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Organic Rankine cycle performance evaluation and thermoeconomic assessment with various applications part I: Energy and exergy performance evaluation

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ABSTRACT

The utilization of low grade energy and renewable energy heat sources for power generation in organic Rankine cycle (ORC) system has received more attention in recent decades. In this study, working fluid candidates for various ORC applications based on the heat source temperature domains have been investigated for the thermal efficiency, exergy destruction rate and mass flow rate under different ORC configurations. The net power output from the ORC remains constant. The thermal efficiency increases as the condensing temperature diminishes, and decreases as the evaporating pressure recedes. As the condensing temperature and evaporating pressure are fixed, it can be found that as the critical temperature of the working fluid is increased, the thermal efficiency can be increased. As the heat source temperature scale increases, the operating evaporating pressure of the working fluids can be extended. The ORC with internal heat exchanger (IHX) has a higher thermal efficiency than the baseline ORC. The reheat ORC thermal efficiency is close to the baseline ORC. The regenerative ORC can achieve higher thermal efficiency than the baseline by reducing the addition of heat from the evaporator heat source. The performance of working fluid mass flow rate can reach their maximum in the low thermal efficiency region. The ORC with IHX and regenerative ORC have a lower value for exergy destruction as compared to baseline. Reheat ORC has a slightly higher exergy destruction rate. The evaporator is the largest contributor for the exergy destruction rate. In addition, the effect of IHX effectiveness, reheat pressure and regenerative intermediate pressure on system performance has been revealed and identified.

Contents

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1. Introduction

The utilization of waste or renewable energy has attracted much interest recently facing the shortage of fossil fuels and serious environmental pollution including global warming caused by the growing industrialization. Great efforts from both the governments and several organizations have been carried out to relieve such issues. Regarding the thermodynamic cycles, researchers have proposed several cycles including organic Rankine cycle (ORC), Kalina cycle, supper critical CO_2 cycle, triangle cycle, and heat pipe technology [1–4]. Among various cycles, ORC is more practical and more widely used. It has the main advantages of simplicity and the component availability. The working fluid as the organic substance can be better adapted than water for lower heat source temperatures. In addition, the local and small scale power generation makes it possible to utilize the ORC technology, which is unlike the traditional Rankine power cycles. The high waste energy utilization can be achieved by ORC when compared with other waste heat-recovery approaches and it is easy to downsize the system volume and weight. What is more, the cost of ORC is cheaper than others such as a thermoelectric generator.

Many investigations about ORC were carried out with various categories according to their application domains, such as solar energy [5], biomass heat [6], geothermal energy [7], waste heat recovery (WHR) of internal combustion (IC) engines [8], WHR of gas turbine exhausts [9] and bottoming of the water/steam Rankine cycle [1].

Regarding the geothermal power plants, one study was performed to investigate 31 pure component working fluids for sub-critical and supercritical ORCs [10]. For low-temperature solar organic Rankine cycle systems. another study by Tchanche et al. [11] comparatively accessed 20 working fluids. With waste energy sources as the heat source, Maizza and Maizza [12] investigated the thermodynamic and physical properties of 20 unconventional fluids used in organic Rankine cycles. For application in ORC biomass power and heat plants, Drescher and Bruggemann [6] developed software to find thermodynamically suitable fluids.

Although an abundant literature is available on the fluid selection, there is a lack of comprehensive modeling work from both the energy and exergy aspects with various heat source levels, i.e. the various application domains. In addition, there is a lack of comprehensive performance comparison of simple ORC, ORC with internal heat exchanger (IHX), reheat ORC and regenerative ORC configurations. Therefore, the objective of the present study is to comprehensively investigate the energy and exergy performance with different working fluids under various applications. The thermodynamic models of various organic working fluids under these constrained situations were fabricated and calculated using Engineering Equation Solver (EES) software package program [13]. The performance comparison is performed for each fluid in a feasible pre-defined operating region under the defined application domain based on the evaporating pressure and condensing temperature. The organization for this study is performed as follows: first, the background, motivation and objective are presented. Then the working fluid selection and ORC configuration are provided and described. After that the main part, “Section 3” details the energy and exergy performance comparison for various working fluids under different configurations for different application domains. The final discussion, makes the main summaries and show the main perspectives for performance and design improvements.

2. Working fluid selection and cycle design configuration

2.1. Working fluid selection

The working fluid selection is critical for the system to achieve high thermal efficiencies with utilizing available heat source efficiently. There is a wide selection of the working fluids for various ORC applications. The saturation vapor curve affects the fluid applicability, cycle efficiency for power generation system. Usually a dry fluid has a positive slope while a wet fluid has a negative slope. An isentropic fluid has infinitely large slopes. It is generally accepted that the dry and isentropic fluids show better thermal efficiencies since the fluid going through the turbine do not experience condensing process while the wet fluid not. A comparison of the temperature–entropy diagram for dry, wet, and isentropic fluids is presented in Fig. 1. Good working fluids usually have the following characteristics:

- Dry or isentropic fluids.
- High densities in both liquid and gas phase.
- Moderate critical parameters and high specific heat.
- Moderate evaporating and condensing pressures.
- Low toxicity, good material compatibility.
- Low flammability and corrosion.
- Good fluid stability.

Isentropic fluids such as R12 and R22 will not be investigated since they are being phased-out. The working fluids investigated are shown in Fig. 2. There are four ORC applications: geothermal application (heat source: 100 °C), low temperature solar application (heat source: 130 °C), high temperature waste heat recovery (heat source: 240 °C), and high temperature solar/biomass application (heat source: 290 °C). To have a better thermal match, applications with higher heat source temperatures usually have the working fluids with higher critical temperatures. Based on the literature review from the extensive work carried out, no working