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# Optimum exergetic performance parameters and thermo-sustainability indicators of low-temperature modified organic Rankine cycles (ORCs)

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ABSTRACT

The optimum exergetic performance parameters and thermo-sustainability indicators (TSIs) of low-temperature Organic Rankine cycles (ORCs) are presented. The study objectives are (i) to determine the exergetic performance, and TSIs of modified ORCs based on different thermodynamic inputs and (ii) compare the optimum exergetic performance parameters and the TSIs of the ORCs. The TSIs considered include, waste exergy ratio (WER), exergy efficiency (EE), exergetic sustainability index (ESI) and environmental effect factor (EEF). Additionally, a component by component exergy analysis was first performed, followed by the application of the TSI models established by modifying the existing TSI model for open cycle thermal plants. The results indicated that the increase in EE across the ORCs was not greater than 0.3%. The exergy destruction gap across the ORCs was between 1.2 and 23%. The ESI was low with the basic ORC while the modified systems had improved ESIs. However, best exergetic performance and TSIs were obtained at optimum conditions of $0.127 \le p_1 \le 2.144$ MPa, $0.17 \le p_2 \le 2.5$ MPa and $416 \le t_3 \le 426$. The study inferred that system configuration and type of working fluids are paramount in determining the ORC performance. Moreover, the results obtained can further be used to evaluate the functional sustainability limits of working fluids.

## Introduction

In recent times the global sustainability challenges are taking a new dimension which has raised concern from different works of life. The sustainability challenges are worsened due to the increasing rate of conventional energy consumption, climaxed by the increase in global energy demand. However, energy sustainability is indispensable as this will enhance economic and social expansion as well as improved quality of life [1]. One approach to surmounting this problem is the development of renewable energy resources and improvement on the existing thermodynamic cycles for conventional energy conversion [2]. Furthermore, the exergy procedure and application in recent times have been extended to various areas of science and engineering making it possible to understand the real thermodynamic losses taking place in an energy conversion device as well as system sustainability levels. Studies in this areas include the works of [3] who performed a comprehensive energy and exergy analysis of a novel combined cycle for power and cooling applications. Similarly [4], considered the environmental and sustainability of a recirculating agricultural system while [5] and [6] presented environmental sustainability levels of industrial gas turbine plants and low by-pass turbo engines based on the exergy technique. Several scholars in the open literature have suggested different methods for clean energy production by utilizing low- heat-temperature energy cycles such as [7] who suggested a combined ORC and photovoltaic whereas [8,9] have considered the suitability of low-heat cycles in terms of working fluid, economics, and environmental sustainability. These cycles occur as follows: ORC (Organic Rankine cycle) [10,11], SRC (supercritical organic Rankine cycle) [12], the Kalina cycle and Goswami cycle [13]. Additionally, among these existing cycles, the organic Rankine cycle is the most popular cycle which has drawn attention in the most published literature. The ORC system is classified based on the heat source utilization, for instance, geothermal [14], biomass utilization [15], waste from industrial materials [16] and solar energy [17]. Extended studies in recent times on ORCs applications and prospects include [18] who measured the potential of zeotropic combinations as suitable working fluids for the ORC systems. The study

