

Abam, F. I.; Ekwe, E. B.; Effiom, S. O.; Ndukwu, M. C.

Article

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A comparative performance analysis and thermo-sustainability indicators of modified low-heat organic Rankine cycles (ORCs): An exergy-based procedure



F.I. Abam^{a,*}, E.B. Ekwe^b, S.O. Effiom^c, M.C. Ndukwu^d

^a Energy, Exergy and Environment Research Group (EEERG), Department of Mechanical Engineering, Michael Okpara University of Agriculture, Umudike, P.M.B 7267 Umuhia, Nigeria

^b Department of Mechanical Engineering, Gregory University Uturu, Abia State, Nigeria

^c Department of Mechanical Engineering, Cross River University of Technology, P.M.B 1122 Calabar, Nigeria

^d Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, P.M.B 7267 Umuhia, Nigeria

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ABSTRACT

The paper presents a comparative analysis of thermo-sustainability indicators (TSIs) and performance of organic Rankine cycles (ORCs) with different working fluids. The objective of the study is to determine the sustainability of the ORCs using R245fa, R1234yf, and R1234ze refrigerants. The ORC configurations include the ORC-basic (ORCB), ORC-internal heat exchanger (ORCIHE), ORC-turbine bleeding (ORCTB), and ORC-turbine bleeding/regeneration (ORCTBR). The TSI evaluated comprise overall exergy efficiency (OEF), exergy waste ratio (EWR), and environmental effect factor (EEF) in addition to exergetic sustainability index (ESI). The results indicate that the OEF obtained using R245fa fluctuated between $30.26 \leq \text{OEF} \leq 38.82$ with 8.56% efficiency difference between ORCB and ORCTBR at evaporator pressure (EVP) of 2 and 3 MPa. The ESI values were maximum with R245fa while EEF values of 1.5 and 1.58 were obtained at same EVP range. Additionally, the ORCTBR and ORCTB had the least environmental impact and were ecologically stable with R245fa than R1234yf, and R1234ze. In conclusion, the performance of the ORCs is dependent on the following: working fluid, system configuration and operating conditions. Thus optimum conditions for each working fluid for a particular system configuration is central to achieving environmental stability.

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1. Introduction

The sustainability of energy resources in addition to the efficiency of energy conversion systems has been a subject of concern to governments, organisations, private sectors and the academia. Furthermore, in the last two decades, the situation is worse owing to the rate at which conventional energy resources are fast declining. Sustainability as a concept denotes the supply of energy resources in an available and equitable cost with little or perhaps no effect on the environment. Also, the exergy technique has been applied to different engineering fields thereby bringing understanding to the actual losses involved in energy conversion processes, sustainability level of energy systems and material interaction with the environment (Thawonngamyingsakul and Kiatiriroat, 2012; Gingerich and Mauter, 2015; Midilli et al., 2012; Aydin, 2013; Onder and Aydin, 2016; Abam et al., 2017). Different scholars have proposed cleaner energy production methods for low carbon emissions through low-temperature heat energy cycles

(Vikas et al., 2017; Shokati et al., 2015; Chen et al., 2010). These cycles exist in the following: ORC (Organic Rankine cycle), SRC (Supercritical Rankine cycle), Kalina cycle, trilateral flash cycle and Goswami cycle (Li et al. 2017; Wenqiang et al. 2017; Pei et al., 2011; Wang et al., 2010; Kang, 2012).

Additionally, among these cycles, the ORC has attracted substantial research contribution in open literature. The ORC is characterised by the type of heat source application such as geothermal (Marin et al., 2014), biomass (Schuster et al., 2009), industrial waste (Srinivasan et al., 2010) and solar energy (Delgado-Torres and Garcia-Rodriguez, 2010). Recent studies in ORCs include the works of Li et al. (2014) who considered the prospect of using zeotropic mixtures as working fluid in ORC. The study obtained improvement in the ORC efficiency with zeotropic mixtures than the conventional working fluids. Gao et al. (2015) applied different scroll expander in ORC and achieved approximately 3.2% enhancement in efficiency. Xia et al. (2015) performed a similar experiment using a single scroll at different vapour dryness inlet. The results indicate an improvement in the power output for an increase in vapour dryness. Other researchers like Hettiarachchi et al. (2007) have measured the performance of ORC for a geothermal

* Corresponding author.

E-mail address: abamfidelis@mouau.edu.ng (F.I. Abam).

Nomenclature

c_p	heat capacity (kJ/kg K)
\dot{E}_x	exergy flow rate (kW)
\dot{e}_x	specific exergy (kJ/kg)
e_{ch}^0	standard chemical exergy [kJ/kmol]/ ϵ^{-0}
ED	exergy destruction (kW)
EEF	environmental effect factor
ESI	exergetic sustainability index
EVP	evaporator pressure (MPa)
EWR	exergy waste ratio
\dot{I}	exergy destruction rate (kW)
\dot{m}_e	exergy flow of working fluid (kg/s)
\dot{m}	mass flow rate of heat source (kg/s)
OED	overall exergy destruction (kW)
OEF	overall exergy efficiency (%)
ORCB	organic Rankine cycle basic
ORCIHE	organic Rankine cycle with internal heat exchanger
ORCTB	organic Rankine cycle with turbine bleeding
ORCTBR	organic Rankine cycle with turbine bleeding and regeneration
P_0	pressure at dead state (Mpa)
\dot{Q}	heat transfer rate (kW)
T_0	temperature at dead state (K)
TSI	Thermo-sustainability indicator
\dot{W}	work transfer rate (kW)

Greek symbols

ΔH_0	Standard enthalpy of devaluation [kJ/kmol]/ \bar{h}_v^0
η	isentropic efficiency (%)
ψ	exergy efficiency (%)

Subscript

e	exit
i	inlet
out	outlet
gen	generation

plant using different refrigerants, PF 5050, R123, and n-pentane. The influence of condensation and evaporation temperatures were evaluated for different inlet velocities of the cooling water. Furthermore, Saleh et al. (2007) examined and established the performance of thirty-one refrigerants for both supercritical and subcritical ORCs for a geothermal plant. Wei et al. (2007) considered the influence of factors like exhaust flow rate, inlet temperature of the exhaust, air flow rate and the ambient temperature on the cycle power output, efficiency and the rate of exergy destruction of an ORC. The results show that the cycle efficiency and power output could be improved by choosing an appropriate nominal state. However, most theoretical and experimental studies in literature had considered the performance of ORC configurations for the geothermal power plant, refrigerants performance, best operating conditions and exergy analysis (Marin et al., 2014; Roy and Misra, 2016; Sun et al. 2017; Safarian and Aramoun, 2015). Additionally, comparative study on thermoenvironmental or thermo-sustainability analysis of ORC configurations with the operating refrigerants is not emphasised in the open literature. This study provides a comparative performance analysis and thermo-sustainability indicators (TSI) of ORC configurations using different working fluids. The TSI will include the exergetic sustainability index, exergy waste ratio and environmental effect factor. Nonetheless, the latter knowledge may provide a basis for system modification and best optimum operating conditions.

