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

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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 (ORC-IHE), ORC-turbine bleeding (ORCTB), and ORC-turbine bleeding/regeneration (ORC-TR). The TSI evaluated comprise overallexergy efficiency (OEF), exergy waste ratio (EWR), and environmental effect factor (EEF) in addition to exergeticsustainability index (ESI). The results indicate that the OEF obtained using R245fa fluctuated between 30.59 ≤ OEF ≤ 38.82 with 8.56% efficiency difference between ORCB and ORCTB. Ratevaporator 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 (Thawonmagyingsakul and Kittisiriroat, 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...
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 ($Q_{in}$) 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 TSI 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).

$$\dot{I} = \sum_{\text{in}} \dot{m}_{\text{ex}} - \sum_{\text{out}} \dot{m}_{\text{ex}} - \dot{E}_{\text{ex,in}} - \dot{E}_{\text{ex,out}} = T_0 \dot{S}_{\text{gen}}$$

(1)

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

$$e_s = h - h_0 - T_0 (s - s_0)$$

(2)

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

$$\sum Q_k f_k + \sum \dot{m}_s s_e + \dot{S}_{\text{gen}} = \frac{dS_c}{dt}$$

(3)

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

$$\dot{S}_{\text{gen}} = \sum \dot{m}_s s_e + \sum \dot{m}_s s_i - \sum \frac{Q_k}{T_k}$$

(4)

where:

- $\dot{m}_s$, $T_k$ and $Q_k$ 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).

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

(5)

where $e_{ch}^0$ and $\Delta H_0$ 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
(17) and (18) to (Box I) respectively.

Evaporator (2–3), \[ 1 - \frac{T_0}{T_{in}} \] \( Q_m + \dot{E}_X = \dot{E}_x + \dot{E}_{\text{Devap}} \) (6)

Turbine (3–4), \[ \dot{E}_{X3} = \dot{E}_{X4} + \dot{W}_{\text{turb}} + \dot{E}_{\text{D turb}} \] (7)

Pump (1–2), \[ \dot{W}_{\text{pump}} = \dot{E}_{X4} + \dot{E}_{\text{D cond}} \] (9)

where: \( \dot{E}_{\text{Devap}}, \dot{E}_{\text{D turb}}, \dot{E}_{\text{D pump}}, \) and \( \dot{E}_{\text{D cond}} \) denotes exergy destruction in the evaporator, turbine, pump, and condenser respectively.

\[
\dot{E}_{X1} = m_1 \left[ c_p \left( T_1 - T_0 \right) - T_0 \left( c_p \ln \frac{T_1}{T_0} - Rln \frac{P_1}{P_0} \right) \right]
\] (10)

\[
\dot{E}_{X2} = m_2 \left[ c_p \left( T_2 - T_0 \right) - T_0 \left( c_p \ln \frac{T_2}{T_0} - Rln \frac{P_2}{P_0} \right) \right]
\] (11)

\[
\dot{E}_{X3} = m_3 \left[ c_p \left( T_3 - T_0 \right) - T_0 \left( c_p \ln \frac{T_3}{T_0} - Rln \frac{P_3}{P_0} \right) \right]
\] (12)

\[
\dot{E}_{X4} = m_4 \left[ c_p \left( T_4 - T_0 \right) - T_0 \left( c_p \ln \frac{T_4}{T_0} - Rln \frac{P_4}{P_0} \right) \right]
\] (13)

\[
\dot{E}_{\text{D pump}} = \frac{c_p \left[ T_2 - T_1 \right]}{\eta_{\text{pump}}}
\]

\[
= m_2 \left[ c_p \left( T_2 - T_0 \right) - T_0 \left( c_p \ln \frac{T_2}{T_0} - Rln \frac{P_2}{P_0} \right) \right]
\] (14)

\[
\dot{E}_{\text{Devap}} = m_2 \left[ c_p \left( T_2 - T_0 \right) - T_0 \left( c_p \ln \frac{T_2}{T_0} - Rln \frac{P_2}{P_0} \right) \right]
\]

\[
+ \left[ 1 - \frac{T_0}{T_{in}} \right] Q_m - \dot{E}_{X3} \left[ c_p \left( T_3 - T_0 \right) - T_0 \left( c_p \ln \frac{T_3}{T_0} - Rln \frac{P_3}{P_0} \right) \right]
\]

