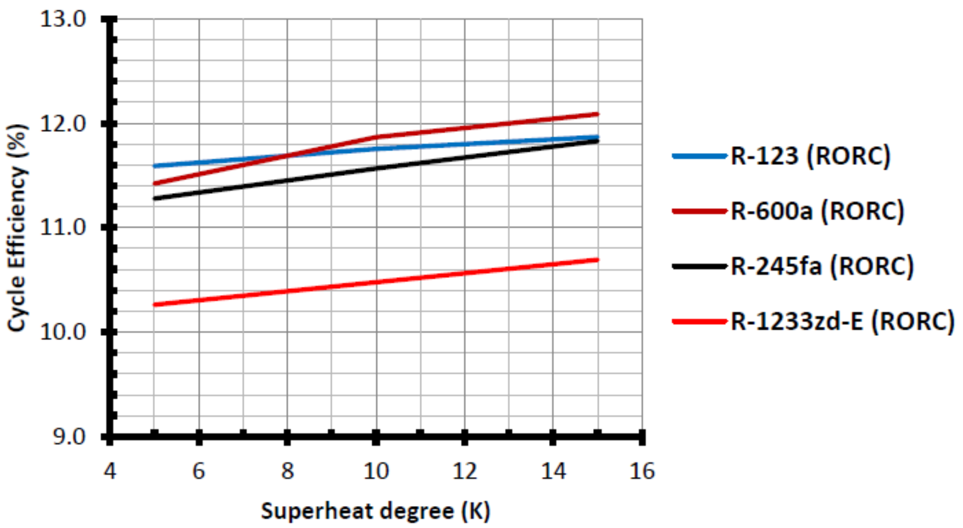

Figure 7.b: (RORC) unit

Figure 7: The net cycle thermal efficiency comparison of examined fluids at the evaporator temperature of (130) °C.

The net cycle thermal efficiency is essentially an independent parameter of the superheat degree for the (SORC), Fig. 7.a. It showed a minor dependency on the superheat degree for the (RORC) for the examined range of operating conditions in this work; Fig. 7.b. Figure 8 illustrates the comparison of the thermal efficiency at different superheat degrees. The results showed that R-600a and R-123 achieved similar thermal performance and they were higher than those of R-245fa and R-1233zd-E. The numerical values of the net thermal efficiency were ranged between (10.3) % and (12) % for the examined range of superheat degrees.

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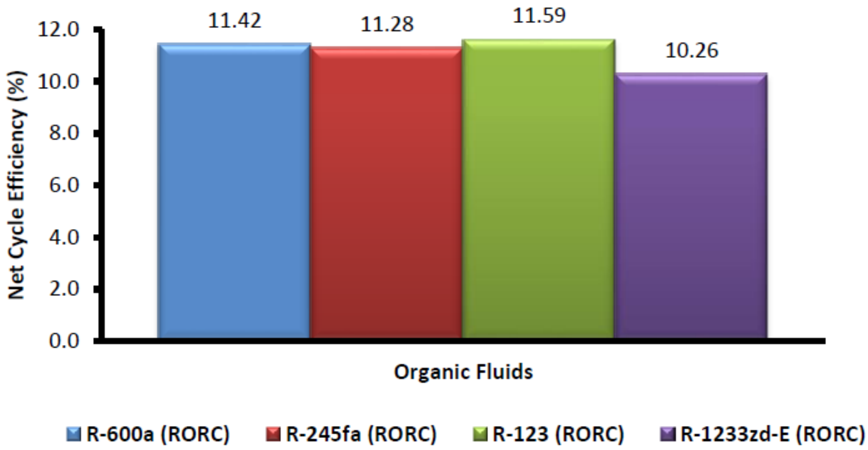