2. The ORCs process description and exergy balancing

The flow diagrams for the considered ORC configurations are shown in Fig. 1. The following processes exist (Fig. 1a), ORC-basic (ORCB) the pumping process (1–2), constant pressure heat addition (2–3), expansion adiabatic process (3–4) and constant pressure heat rejection (4–1). Fig. 1(b) describes the modified cycle with an internal heat exchanger. Fig. 1(c), the ORC is incorporated with a feed water heater ORC-turbine bleeding (ORCTB). The extracted vapour from the turbine mixes with the feed water heater leaving as a saturated liquid in process 3–4 while in Fig. 1(d), ORC-turbine bleeding/regeneration (ORCTBR). Here the ORC is integrated with a turbine bleeding and a regenerative system.

2.1. Thermodynamic assumptions

The study considers the following assumptions: (1) Steady state flow condition. (2) The pressure drop and heat losses in the system components are neglected. (3) The study considered three different refrigerants (i) R 245fa, (ii) R1234yf and (iii) R 1234ze. (4) The inlet temperature and pressure to the condenser and evaporator were set at 25 °C (298 K) and 2.5, 3.15 and 3.5 MPa for R 245fa, R1234yf and R 1234ze respectively. (5) The turbine and pump isentropic efficiencies were set at 85 and 90%, respectively. (6) The heat input (\dot{Q}_{in}) to the ORC is a hot stream of gas which exist at the rate of 252 kW at 300°C (573 K) from a micro gas turbine plant. (7) The exergy of hot gas leaving the evaporator and the exergy of water entering and leaving the condenser are considered negligible. (8) The condition of fluid entering the turbine is superheated.

Furthermore, to evaluate the TSIs a comprehensive exergy balance for the ORCs is performed. For a steady-state energy flow process, the exergy balance is obtained as (Tchanche et al., 2010).

$$\dot{I} = \sum_{in} \dot{m}_{ex} - \sum_{out} \dot{m}_{ex} - \dot{E}x_{in}^Q - \dot{E}x_{out}^W = T_0 \dot{S}_{gen} \tag{1}$$

where \dot{I} is exergy destruction rate, \dot{m}_{ex} is the exergy flow of the working fluid, $\dot{E}x_{in}^Q$ and $\dot{E}x_{out}^W$ are the exergy of heat input and work output while \dot{S}_{gen} , is the rate of entropy generation. The thermomechanical exergy flow is expressed in Eq. (2)

$$e_x = h - h_0 - T_0 (s - s_0) \tag{2}$$

where h_0 and s_0 are specific enthalpy and entropy at dead state temperature and pressure (P_0, T_0) respectively.

The common equation for the rate of entropy generation in a steady state thermodynamic process is presented in Eq. (3) (Cengel and Boles, 2007).

$$\sum \frac{Q_k}{T_k} + \sum \dot{m}_e s_e + \dot{S}_{gen} = \frac{ds_{cv}}{dt} \tag{3}$$

$\frac{ds_{cv}}{dt}$ in Eq. (3) for steady state situation is zero. Thus Eq. (3) is rearranging as follows:

$$\dot{S}_{gen} = \sum \dot{m}_e s_e + \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k} \tag{4}$$

where:

\dot{m} , T_k and \dot{Q}_k are mass flow rate, temperature of the heat source and heat transfer rate respectively. Eq. (5) expresses the chemical exergy of the refrigerants (Safarian and Aramoun, 2015).

$$e_{ch} = \frac{e_{ch}^0}{M} \left[\frac{T_0}{298.15} \right] + \frac{\Delta H_0}{M} \left[\frac{T_0 - 298.15}{298.15} \right] \tag{5}$$

where e_{ch}^0 and ΔH_0 are exergy of organic fluid and standard enthalpy of devaluation.

The exergy expressions in the ORC components are derived using Eqs. (1) and (2). However, only exergy balance for ORC in

