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Research Paper

# Performance comparison of the liquid–vapor separation, parallel flow, and serpentine condensers in the organic Rankine cycle

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## HIGHLIGHTS

- A mathematical model of newly developed LSC and an ORC that contains LSC is formulated.
- The effects of some key geometric parameters on the LSC performance are examined.
- The LSC is compared with SC and PFC in terms of component performance.
- The systematic performances of ORC containing different condensers are compared.
- A sensitivity analysis of heat source and environment condition is conducted.

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## ABSTRACT

Organic Rankine cycle (ORC)-based power generation is a promising technology for recovering waste energy and effectively utilizing renewable energy with low enthalpy. A condenser is an important unit in ORC. The screening and design optimization of the condenser is significant in achieving high efficiency and low cost. Liquid–vapor separation (LSC) is a newly developed air-cooled fin-tube condenser with low pressure drop, low investment cost, and high compactness. The advantages of LSC have been proven in the refrigeration system. This study theoretically investigates the comprehensive performance of LSC in ORC. A mathematical model of LSC and an ORC that contains LSC is formulated. The effects of some key geometric parameters on the total heat transfer surface area and pressure drop of the condenser are examined. The total cost of investment and operation is selected as the objective function to identify the comprehensive performance of the heat transfer coefficient and presser drop at a constant heat transfer rate. The LSC is also compared with the serpentine condenser (SC) and parallel flow condenser (PFC) in terms of heat transfer coefficients, pressure drop, heat transfer area, and economic cost. The systematic performance of ORC containing different types of condensers is examined and compared in the context of ORC at fixed heat resource parameters and environment parameter. The structural parameter analysis shows that the tube length, tube inner diameter and tube pass arrangement with minimum cost of LSC are 1.5 m, 11 mm and 17-15-10-5-1, respectively. The optimal total cost of LSC is 3.74% and 34.50% lower than that of PFC and SC under a given design condition. The comparison of ORC with different condensers shows that the thermal efficiency (exergy efficiency) of ORC-LSC and ORC-PFC are 0~13.75% (0~11.82%) and 25.25~65.53% (21.83~52.3%) higher than those of ORC-SC, respectively. The sensitivity analysis of heat resource parameters and environment parameter is also performed, and quantitative comparisons of three ORCs are provided.

## 1. Introduction

Energy shortage and environmental deterioration are two serious issues today. A significant amount of waste heat is being released into the environment, which leads to serious energy loss and environmental pollution. Large amounts of renewable resources with low enthalpy (e.g., solar, geothermal, and biomass energy) are far from being effectively utilized. Organic Rankine cycle (ORC)-based power generation is a promising technology for recovering waste energy and/or effectively utilizing renewable energy with low enthalpy [1–3]. However, ORC has relatively high built-up costs and needs urgent improvement in terms of comprehensive performance. Research shows that the enhancement of the thermal efficiency and reduction of investment cost of ORC are significant

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in the conversion of energy to power of renewable energy and low-grade waste heat [4]. Heat exchangers, such as evaporators and condensers, are the most important ORC components. Research shows that the exergy loss of condensers and evaporators accounts for 70–90% of the total exergy loss of ORC [5]. Similarly, the total capital investment of a heat exchanger accounts for 40–90% of the total ORC investment cost. Among the heat exchangers, the condenser (especially the air cooled condenser) possesses the largest proportion of investment cost in low-heat source-driven ORC [6,7]. The heat transfer coefficient and pressure drop both have a significant impact on the heat exchanger and ORC. Therefore, the screening, design, and optimization of the condenser are significant in improving the comprehensive performance of ORC.

Researchers have conducted many studies to improve the overall performance of fin-and-tube condensers to reduce material costs and occupied space. In the condensation process, vapor quality and mass flux are the two main factors that influence in-tube condensation heat transfer and pressure drop. Berrada et al. [8] investigated the influence of working medium vapor quality on the condensation heat transfer of R134a in a smooth copper tube. They found that the condensation heat transfer coefficients of a vapor quality of 0.8 are nearly twice those of a vapor quality of 0.3. Cavallini et al. [9] investigated the condensation heat transfer and pressure drop performance of R134a, R125, R236ea, and R32 inside a smooth tube and found that the condensation heat transfer coefficients increase rapidly with an increase in the vapor quality in the region of high mass flux. Wongwises and Polsongkram [10] and Laohalertdecha and Wongwises [11] found that the condensation heat transfer coefficients of R134a increase linearly with vapor quality and that pressure drop increases noticeably with an increase in vapor quality and mass flux. Jung et al. [12] investigated the condensation heat transfer coefficients inside plain and micro-fin tubes and found that the heat transfer coefficients of micro-fin tubes are twice those of plain tubes. Sapali and Patil [13,14] compared the inside condensation performances of horizontal smooth and micro-fin tubes and observed that the heat transfer coefficients and pressure drops of the latter are 1.3–2.5 times and 1–2.1 times higher than those of the former, respectively. These studies show that high mass flux and high vapor quality help improve heat transfer coefficients but also lead to large pressure drops [15]. They also show that, in many cases, the enhancement of heat transfer usually results in an increase in pressure drop [16]. In general, all means of research on condensers are being sought to balance heat transfer and pressure drop behaviors. A higher heat exchanger coefficient results in a lower condenser area. A lower pressure drop results in a higher pump power consumption or lower net power generation. Low-enthalpy heat source-driven ORC is more easily affected by pressure drop and area than traditional power generation technology. Therefore, the design and optimization of condensers are important in increasing thermal efficiency and reducing cost.