Figure 8.a: Cycle efficiency at (5) °C

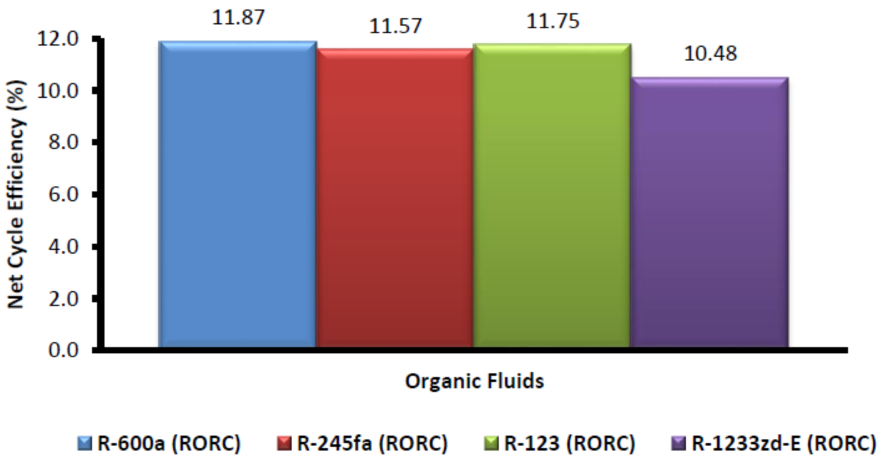

Figure 8.b: Cycle efficiency at (10) °C

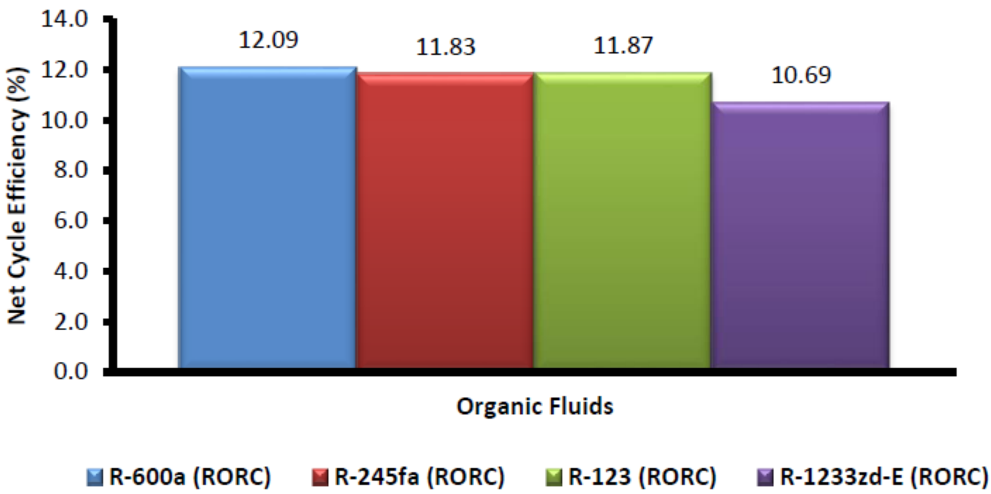

Figure 8.c: Cycle efficiency at (15) °C

Figure 8: A comparison of net cycle efficiency of test fluids for (RORC) at evaporator temperature of (130) °C.

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The effect of the presence of the regenerator in the cycle is clear, Fig. 7. The results indicated that the enhancement factor of the regenerative cycle as compared to the simple one was in the range of (8-15) %. R-600a, R-245fa, R-123, and R-1233zd-E regenerative cycle showed higher efficiency than that of the simple one by (10-15) %, (10-14), (8.5-11) % (8-11) % respectively.

R-600a, R-123, and R-245fa exhibited thermal efficiency enhancement of (10-12) %, (10-12), and (9-10) % respectively when they were compared to that of R-1233zd-E for the case of (RORC). The corresponding values for the (SORC) fell in the ranges of (7-9) %, (10-11) % and (7) % for the R-600a, R-123, and R-245fa respectively. Figure 9 illustrates a comparison of the thermal efficiency between test fluids at (15) °C superheat degree and evaporator temperature of (130) °C.