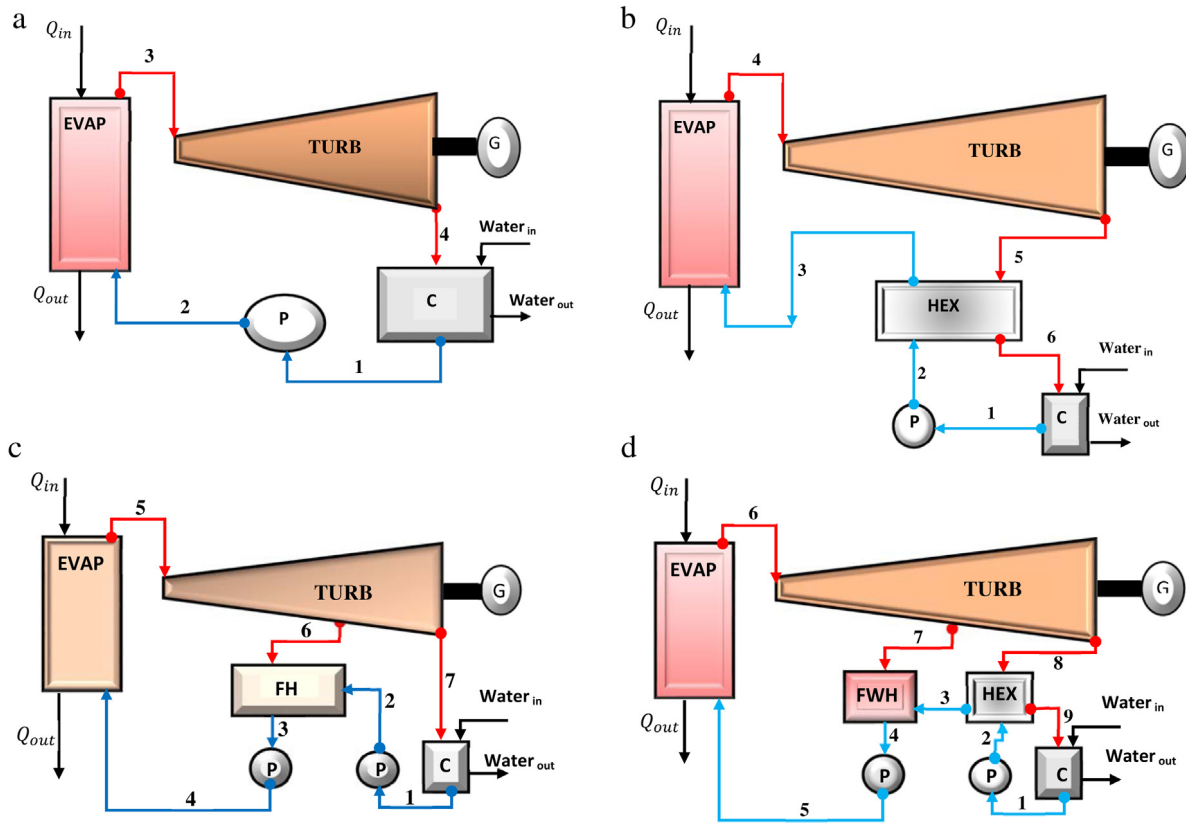


Fig. 1. The different ORCs (a) ORC-basic (b) ORC-internal heat exchanger (c) ORC-turbine bleeding. (d) ORC-turbine bleeding/regeneration.

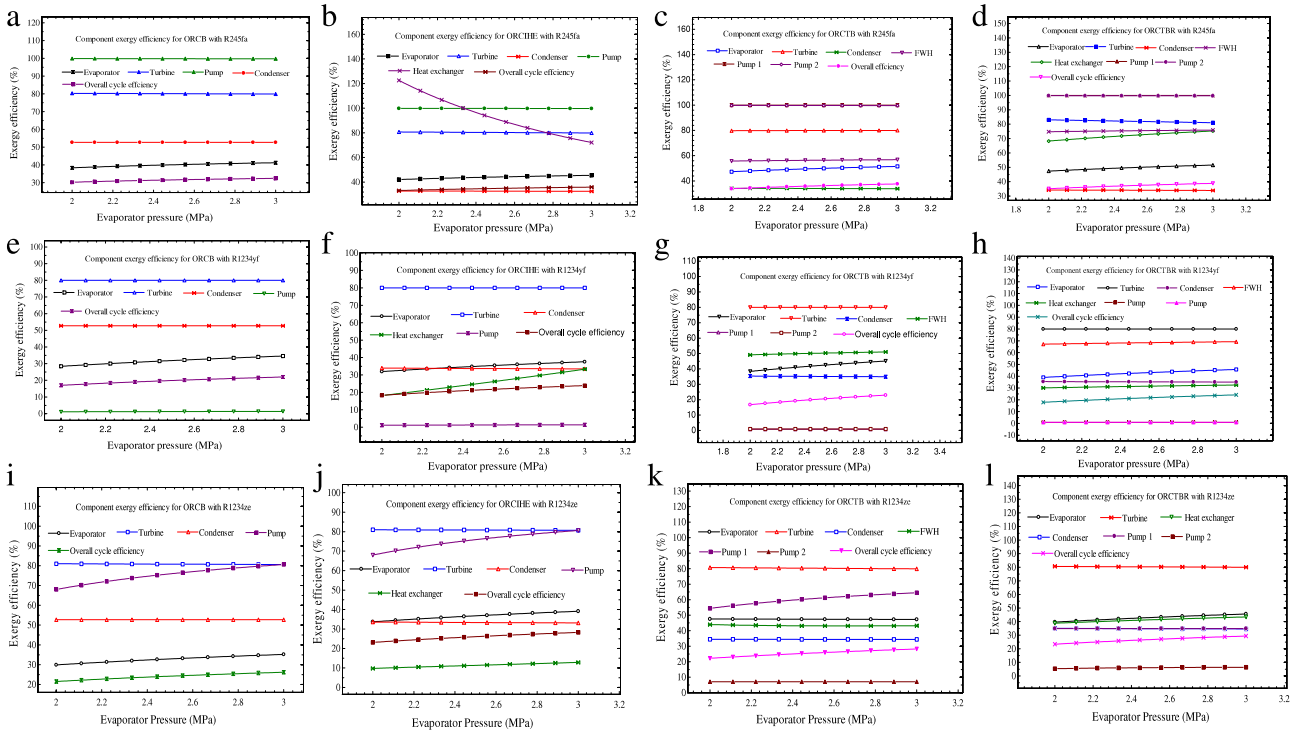


Fig. 2. Component exergy efficiency and overall cycle efficiency for the ORCs with (a–d) R245fa, (e–h) R1234yf and (i–l) R1234ze.

Fig. 1(a) is presented below whereas the same methods were applied in balancing the exergy flows for other ORCs Fig. 1(c) to (d) (not shown). The general exergy balance for the components

is presented in Eqs. (6) to (9). A further breakdown in the actual exergy flows, exergy destruction in the components and components exergy efficiencies are presented in Eqs. (10) to (13), (14) to