Given the importance of the condenser in ORC, many studies use different types of condensers in the ORC system, such as plate [17,18], shell and tube [19], and air cooled condensers [20,21]. Li et al. [22] optimized a condenser in the ORC system through exergoeconomic analysis. Wang et al. [23] developed a multi-objective optimization method of designing a plate heat exchanger in the ORC system. The optimum geometric parameters were obtained by minimizing both the heat transfer area and pressure drop. Lecompte et al. [24] presented a thermo-economic design methodology that requires optimizing the size of heat exchangers (fin-and-tube condenser and plate evaporator), mass flow rate, and power of pumps for an ORC system. Although the aforementioned studies present the optimization of heat exchangers in ORC, most of them focus on the structural and parametric optimization of traditional condensers. Only very few studies focus on the feasibility analysis and comparison of different types of condensers in ORC. Walraven et al. [25] performed a configuration optimization and comparison of plate and shell-and-tube heat exchangers in the context of ORC. The ORC with plate heat exchanger was compared with the ORC with shell-and-tube heat exchanger in terms of cycle performance. The results showed that the cycle performance of ORC is greatly affected by the type and geometries of the heat exchanger.

The parallel flow condenser (PFC) is an emerging technology used to enhance condensation. PFC has several advantages over traditional fin-and-tube condensers in terms of compactness, pressure drop, and cost. The configuration of multiple short parallel circuits is favorable to pressure drop, but may result in a low heat transfer coefficient. Peng et al. [26] proposed a liquid–vapor separation condenser (LSC) based on PFC. The heat transfer tube of the LSC is divided into several passes to reduce the mass flow rate and gain a lower pressure drop. A number of liquid–vapor separators are designed to remove the condensate between each two adjacent passes so that the fluid with high vapor quality enters the next pass. Thus, LSCs may possess both a high heat transfer coefficient and low pressure drop. The advantages of using LSC over traditional tube-fin condenser in refrigeration systems have been reported by Chen et al. [27,28].

In the present study, LSC is applied and analyzed in the ORC system for the first time. The mathematical model of LSC is formulated, and the influence of some key geometric parameters on the total heat transfer surface area and pressure drop of the condenser is examined. An economic model and objective function are presented for the evaluation of LSC. The LSC is compared with other condensers in terms of total heat transfer surface area, pressure drop, investment cost, operation cost, and total cost. The thermodynamic analysis model of ORC with LSC is then formulated and compared with ORC with PFC and serpentine condenser (SC) at fixed and varied heat resource parameters and environmental parameters. The novelty of the present study is the simulation and comparison of different condensers in the context of ORC both in economic and thermodynamic terms for the screening and optimization of the condenser for ORC. As seen in the literature survey, studies on the screen and comparison of fin-tube condenser in the context of ORC were not found.

The rest of this paper is organized as follows: Section 2 presents a description of ORC and three types of air cooled condenser. Section 3 presents a detailed simulation model of LSC and ORC with different air cooled condensers. Section 4 presents the performance comparison of LSC with PFC and SC both individually and in the context of ORC. Section 5 provides the conclusions of the study.

## 2. Description of ORC and three types of air cooled condenser

### 2.1. Description of ORC

The schematic diagram of an ORC is shown in Fig. 1. The working fluid is compressed by a booster pump (point 1) and is led to the evaporator, where the working fluid is evaporated and superheated by the heat resource (point 2). The superheated vapor enters a turbine and expands (point 3) to low pressure to generate power. The turbine exhaust is subsequently condensed into liquid in the air cooled condenser (point 4). The cooled liquid is again pumped (point 1) into the evaporator, and the cycle continues.

### 2.2. Description of three types of condenser

The condenser is an important component that influences the thermodynamic efficiency and economic cost of ORC. A newly developed enhanced condenser, LSC is used in ORC and compared with two other traditional condensers in terms of component cost and system efficiency.