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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 (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.

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 Kiatsiriroat, 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

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Nomenclature

c_p	heat capacity (kJ/kg K)
$\dot{E}_x$	exergy flow rate (kW)
$\dot{e}_x$	specific exergy (kJ/kg)
e^0_{ch}	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]/$\bar{h}^0_v$
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 (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).

$$\dot{I} = \sum_{\text{in}} \dot{m}_{\text{ex}} - \sum_{\text{out}} \dot{m}_{\text{ex}} - \dot{E}x^{Q}_{\text{in}} - \dot{E}x^{W}_{\text{out}} = T_0 \dot{S}_{\text{gen}} \quad (1)$$

where $\dot{I}$ is exergy destruction rate, $\dot{m}_{\text{ex}}$ is the exergy flow of the working fluid, $\dot{E}x^{Q}_{\text{in}}$ and $\dot{E}x^{W}_{\text{out}}$ 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)

$$e_x = h - h_0 - T_0 (s - s_0) \quad (2)$$

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).

$$\sum \frac{Q_k}{T_k} + \sum \dot{m}_e s_e + \dot{s}_{gen} = \frac{ds_{cv}}{dt} \quad (3)$$

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

$$\dot{s}_{gen} = \sum \dot{m}_e s_e + \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k} \quad (4)$$

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).

$$e_{ch} = \frac{e^0_{ch}}{M} \left[\frac{T_0}{298.15} \right] + \frac{\Delta H_0}{M} \left[\frac{T_0 - 298.15}{298.15} \right] \quad (5)$$

where e^0_{ch} 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