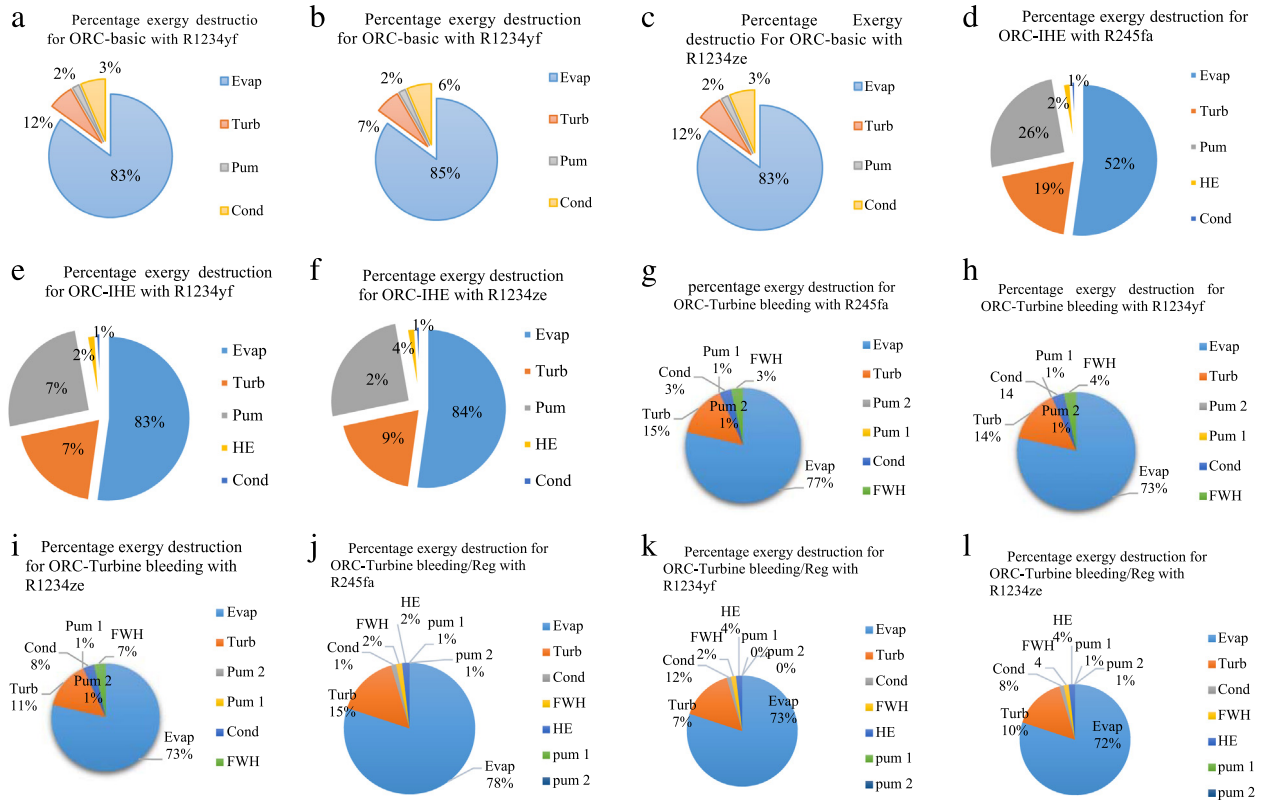


Fig. 3. Percentage of components exergy destruction for the ORCs (a–l) with R245fa, R1234yf and R1234ze refrigerants.

(17) and (18) to (Box 1) respectively.

$$\text{Evaporator (2-3), } \left(1 - \frac{T_0}{T_{in}}\right) Q_{in} + \dot{E}x_2 = \dot{E}x_3 + \dot{E}D_{\text{Evap}}. \quad (6)$$

$$\text{Turbine (3-4), } \dot{E}x_3 = \dot{E}x_4 + \dot{w}_{\text{turb}} + \dot{E}D_{\text{Turb}} \quad (7)$$

$$\text{Pump (1-2), } \dot{w}_p + \dot{E}x_1 = \dot{E}x_2 + \dot{E}D_{\text{Pump}} \quad (8)$$

$$\text{Condense (4-1), } \dot{E}x_4 = \dot{E}x_5 + \dot{E}D_{\text{Cond}} \quad (9)$$

where: $\dot{E}D_{\text{Evap}}$, $\dot{E}D_{\text{Turb}}$, $\dot{E}D_{\text{Pump}}$, and $\dot{E}D_{\text{Cond}}$ denotes exergy destruction in the evaporator, turbine, pump and condenser respectively.

$$\dot{E}x_1 = \dot{m}_1 \left\| c_p [T_1 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_1}{T_0} \right] - R \ln \left[\frac{P_1}{P_0} \right] \right\} \right\| \quad (10)$$

$$\dot{E}x_2 = \dot{m}_2 \left\| c_p [T_2 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_2}{T_0} \right] - R \ln \left[\frac{P_2}{P_0} \right] \right\} \right\| \quad (11)$$

$$\dot{E}x_3 = \dot{m}_3 \left\| c_p [T_3 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_3}{T_0} \right] - R \ln \left[\frac{P_3}{P_0} \right] \right\} \right\| \quad (12)$$

$$\dot{E}x_4 = \dot{m}_4 \left\| c_p [T_4 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_4}{T_0} \right] - R \ln \left[\frac{P_4}{P_0} \right] \right\} \right\| \quad (13)$$

$$\dot{E}D_{\text{pump}} = \left[\frac{c_p [T_2 - T_1]}{\eta_{\text{pump}}} \right] \quad (14)$$

$$- \dot{m}_2 \left\| c_p [T_2 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_2}{T_0} \right] - R \ln \left[\frac{P_2}{P_0} \right] \right\} \right\| \quad (14)$$

$$\dot{E}D_{\text{Evap}} = \dot{m}_2 \left\| c_p [T_2 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_2}{T_0} \right] - R \ln \left[\frac{P_2}{P_0} \right] \right\} \right\| \quad (15)$$

$$+ \left[1 - \frac{T_0}{T_Q} \right] Q_{in} - \dot{m}_3 \left\| c_p [T_3 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_3}{T_0} \right] - R \ln \left[\frac{P_3}{P_0} \right] \right\} \right\| \quad (15)$$

$$- T_0 \left\{ c_p \ln \left[\frac{T_3}{T_0} \right] - R \ln \left[\frac{P_3}{P_0} \right] \right\} \quad (15)$$

$$\begin{aligned} \dot{E}D_{\text{Turb}} = & \dot{m}_3 \left\| c_p [T_3 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_3}{T_0} \right] - R \ln \left[\frac{P_3}{P_0} \right] \right\} \right\| \\ & - \dot{m}_3 c_p [T_3 - T_4] - \dot{m}_4 \left\| c_p [T_4 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_4}{T_0} \right] - R \ln \left[\frac{P_4}{P_0} \right] \right\} \right\| \end{aligned} \quad (16)$$

$$\begin{aligned} \dot{E}D_{\text{cond}} = & \dot{m}_4 \left\| c_p [T_4 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_4}{T_0} \right] - R \ln \left[\frac{P_4}{P_0} \right] \right\} \right\| \\ & - \dot{m}_1 \left\| c_p [T_1 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_1}{T_0} \right] - R \ln \left[\frac{P_1}{P_0} \right] \right\} \right\| \end{aligned} \quad (17)$$

$$\psi_{\text{pump}} = \frac{\dot{m}_2 \left\| c_p [T_2 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_2}{T_0} \right] - R \ln \left[\frac{P_2}{P_0} \right] \right\} \right\|}{\left[\frac{c_p [T_2 - T_1]}{\eta_{\text{pump}}} \right]} \quad (18)$$

and also see the equations given in Box I.

3. Thermo-sustainability indicators

The thermo-sustainability or exergetic sustainability indicators are considered for the different ORCs in (Fig. 1) and derived from the respective exergy balanced equations for each cycle.

