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Comparative performance analysis of low-temperature Organic Rankine Cycle (ORC) using pure and zeotropic working fluids

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HIGHLIGHTS

- ► Combined energy and exergy analysis is conducted for Organic Rankine Cycle.
- ► Comparative assessment is performed for different pure and zeotropic working fluids.
- ► Exergy and energy efficiency, cycle irreversibility, and required external heat are analyzed.
- ► Toxicity, flammability, ODP and GWP of considered working fluids are studied.
- ► Environmental benefits of the renewable/waste heat-based ORC are investigated.

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ABSTRACT

In this paper, a comprehensive thermodynamic analysis of the low-grade heat source Organic Rankine Cycle (ORC) is conducted and the cycle performance is analyzed and compared for different pure and zeotropic-mixture working fluids. The comparative performance evaluation of the cycle using a combined energy and exergy analysis is carried out by sensitivity assessment of the cycle certain operating parameters such as efficiency, flow rate, irreversibility, and heat input requirement at various temperatures and pressures. The environmental characteristics of the working fluids such as toxicity, flammability, ODP and GWP are studied and the cycle CO_2 emission is compared with different fuel combustion systems. R123, R245fa, R600a, R134a, R407c, and R404a are considered as the potential working fluids. Results from this analysis provide valuable insight into selection of the most suitable working fluids for power generating application at different operating conditions with a minimal environmental impact.

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1. Introduction

Concerns of energy industries have increased over utilization of fossil fuels towards global warming, air pollution and stratospheric ozone depletion. Also, waste heat energy being released from process industries and power plants causes serious thermal pollution [1]. In this context, utilization of the renewable and industrial waste heat for electricity generation has become a significant point of interest. In addition, due to the fact that the thermal efficiency of the conventional steam power generation becomes uneconomically low when the gaseous steam temperature drops below 370 °C, using water as a working fluid become considerably less efficient and more costly [2].

In recent years, Organic Rankine Cycle (ORC) has become a field of intense research and development as a promising technology for conversion of low-grade heat into useful work and hence electricity. The heat source can be of various origins such as solar radiation [3], biomass combustion [4], geothermal energy [5] or waste heat from process industries [6,7]. Some actual applications have been installed for recovering geothermal and waste heat for power generation in various locations [8,9]. Examples are the plants in Altheim, Austria, with a power production of 1 MW [10] and in Neustadt-Glewe, Germany, with a power production of 0.2 MW [11].

Unlike in the steam power cycle where vapour steam is the working fluid, ORCs employ organic fluids, namely refrigerants or hydrocarbons. Right selection of a working fluid is crucial to achieve higher energetic and exergetic efficiencies. Optimum utilization of the available heat source in different operating conditions involves various trade-offs. Moreover, the organic working fluid must be carefully selected based on safety and environmental properties

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assessment. General criterion such as cycle thermodynamic performance, fluid stability limit, flammability, safety, and environmental impact could be considered to analyze using different working fluids. As an example, utilizing the non-flammable and non-toxic refrigerants is promoted previously as attractive working fluids. R113 and R114 have been also banned because of their ozone layer depletion potential. It should be mentioned that this regulation will include R123 in the near future [12].

Vijayaraghavan and Goswami [13], Badr et al. [14], Hettiarachchi et al. [15], Saleh et al. [16], and Tchanche et al. [17] are some of the researchers who have analyzed the characteristics of different working fluids in various ORC applications. A large number of previous studies regarded mostly to pure components as the working fluid for ORC performance assessment. However, using single working fluid component brings substantial deficiencies. In the most studied applications, the temperatures of a pure working fluid remain constant during evaporating and condensing processes, whereas the temperatures of the heating and cooling sources are changing during the heat transfer process. Consequently, pinch point imposes larger temperature differences leading to higher system irreversibility which considerably decreases the cycle exergy efficiency. In other words, an important limitation of using pure working fluids is the constant temperature of evaporation and condensation that is not suitable for sensible heat sources such as waste heat. In contrast, working fluid mixtures present variable temperature profile during the phase change process, which could considerably reduce the mismatch between heating or cooling sources and the evaporating or condensing working fluid mixtures respectively. So, the cycle overall efficiency could increase noticeably since system irreversibilities can be minimized. Wang and Zhao [18] presented a theoretical analysis of zeotropic mixtures R245fa/R152a in the low-temperature solar Rankine cycle. Radermacher [19] analyzed the mutual influence of working fluid mixtures properties on the ORC overall performance and suggested simple counter-flow heat exchangers.