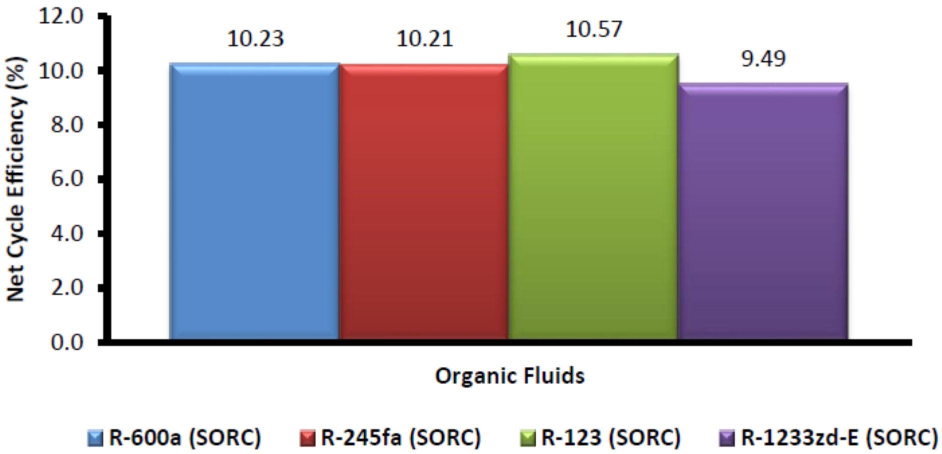

Figure 9: A comparison of net cycle efficiency of test fluids for (SORC) at nominal cycle heat load of (10) kW and (130) °C evaporation temperature and (15) °C superheat

3.5 Effect of Volumetric Efficiency

The volumetric efficiency of the expander was increased by (10) % to investigate its influence on the net cycle thermal efficiency. The results are shown in Fig. 10 for the regenerative organic Rankine cycle (RORC) at 130 °C evaporation temperature and nominal evaporation load of (10) kW in the evaporator.

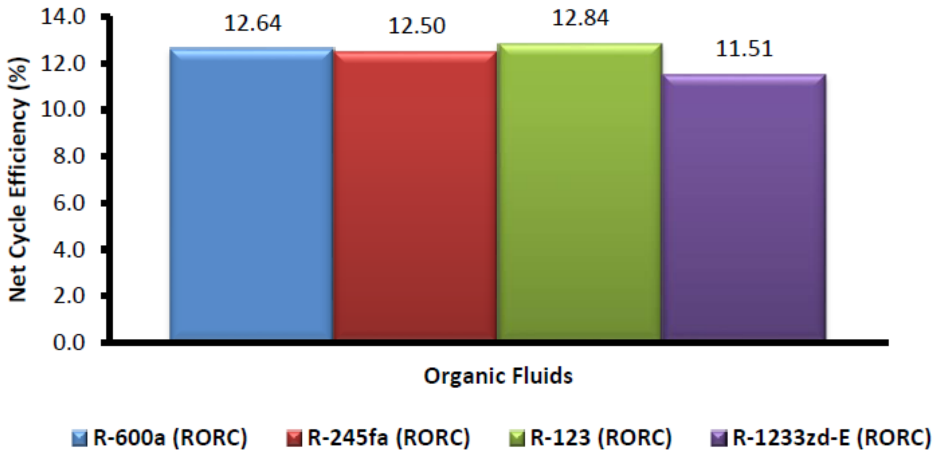

Figure 10.a: Cycle efficiency at (5) °C and η_{vol}=94 %

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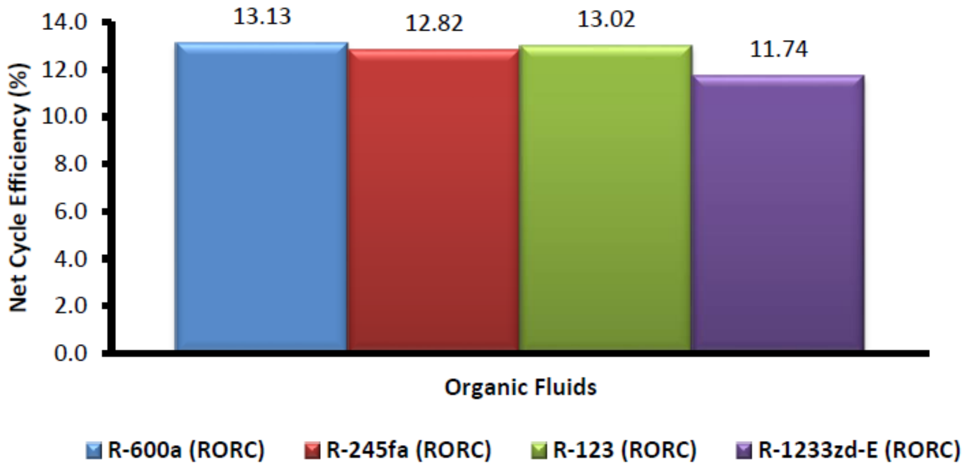