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achieved a reasonable improvement in the overall thermal efficiency and performance with zeotropic combinations than the normal working fluids. Also [19] applied multiple scroll expanders in ORC and attained an efficiency improvement of about 3.2% while [20] had used a single-scroll expander at varying vapour dryness and obtained enhancement in the output power for a rise in the vapour dryness input. Other investigators like [21] and [22] have considered ORC performance based on varied working fluids. For example [21] measured the thermal performance of organic Rankine cycle with PF 5050, R123, and n-pentane and determined the ORC performance at the different evaporator and condensation temperatures as well as at varying cooling water inlet velocities. Others like [22] studied the performance of thirty-one refrigerants for sub-critical and supercritical ORC systems for a geothermal power plant. The study shows that the performance of the ORC system is influenced by the thermodynamic properties of the working fluid. Many experimental and theoretical studies in open literature had measured the efficiency and performance of different ORC structures such as [14], [23] and [24] had considered refrigerants performance, exergy analysis and best operating conditions using the different thermodynamic index. [25] Presented a pumpless organic Rankine system and investigated the performance with a low heat temperature source lower than 100 °C using R245fa as refrigerants. The results indicate that a maximum power output power of 232 W, was obtained at 95 °C water temperature. Similarly, [26] carried out an experimental study of ORC for electricity generation using R245fa as working fluid. The components of the ORC systems such as the turbine and the generator were designed based on the thermodynamic properties of the refrigerants R245fa. The ORC performance was examined experimentally, and the performance data obtained were further used to improve the design and formed the basis for further optimization. Nonetheless, exergoenvironmental and life cycle analysis (LCA) for ORCs have been reported in the literature. For example, [27] performed exergoenvironmental and life cycle analysis of an ORC including the manufacturing stages of the components system and refrigerant leakage. Their results show that the component materials have little impact on the environment while the working fluid has more severe consequences on the environment. Other studies in [28] investigated the environmental impact of organic Rankine cycle power plant (ORCPW) using different refrigerants. The Life cycle analysis (LCA) was divided into construction, operation and decommissioning. The obtained results indicate that the construction stage of the ORCPW contributes highly to the global warming potential and eutrophication potential. The calculated average payback periods of the greenhouse gas emitted from the ORCPW for the considered working fluids was 3–5 years, one year and 3–6 years for $CO_2$, $CH_4$, and NOx, respectively. Additionally, the study concluded that the CO was difficult to be paid back during the life cycle of the ORCPW. The exergy-based environmental analysis has been extended to combined cycles as in [29]. In this study, an oxy-fuel generating power plant integrated with chemical looping combustion (CLC) was presented for total $CO_2$ capture. The study compared as reference a power plant of the parallel structure without carbon dioxide capture. Lower irreversibilities, as well as low NOx emissions, were obtained using the plant with CLC than the reference plants. The study concluded that the system with CLC was found to have a high cost of electricity but decrease environmental impact. Similarly, [30] performed exergoenvironmental analysis for a trigeneration power plant based on ORC. The findings show that the efficiency of the trigeneration plant was higher than the efficiency of a typically combined gas turbine power system. Also, the $CO_2$ emissions for the trigeneration plant were found to be lower than that for the gas turbine combined plant. Further research has presented specific studies on the optimization of ORC to determine best operating conditions. The work of [31] presented, a method for the actual design of ORC based power systems using multistage and turbine cycle design criteria and obtained optimal conditions. The results show that the efficiency of the turbine varies from 74% to 93% for the different design conditions and fluids used. Likewise, [32] developed mathematical models for the optimization of a simple ORC using R134a at different operating conditions. Their findings indicate that the mass flow rate of the working fluid has more impact on the efficiency, power output than the air mass flow rate of the condenser fan. Furthermore, [33] presented a cost optimization of ORC using eight coolants and combining different algorithms. They concluded that R11, R141b, and R123 have the best efficiency as well as low costs. Moreover, the objective of this study is to perform a parametric analysis on non-hybrid modified ORCs to determine (i) the exergetic performance parameters and thermo-sustainability indicators (TSIs) and (ii) evaluate the parameters in (i) at optimum conditions to ascertain the exergetic sustainability levels of the cycle with the applied working fluids. The approach for this current research differs from that obtained in [27–30] in terms of sustainability analysis. However, the authors modified the equations for exergo-sustainability analysis used in combined and open cycles thermal plants [5,6,34] by making some assumptions. The latter assumptions provided the flexibility of applying these equations directly in the considered ORCs making itunique. The understanding from this study may further provide a method of determining thermo-sustainability limits of working fluids in ORCs.

## Thermodynamic process description of the ORCs

The flow diagrams for the considered ORC configurations are shown in Fig. 1. The following flow processes occur (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 (ORCIHE). Fig. 1(c), the ORC is incorporated with a feedwater 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.

## Thermodynamic assumptions

The study considers the following assumptions: (1) Steady-state flow condition. (2) The pressure drop, heat and friction losses in the components of the ORCs are ignored. (3) The inlet conditions of temperature to the evaporator are taken at 25 °C (298 K) while for condenser the pressure ranged between $2.5 \le p_{con} \le 3.5$ MPa based on the working fluids. (4) The evaporator heat input ($Q_{in}$) is a stream of hot gas taken at 252 kW, at 120 °C (393 K) from an open cycle micro gas- turbine plant [35]. (5) The exergy stream exiting the evaporator and that of water entering and exiting the condenser are ignored. (6) The inlet fluid condition into the turbine exist as superheated. The isentropic efficiencies of the turbine and pump are kept at 85 and 75% respectively [36]. (7) The pitch point temperature difference in the evaporator and condenser are kept at 5 and 10 °C respectively [27,37].

## Thermodynamic modelling of the ORCs

Steady-state flow processes involving energy and exergy streams are presented in Eqs. (1) and (2) [38,39].

$$\Sigma\dot{Q}_k + \Sigma\dot{m}_i(h_1 + \frac{C_i^2}{2} + gz_1) = \Sigma\dot{m}_i(h_0 + \frac{C_0^2}{2} + gz_0) + \Sigma W \quad (1)$$

$$\sum\left(1 + \frac{T_0}{T}\right)\dot{Q}_k + \sum(\dot{m}_i\dot{\varphi}_i) = \sum\varphi w + \sum(\dot{m}_0\dot{\varphi}_0) + E_D \quad (2)$$

The energy, exergy and mass balances are equally defined for a steady state neglecting kinetic and potential energy terms:

$$\sum\dot{m}_i = \sum\dot{m}_0 \quad (3)$$