In the present work, energy and exergy analyses of the low-temperature heat source ORC are conducted for different pure and zeotropic-mixture working fluids and results are studied and compared. Performance comparison between pure and multi-component mixtures as a working fluid, which is the key missing part in a majority of the previous works, is also included. The cycle energy and exergy efficiencies, total irreversibility, external heat requirements, and mass flow rate of the potential working fluid are calculated and compared for a 100 kW power generation system. In addition, the environmental characteristics of the working fluids such as toxicity, flammability, ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) are studied and the cycle CO_2 emission is compared with different fuel combustion systems.

2. Methodology

The components of an ORC are essentially similar to the conventional Rankine Cycle which consists of a pump, evaporator, expander and condenser. The working fluid is saturated liquid when passing out the condenser and is then pumped to the evaporator to gain heat from a heating source. Resulting hot pressurized working fluid that could be saturated or superheated expands in the expander and generates useful work. The layout of a typical ORC is shown in Fig. 1. The expander is considered similar to the scroll expander investigated by Zamfirescu and Dincer [20] and Quoilin et al. [21].

The appropriate selection of working fluids for different operation conditions, as it was mentioned earlier, is the most important criteria to system performance. Thermodynamic properties of selected working fluid will affect the system efficiencies and the cycle environmental impact. Technically, the working fluid can be

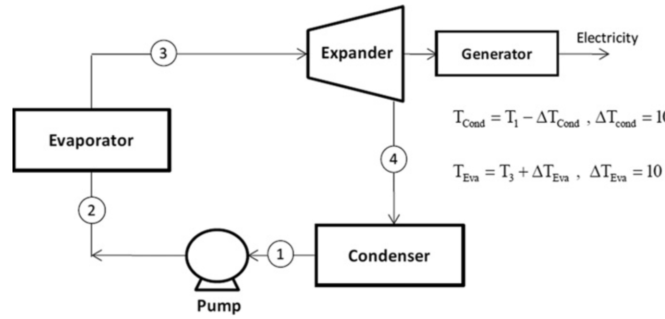

Fig. 1. Schematic of a typical Organic Rankine Cycle (ORC).

classified into three categories. Those are dry, isentropic, and wet depending on the slope of the cycle T–s diagram to be positive, infinite, and negative respectively. Also ORC can be classified in two groups according to the level of expander inlet pressure, including supercritical ORCs and sub-critical ORCs which is the one investigated in the present study.

Figs. 2 and 3 show T–s diagrams of two types of ORC processes with the negative slope of the saturated vapour curves. As it is shown in Fig. 2, the working fluid leaves the condenser as saturated liquid, state point 1. Then, it is compressed by the liquid pump to the sub-critical pressure, state point 2. The working fluid then is heated up in the evaporator until it becomes superheated vapour, state point 3. The superheated vapour flow is then expanded after to the condensing pressure, state point 4. At the condensing pressure, the working fluid lies in the two-phase region. The two-phase fluid passes through the condenser where heat is removed until it becomes a saturated liquid, state point 1. The processes in Fig. 3 are similar to those in Fig. 2 with the only difference being that the state point 4 after expansion lies in the superheated vapour region.

Figs. 4 and 5 show T–s diagrams of the other two types of ORC processes with the positive slope of the saturated vapour curves. The state points 1 and 2 are in the same condition as the ORC system in Figs. 2 and 3. Starting from state 2, the working fluid is heated up in the evaporator at constant sub-critical pressure until it becomes saturated, state point 3 in Fig. 3, or it is superheated, state point 3 in Fig. 4. Then, it is expanded to state point 4, which is in the superheated vapour region.

The key point for performance analysis of ORCs which have been also presented by Hung [22], Gurgenci [23], Yamamoto et al. [24],

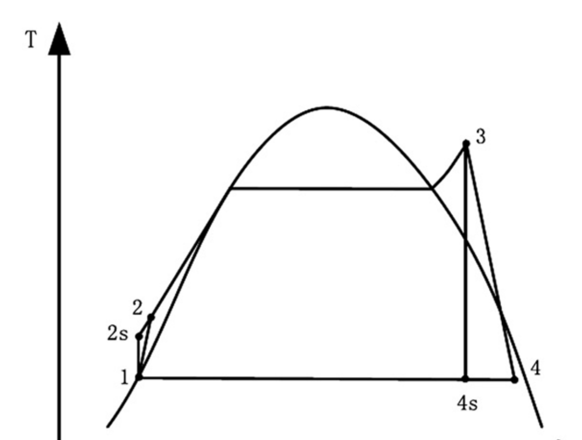

Fig. 2. ORC with a negative slope of the saturated vapour curve and wet vapour at the expander outlet.

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