Figure 10.b: Cycle efficiency at (10) °C and η_{vol}=94 %

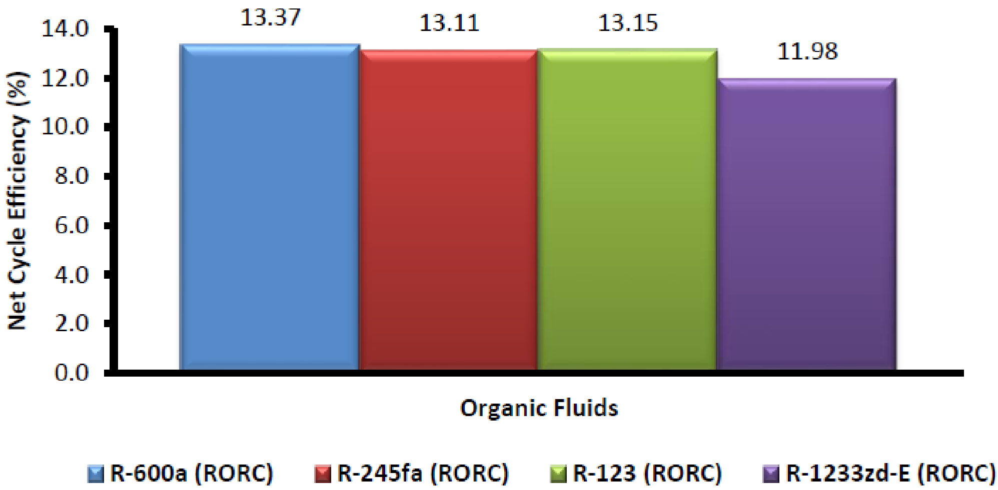

Figure 10.c: Cycle efficiency at (15) °C and η_{vol}=94 %

Figure 10: A comparison of net cycle efficiency of test fluids for (RORC) and η_{vol}=94 %

Increasing of the expander volumetric efficiency by (10) % has improved the thermal efficiency by the range of (10-11) % for the test fluids in both cycle modes of (SORC) and (RORC). In both cycles, R-600a and R-123, R-245fa showed an enhancement of (10) % whereas, R-1233zd-E produced an enhancement factor of (11) %.

3.6 Effect of Evaporator Temperature

The simple organic Rankine cycle thermal efficiency is compared in Fig. 11 for two different evaporation temperatures. The higher evaporator temperature of (130) °C achieved higher thermal efficiency than that of (90) °C by the ranges of (41) %, (34-38) %, (37) % and (36-40) % for R-600a, R-245fa, R-1233zd-E and R-123 working fluids respectively.

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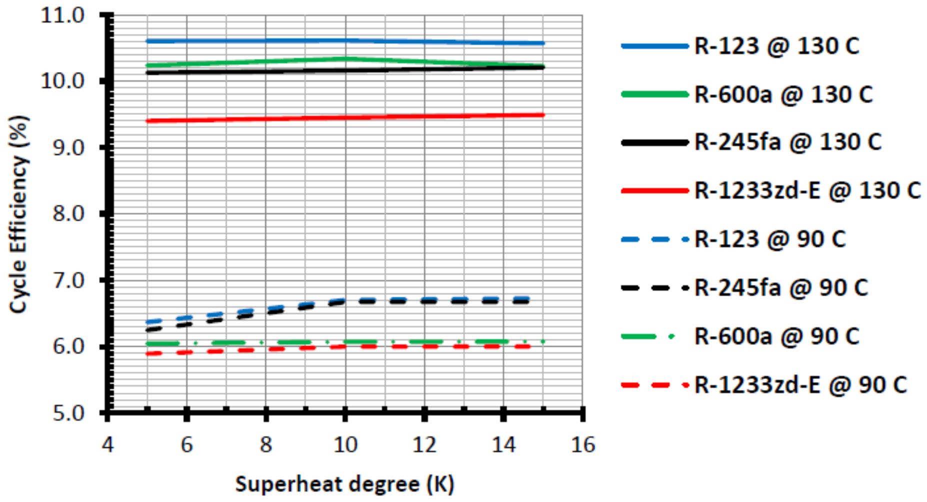

Figure 11: Cycle thermal efficiency comparison between (90) °C and (130) °C evaporation temperatures for (SORC) for nominal evaporator heat load of (10) kW

The thermal efficiency of the test fluids at (130) °C occupied the higher zone of the assessment map; its value fell in the range of (9.5-10) %. In contrast, these fluids exhibited low values of thermal efficiency at (90) °C evaporation temperature and occupied the lower part of the map; it is ranged between (6) % and (6.7) % for the examined operating conditions envelope.