3.1. Exergy waste ratio (EWR)

The waste exergy is the summation of the lost exergy and the destroyed exergy calculated as in Eq. (22) while the EWR can be calculated as the ratio of the overall waste exergy to the overall input exergy as expressed in Eq. (23) (Aydin, 2013).

$$\sum Ex_{\text{we, out}} = \sum \dot{E}x_{\text{dest, out}} + \sum \dot{E}x_{\text{loss, out}} \quad (22)$$

$$\text{EWR} = \frac{\text{Overall exergy waste}}{\text{overall exergy input}} \quad (23)$$

$$\psi_{evap} = \frac{\dot{m}_3 \left\| c_p [T_3 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_3}{T_0} \right] - R \ln \left[\frac{P_3}{P_0} \right] \right\} \right\| - \dot{m}_2 \left\| c_p [T_2 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_2}{T_0} \right] - R \ln \left[\frac{P_2}{P_0} \right] \right\} \right\|}{\left[1 - \frac{T_0}{T_Q} \right] Q_{in}} \quad (19)$$

$$\psi_{turb} = \frac{m_{ref} c_p [T_3 - T_4]}{\dot{m}_3 \left\| c_p [T_3 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_3}{T_0} \right] - R \ln \left[\frac{P_3}{P_0} \right] \right\} \right\| - \dot{m}_4 \left\| c_p [T_4 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_4}{T_0} \right] - R \ln \left[\frac{P_4}{P_0} \right] \right\} \right\|} \quad (20)$$

$$\psi_{cond} = \frac{\dot{m}_4 \left\| c_p [T_4 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_4}{T_0} \right] - R \ln \left[\frac{P_4}{P_0} \right] \right\} \right\| - \dot{m}_1 \left\| c_p [T_1 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_1}{T_0} \right] - R \ln \left[\frac{P_1}{P_0} \right] \right\} \right\|}{\dot{m}_1 \left\| c_p [T_1 - T_0] - T_0 \left\{ c_p \ln \left[\frac{T_1}{T_0} \right] - R \ln \left[\frac{P_1}{P_0} \right] \right\} \right\|} \quad (21)$$

Box 1.

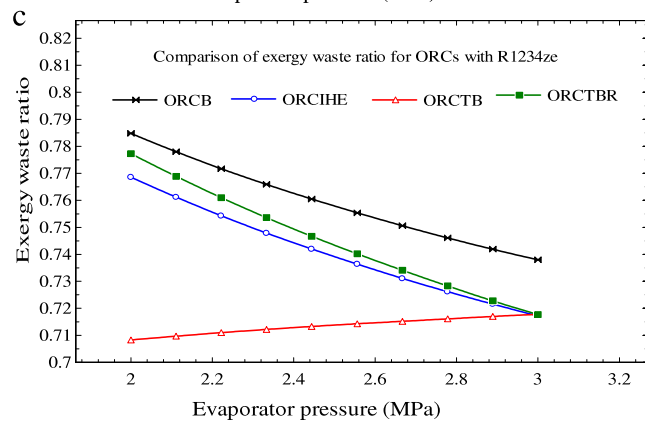
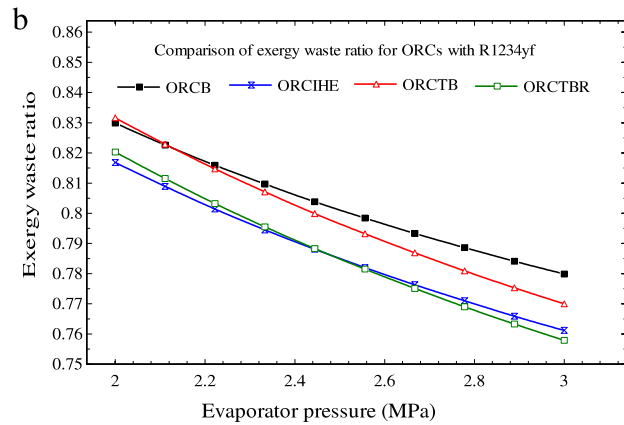
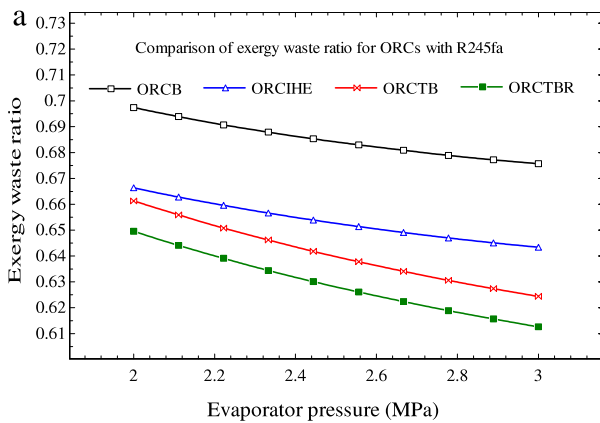


Fig. 4. Comparison of Exergy waste ratio for the ORCs with (a) R245fa (b) R1234yf and R1234ze at varying EVP.

3.2. Environmental effect factor (EEF)

The EEF is an important environmental sustainability indicator since it indicates whether there exists a damage to the environment due to the waste exergy destruction (Aydin, 2013). The EEF is defined as follows,

$$EEF = \frac{\text{Waste exergy ratio}}{\text{Exergy efficiency}} \quad (24)$$

3.3. Exergy efficiency

The overall exergetic efficiency ($\psi_{overall}$) is defined as the ratio of the total exergy output to the total exergy input. Eq. (18) to (Box 1) expresses component exergy efficiency while the overall exergy efficiency OEF is presented in Eq. (25) (Tchanche et al., 2010).

$$\psi_{overall} = \left(\frac{\dot{E}x_{out}}{\dot{E}x_{in}} \right) \quad (25)$$

3.4. Exergetic sustainability index (ESI)

The ESI is also a useful parameter among other indicators. It accesses the degree of sustainability and is defined as the reciprocal of the environmental effect factor (Midilli et al., 2012)

$$ESI = \frac{1}{\text{Environmental effect factor}} \quad (26)$$

4. Results and discussion

4.1. Thermodynamic performance of the ORCs

The performance breakdown of the ORCs with different refrigerants R245fa, R1234yf and R1234ze, is presented. The preliminary operating conditions for R245fa, R1234yf and R1234ze at 298 K are considered at EVP of 0.419, 0.686 and 0.500 MPa, respectively. Additionally, the intensive properties (temperature and pressure) and the thermodynamic flow data: specific exergy and exergy flow for the ORCs configurations at respective state points are shown in Table 1. The information in Table 1 was used to compute the performance parameters of the ORCs. The results indicate that the exergy efficiencies of the components system (Fig. 2) varied with the working fluids for the same cycle. However, component efficiencies were relatively high in ORC-turbine bleeding/regeneration (ORCTBR), ORC-turbine bleeding (ORCTB) and ORC-internal heat exchanger (ORCIHE) in that order (Fig. 2). For all the ORCs an improvement not greater than 0.3% in the component efficiency was achieved irrespective of the working fluid between ORCB and ORCTBR. The percentage exergy destruction (ED) in the ORC components with different refrigerants is shown in Fig. 3. The largest

Table 1
Thermodynamic flow parameters at different state points for the ORCs with R245fa, R1234yf and 1234ze refrigerants.