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 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).

\[
\sum \dot{E}_{\text{waste, out}} = \sum \dot{E}_{\text{dest, out}} + \sum \dot{E}_{\text{loss, out}}
\] (22)

\[
\text{EWR} = \frac{\text{Overall exergy waste}}{\text{overall exergy input}}
\] (23)
$\psi_{\text{eap}} = \frac{m_3 \left[ c_p \left( T_3 - T_0 \right) - T_0 \left( \frac{c_p}{T_0} \right) \right] - m_2 \left[ c_p \left( T_2 - T_0 \right) - T_0 \left( \frac{c_p}{T_0} \right) \right]}{c_p \ln \left( \frac{T_3}{T_0} \right) - R \ln \left( \frac{P_3}{P_0} \right)} - \frac{m_1}{m_{\text{ref}} c_p \left[ T_1 - T_0 \right] - T_0 \left( \frac{c_p}{T_0} \right) \left( 1 - \frac{T_0}{T_Q} \right) Q_{in}}$ \hspace{1cm} (19)

$\psi_{\text{turb}} = \frac{m_3 \left[ c_p \left( T_3 - T_0 \right) - T_0 \left( \frac{c_p}{T_0} \right) \right]}{c_p \ln \left( \frac{T_3}{T_0} \right) - R \ln \left( \frac{P_3}{P_0} \right)} - \frac{m_4}{m_{\text{ref}} c_p \left[ T_4 - T_0 \right] - T_0 \left( \frac{c_p}{T_0} \right)}$ \hspace{1cm} (20)

$\psi_{\text{cond}} = \frac{m_4 \left[ c_p \left( T_4 - T_0 \right) - T_0 \left( \frac{c_p}{T_0} \right) \right]}{c_p \ln \left( \frac{T_4}{T_0} \right) - R \ln \left( \frac{P_4}{P_0} \right)} - \frac{m_1}{m_{\text{ref}} c_p \left[ T_1 - T_0 \right] - T_0 \left( \frac{c_p}{T_0} \right)}$ \hspace{1cm} (21)

### 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,

$$\text{EEF} = \frac{\text{Waste exergy ratio}}{\text{Exergy efficiency}}$$ \hspace{1cm} (24)

### 3.3. Exergy efficiency

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

$$\psi_{\text{overall}} = \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{in}}}$$ \hspace{1cm} (25)

### 3.4. Exergetics 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)

$$\text{ESI} = \frac{1}{\text{Environmental effect factor}}$$ \hspace{1cm} (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
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 overallergy efficiency (OEF) is also shown in Fig. 2. The OEF ranged between 22.01 ≤ OEF ≤ 32.43% for the ORCB while ORCHE, ORCTB and ORCTBR ranged between 22.07 ≤ OEF ≤ 35.91%, 22.96 ≤ OEF ≤ 37.63% and 24.21 ≤ OEF ≤ 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.
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 1234ze had the lowest cycle efficiency of about 29% at EVP of 2 MPa (Fig. 2I). 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 ORCIE.

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 ORCIE. The results indicate that the ESI increases with increasing evaporator pressure. Nonetheless, the ORCIE performance with 1234yf and 1234ze 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 1234ze 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, ORCIE 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 $81.225 \leq \text{OED} \leq 99.79\ kW, 77.37 \leq \text{OED} \leq 98.22\ kW, 75.08 \leq \text{OED} \leq 98.97\ kW$ 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 ORCIE 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, ORCIE, ORCTB and ORCTBR in that order, using R245fa.
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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