IV. Conclusion

The R-600a cycle requires higher loads than those of R-123, R-245fa, and R-1233zd-E fluids for both of (SORC) and (RORC). R-245fa and R-123 fluids showed a similar heat extraction load and the discrepancies were within (± 0.4) %. The maximum absorbed heat loads reached values of (11.7) kW and (10.7) kW for R-600a and R-123 respectively for the (SORC) case. The corresponding values of the extracted load in (RORC) were (9.9) kW and (9.5) kW for R-600a and R-123 respectively. R-600a, R-245fa, R-123, and R-1233zd-E simple cycles (SORC) require higher values of heat load than those of the regenerative (RORC) ones by (10-15) %, (10-14) %, (9-11) % and (8-11) % respectively. The maximum values of the cycle net power output were experienced at (15) °C superheat degree, they were ranged between (1.0) kW and (1.2) kW R-1233zd-E and R-600a respectively. R-600a, R-245fa, and R-123 showed higher cycle net power output than that of R-1233zd-E by (10-12) %, (8-9) %, and (9-11) for the examined range of fluid superheat degrees.

The net cycle thermal efficiency is essentially an independent parameter of the superheat degree for the (SORC), but it manifested a minor dependency on the superheat degree for the (RORC) for the examined range of operating conditions in this work. R-600a and R-123 achieved similar thermal performance and they were higher than those of R-245fa and R-1233zd-E. The numerical values of the net thermal efficiency of the test fluids were ranged between (10.3) % and (12) % for the examined range of operating conditions. For the (RORC), the working fluids R-600a, R-123, and R-245fa exhibited thermal efficiency enhancement of (10-12) %, (10-12), and (9-10) % respectively when they were compared to that of R-1233zd-E. The corresponding values for the (SORC) fell in the ranges of (7-9) %, (10-11) % and (7) % for the R-600a, R-123, and R-245fa respectively. R-600a, R-245fa, R-123, and R-1233zd-E regenerative cycle (RORC) showed higher efficiency than that of the simple one (RORC) by (10-15) %, (10-14), (8.5-11) % (8-11) % respectively.

Increasing of the expander volumetric efficiency by (10) % has improved the net cycle thermal efficiency by the range of (10-11) % for the test fluids in both cycle modes of (SORC) and (RORC). In the (SORC), the evaporator temperature of (130) °C achieved higher thermal efficiency than that of (90) °C by the ranges of (41) %, (34-38) %, (37) % and (36-40) % for R-600a, R-245fa, R-1233zd-E and R-123 working fluids respectively.

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Nomenclature

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

Subscription

Parameter	Definition
b	Boiling point
c	Cold stream, critical value
cond	Condenser
evap	Evaporator
exp	Expander
g	Gas condition
h	Hot stream
i	Inlet side
is	Isentropic
min	Minimum value
n	Fluid, normal point
net	Net value
o	Outlet side
pump	Feed pump
ref	Reference fluid
sub	Subcooled liquid
sup	Superheated vapor
t	Total
vol	Volumetric
waste	Waste heat source

Greek Letter

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

Abbreviations

Parameter	Definition
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
RORC	Regenerative Organic Rankine Cycle
SORC	Simple Organic Rankine Cycle

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References

[1]. O. Badr, S.D. Probert, and P.W. O'Callaghan, Selecting a working fluid for a Rankine- cycle engine. *Applied Energy, 21*, 1985, 1–42. doi.org/10.1016/0306-2619(85)90072-8

[2]. T. Yamamoto, T. Furuhata, N. Arai, and K. Mori, Design and testing of the organic Rankine cycle. *Energy, 26*, 2001, 239–251. doi.org/10.1016/S0360-5442(00)00063-3