R245fa				R1234yf				R1234ze				
Points	T (°C)	P (MPa)	e (kJ/kg)	E (kW)	T (°C)	P (MPa)	e (kJ/kg)	E (kW)	T (°C)	P (MPa)	e (kJ/kg)	E (kW)
ORC-basic												
1	25.00	0.1494	0.000	0.000	25.00	0.686	0.000	0.000	25.00	0.500	0.00	0.00
2	26.72	2.500	1.756	1.856	26.57	2.315	0.0314	0.0332	26.67	3.500	2.160	2.287
3	133.50	2.500	47.28	50.07	134.50	2.315	40.06	42.42	137.20	3.500	44.15	46.76
4	27.53	0.1494	0.2437	2.381	81.51	0.686	5.264	5.574	60.56	0.500	1.587	1.681
ORC-internal heat exchanger												
1	25.00	0.1494	0.000	0.000	25.00	0.687	0.000	0.000	25.00	0.500	0.0000	0.000
2	25.80	2.500	1.753	1.856	26.57	3.146	0.031	3.091	26.62	3.500	2.1600	2.289
3	40.00	2.500	2.248	2.381	40.00	3.146	2.919	49.000	40.00	3.500	2.6450	2.801
4	134.70	2.500	52.330	55.42	150.90	3.146	40.270	9.229	149.60	3.500	49.140	52.04
5	42.57	0.1494	0.715	0.757	99.16	0.686	8.715	0.663	75.380	0.500	3.4030	3.603
6	29.16	0.1494	0.262	0.277	41.09	0.686	0.626	0.663	39.090	0.500	0.0067	0.007
ORC-turbine bleeding												
1	25.00	0.149	0.000	0.000	25.00	0.687	0.000	0.000	25.00	0.500	0.000	0.000
2	25.12	0.492	0.256	0.218	25.66	1.717	0.009	0.008	25.52	1.350	0.319	0.274
3	40.00	2.500	3.213	3.400	60.00	3.146	3.958	4.195	62.00	3.500	3.501	3.711
4	62.00	2.500	4.840	5.131	60.94	3.146	4.153	4.402	63.98	3.500	5.424	5.750
5	63.00	2.500	61.290	64.96	175.00	3.146	56.210	59.580	174.30	3.500	59.55	63.120
6	98.85	0.492	27.940	5.822	152.90	0.687	39.980	8.182	136.20	0.500	34.95	6.964
7	68.29	0.492	3.010	2.563	124.20	0.687	14.970	12.800	103.10	0.500	8.291	7.112
ORC-turbine bleeding/regeneration												
1	25.00	0.149	0.000	0.000	25.00	0.687	0.0000	0.0000	25.00	0.500	0.000	0.00
2	25.12	0.492	0.256	0.236	25.16	1.717	0.0095	0.0087	25.52	1.350	0.319	0.295
3	40.00	2.500	0.756	0.698	40.00	3.146	0.9026	0.8273	40.00	3.500	0.818	0.757
4	62.00	2.500	3.406	3.213	62.00	3.146	4.3920	4.6560	62.00	3.500	3.501	3.711
5	63.00	2.500	4.880	5.131	62.88	3.146	4.5970	4.8730	63.98	3.500	5.424	5.750
6	153.80	0.492	61.290	64.96	177.60	1.717	57.350	60.790	174.30	1.350	59.55	63.12
7	98.85	2.500	27.940	3.818	155.50	3.146	40.960	5.8740	136.20	3.500	34.45	4.641
8	68.29	0.149	3.010	2.779	126.80	0.686	15.720	14.410	103.10	0.500	8.291	7.671
9	47.63	0.149	1.022	0.944	107.20	0.686	10.560	9.6830	83.75	0.500	4.677	4.328

Table 2
Comparison of cycle exergy destruction (kW) with different refrigerants at varying evaporator pressure (EVP).

EVP (MPa)	ORCB R245fa	ORCB R1234yf	ORCB R1234ze	ORCIHE R245fa	ORCIHE R1234yf	ORCIHE R1234ze	ORCTB R245fa	ORCTB R1234yf	ORCTB R1234ze	ORCTBR R245fa	ORCTBR R1234yf	ORCTBR R1234ze
2.000	83.86	99.79	94.37	80.14	98.22	92.43	79.53	100	85.18	78.12	98.64	93.48
2.111	83.44	98.92	93.56	79.71	97.27	91.54	78.87	98.95	85.35	77.46	97.58	92.46
2.222	83.06	98.11	92.8	79.31	96.38	90.71	78.26	97.97	85.5	76.85	96.59	91.51
2.333	82.72	97.36	92.1	78.96	95.54	89.94	77.7	97.05	85.64	76.29	95.66	90.63
2.444	82.41	96.66	91.45	78.63	94.77	89.22	77.18	96.19	85.77	75.77	94.79	89.79
2.556	82.13	96.01	90.84	78.33	94.04	88.55	76.7	95.39	85.9	75.29	93.97	89.01
2.667	81.87	95.4	90.26	78.05	93.35	87.92	76.25	94.63	86.01	74.84	93.2	88.28
2.778	81.65	94.83	89.73	77.8	92.71	87.33	75.83	93.91	86.12	74.42	92.48	87.58
2.889	81.44	94.29	89.22	77.58	92.1	86.77	75.45	93.23	86.22	74.03	91.79	86.92
3.000	81.25	93.78	88.75	77.37	91.53	86.25	75.08	92.59	86.31	73.67	91.15	86.30

Table 3
Comparison of power output (kW) with different refrigerants at varying evaporator pressure (EVP).