[3]. Y. Chen, P. Lundqvist, A. Johansson, and P. Platell, A Comparative study of the carbon dioxide transcritical power cycle compared with an organic Rankine cycle with R123 as working fluid in waste heat recovery. *Applied Thermal Engineering, 26*, 2006, 2142–2147. doi.org/10.1016/j.applthermaleng.2006.04.009

[4]. B.F. Tchanche, G. Lambrinos, A. Frangoudakis, and G. Papadakis, Low-grade heat conversion into power using organic Rankine cycles-A review of various applications. *Renewable & Sustainable Energy Reviews, 15(8)*, 2011, 3963-79. doi:10.1088/1755-1315/291/1/012037

[5]. P. Vignesh, S. Suresh, and C.J. Grashin, issues, comparisons, turbine selections, and applications – An overview in organic Rankine cycle. *Energy Conversion and Management, 166*, 2018, 474-88. doi.org/10.1016/j.enconman.2018.04.058

[6]. V.L. Le, A. Kheiri, M. Feidt, and S. Pelloux-Prayer, 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*, 2014, 622-38. doi.org/10.1016/j.energy.2014.10.051

[7]. M. Astolfi, L.N. Diega, M.C. Romano, U. Merlo, S. Filippini, and E. Macchi, Application of the novel "Emeritus" air cooled condenser in geothermal ORC. *Energy Procedia, 129*, 2017, 479-86.

[8]. H. Xi, M.J. Li, C. Xu, Y.L. He, Parametric optimization of regenerative organic Rankine cycle (ORC), *Energy, 58*, 2013, 473-482. doi.org/10.1016/j.energy.2013.06.039

[9]. H.C. Jung, S. Krumdieck, and T. Vranjes, Feasibility assessment of refinery waste heat-to-power conversion using an organic Rankine cycle, *Energy Conversion, and Management, 77*, 2014, 396-407. doi.org/10.1016/j.enconman.2013.09.057

[10]. M. Imran, B.S. Park, H.J. Kim, D.H. Lee, M. Usman, and M. Heo, Thermo-economic optimization of regenerative organic Rankine cycle for waste heat recovery applications, *Energy Conversion and Management, 87*, 2014, 107-118. doi.org/10.1016/j.enconman.2014.06.091

[11]. K.H. Kim, and S.W. Kim, Exergy analysis of regenerative organic Rankine cycle with turbine bleeding, *International Journal of Mechanical and Production Engineering, 4(4)*, 2016, 34-38.

[12]. A. Javanshir, N. Sarunac, and Z. Razzaghpanah, Thermodynamic analysis of a regenerative organic Rankine cycle using dry fluids, *Applied Thermal Engineering, 123*, 2017, 852-864. doi.org/10.1016/j.applthermaleng.2017.05.158

[13]. E.H. Wang, H.G. Zhang, B.Y. Fan, M.G. Ouyang, Y. Zhao, and Q.H. Mu, Study of working fluid selection of organic Rankine cycle (ORC) for engine waste heat recovery, *Energy, 36(5)*, 2011,3406-3418

[14]. P. Yuan, and C. Zhang, Comparison on thermodynamic performances between basic and regenerative sub-critical organic Rankine cycles coupled with low-grade heat source, *IOP Conf. Series: Materials Science and Engineering, 473*, 2019, 012031. doi:10.1088/1757-899X/473/1/012031

[15]. M.D. Surindra, W. Caesarendra, T. Prasetyo, T.M. Mahlia, and Taufik, Comparison of the utilization of 110 °C and 120 °C heat sources in a geothermal energy system using organic Rankine cycle (ORC) with R245fa, R123, and mixed-ratio fluids as working fluids, *Processes, 7(113)*, 2019. doi.org/10.3390/pr7020113

[16]. A.F.V. Da Cunha, and S.L.S. Souza, Analysis of R134a organic regenerative cycle. *Journal of Power and Energy Engineering, 8*, 2020, 32-45. doi.org/10.4236/jpee.2020.85003

[17]. A.H. Tarrad, A steady-state evaluation of simple organic Rankine cycle (SORC) with low-temperature grade waste heat source, *Journal of Power and Energy Engineering*, 8, 15-31, 2020. doi: 10.4236/jpee.2020.87002

[18]. ANSI/ASHRAE Standard 34, Designation and Safety Classification of Refrigerants, 2016.