EVP (MPa)	ORCB R245fa	ORCB R1234yf	ORCB R1234ze	ORCIHE R245fa	ORCIHE R1234yf	ORCIHE R1234ze	ORCTB R245fa	ORCTB R1234yf	ORCTB R1234ze	ORCTBR R245fa	ORCTBR R1234yf	ORCTBR R1234ze
2.000	37.86	21.73	27.24	41.34	23.30	29.19	42.24	21.38	37.73	43.67	22.8	28.08
2.111	38.37	22.71	28.16	41.95	24.37	30.18	42.99	22.56	37.53	44.42	23.99	29.21
2.222	38.83	23.63	29.02	42.51	25.37	31.11	43.7	23.67	37.35	45.13	25.11	30.27
2.333	39.26	24.49	29.82	43.02	26.31	31.98	44.35	24.71	37.18	45.78	26.16	31.27
2.444	39.66	25.29	30.58	43.5	27.19	32.8	44.97	25.7	37.02	46.4	27.16	32.22
2.556	40.03	26.05	31.29	43.94	28.03	33.57	45.55	26.63	36.86	46.98	28.1	33.12
2.667	40.37	26.77	31.96	44.36	28.82	34.3	46.09	27.51	36.72	47.52	29	33.97
2.778	40.69	27.46	32.6	44.74	29.57	35	46.6	28.36	36.58	48.03	29.85	34.78
2.889	40.98	28.1	33.21	45.1	30.29	35.65	47.09	29.16	36.45	48.52	30.66	35.55
3.000	41.26	28.72	33.78	45.43	30.97	36.28	47.55	29.92	36.33	48.98	31.44	36.29

ED occurs in the evaporator. However, a slight improvement was obtained in the components ED using R245fa and R1234ze for ORCTB and ORCTBR cycles.

4.2. Comparison of ORCs Performance at varying EVP

The performance of the ORCs at varying EVP on the overall exergy efficiency (OEF) is also shown in Fig. 2. The OEF ranged

between $22.01 \leq OEF \leq 32.43\%$ for the ORCB while ORCIHE, ORCTB and ORCTBR ranged between $22.07 \leq OEF \leq 35.91\%$, $22.96 \leq OEF \leq 37.63\%$ and $24.21 \leq OEF \leq 38.82\%$ respectively. Additionally, for each unit increase in evaporator pressure, the cycle efficiency increases by nearly 0.46%. The ORCTB and ORCTBR had the highest OEF while ORCB had the lowest values of OEF at all EVPs.

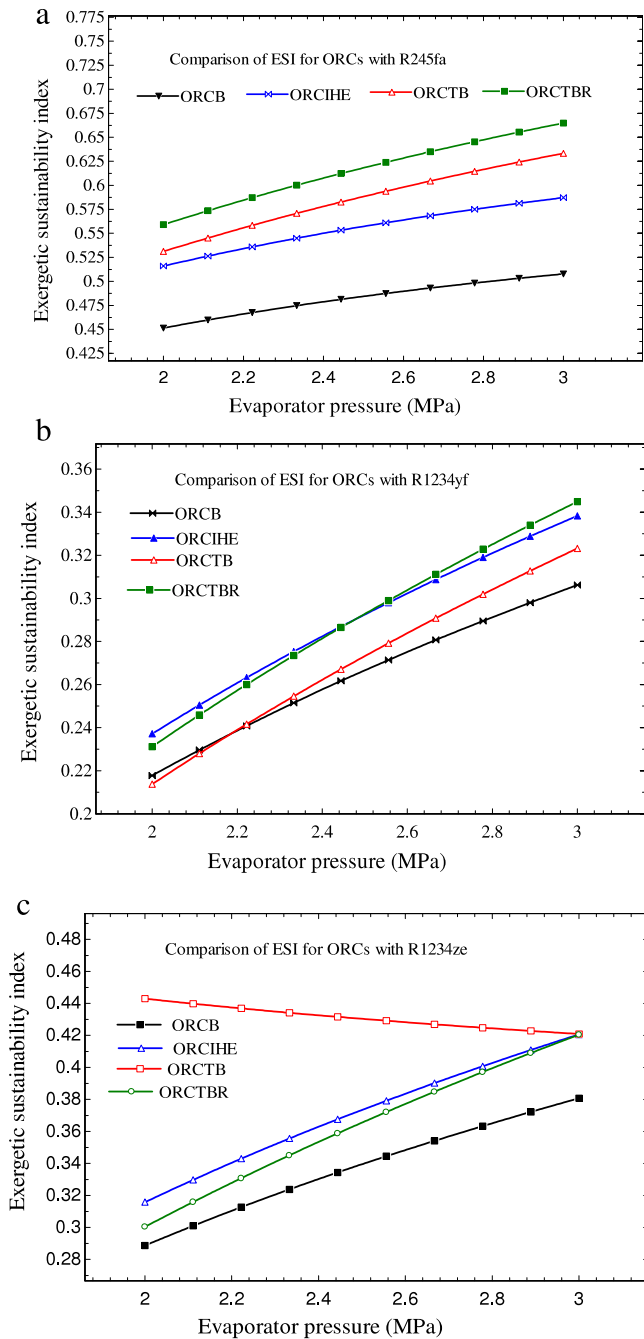


Fig. 5. Comparison of exergetic sustainability index for ORCs with (a) R245fa (b) R1234yf and (c) R1234ze.

The OED across the ORCs was estimated between $81.225 \leq \text{OED} \leq 99.79$ kW, $77.37 \leq \text{OED} \leq 98.22$ kW, $75.08 \leq \text{OED} \leq 98.97$ kW and $73.67 \leq \text{OED} \leq 98.64$ kW (Table 2) for cycle configurations in Fig. 1(a), (b), (c) and (d) respectively. Regarding cycle ED, the ORCB had the highest ED while ORCTBR, ORCTB and ORCIHE had the least ED. The OED decreases in all the ORCs at increasing EVP attributed to the reduction in temperature existing between the hot gas inlet and the evaporator temperature. The latter is responsible for the reduction in entropy generation and hence decrease in ED. The overall power output (POT) is depicted in Table 3. Maximum POT of 41.26, 45.43, 18, 47.55 and 48.98 kW exist at EVP of 3 MPa for ORCB, ORCIHE, ORCTB and ORCTBR in that order, using R245fa.

4.3. Comparison of thermo-sustainability indicators for the different ORCs

The thermo-sustainability indicators are compared with the different refrigerants at varying evaporator pressure conditions. Moreover, R245fa had the highest OEF of 38.82% for ORCTBR at EVP of 3 MPa whereas R1234yf and R1234ze had the lowest cycle efficiency of about 29% at EVP of 2 MPa (Fig. 2l). On per cycle consideration about 8.56% efficiency difference was obtained between the generic cycle (ORCB) and the modified cycle (ORCTBR). Fig. 4(a) to (b) presents the exergy waste ratio (EWR) for the ORCs at varying EVP. The EWR decreases for increasing EVP except for ORCTBR which shows low values of EWR with R1234ze. The lowest EWR of 0.613 was obtained with ORCTBR at 3 MPa using R245fa. Consequently, the ORCTBR with R245fa had the least environmental impact followed by ORCTB and ORCIHE.

The exergetic sustainability index (ESI) for the ORCs is shown in Fig. 5. The ESI values were high using R245fa (Fig. 5a) with values ranging from 0.55 at 2 MPa to 0.675 at 3 MPa. The ORCTBR had the highest ESI followed by ORCTB and ORCIHE. The results indicate that the ESI increases with increasing evaporator pressure. Nonetheless, the ORCIHE performance with R1234yf and R1234ze was marginal while ORCTBR demonstrated high performance with R245fa. The different performance characteristic observed from the ORCs is associated with the following: cycle operating conditions, thermodynamic properties of the working fluids and the variance between the condensing and critical temperatures of the working fluids.

The EEF shows the degree of damage to the environment owing to exergy waste destruction. Fig. 6 depicts ORCs operating with different working fluids. High EEF values were obtained with ORCB using R1234yf and R1234ze refrigerants. The EEF values for these refrigerants were found to vary between $3.266 \leq \text{EEF} \leq 4.327$ at EVP of 2 and 3 MPa. In the same vein, low EEF values of 1.5 and 1.58 were obtained at same EVP range with R245fa for ORCTB and ORCTBR configurations respectively. However, the ORCTBR and ORCTB had the smallest values of EEF and considered to be more sustainable.

5. Conclusion

A comparative performance analysis and thermo-sustainability indicators of low heat Organic Rankine cycles with different refrigerants are presented. The findings include the following:

- The ORCTBR had the highest OEF followed by ORCTB, ORCIHE and ORCB respectively. The OEF with R245fa ranged between $30.26 \leq \text{OEF} \leq 38.82\%$, having efficiency difference of 8.56% between ORCB and ORCTBR at EVP of 2 and 3 MPa. Furthermore, the overall efficiency obtained using R1234yf and R1234ze for all the ORCs configurations was not greater than 29%. The latter implies that the choice of working fluid for a specific system modification is necessary for optimum performance.
- The OED and POT across the ORCs were estimated between $81.225 \leq \text{OED} \leq 99.79$ kW, $77.37 \leq \text{OED} \leq 98.22$ kW, $75.08 \leq \text{OED} \leq 98.97$ kW, $73.67 \leq \text{OED} \leq 98.64$ kW and 41.26, 45.43, 18, 47.55 and 48.98 kW for ORCB, ORCIHE, ORCTB and ORCBTR, respectively. Maximum POT was achieved using R245fa followed by R1234ze and R1234yf. The EWR decreases with increasing EVP for all the ORCs. Additionally, the ORCTBR and ORCTB had the least eco-friendly impact attaining the lowest EWR of 0.613 at 3 MPa. The ESI values were high using R245fa for all cycles than R1234yf and R1234ze

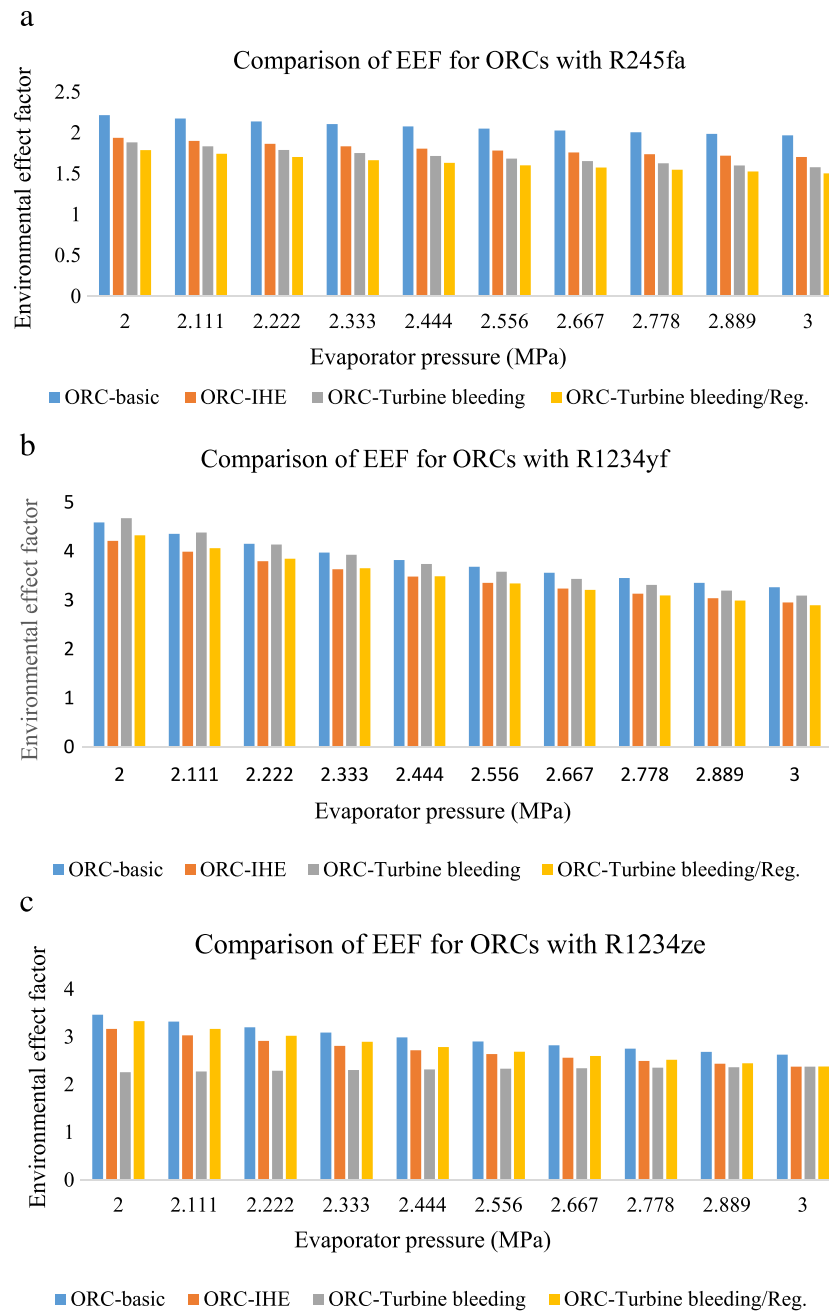


Fig. 6. Comparison of EEF for ORCs with different working fluids (a) R245fa, (b) R1234yf and (c) R1234ze.

- For all the studied cycles, ORCTBR and ORCTB are more environmentally stable with R245fa refrigerants than ORCB and ORCIHE. However, the performance of the ORCs is a function of the working fluid, system configuration and operating parameters. Thus optimum operating conditions for each working fluid and cycle is important to achieving environmental sustainability.

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