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An organic Rankine cycle for two different heat sources: steam and hot water

Taehong Sung[a], Kyung Chun Kim[a,*]

[a]*School of Mechanical Engineering, Pusan National University, Busan 609-735, South Korea*

Abstract

Direct use of a steam heat source for the organic Rankine cycle system is one of the key challenges in various plant industries where low-grade steam is available and is becoming difficult as the parent system has a strong variability. In addition, changing the type of the heat source fluid among steam, hot water, thermal oil and others from the parent plant could increase the operation time of the heat recovery system, which increases system economics and makes it more attractive. Although a variety of ORC systems have been developed mainly using single heat source as hot water heat source or a heat transfer loop. An ORC system with the direct use of a steam heat source has been rarely reported, and a system using two different heat sources have not been reported yet. Here we evaluate the performance characteristics of an ORC system using two different heat source fluids: steam and hot water. The target ORC system was originally developed for the hot water heat source and has a simple cycle configuration with R245fa as working fluid, and is composed of typical four components as: a two-stage radial turbine and a coupled generator, plate-type heat exchangers with a refrigerant tank, and a multi-stage centrifugal pump. The nominal net power output at the design point is 187.9 kW with the turbine expansion ratio of 9.5. The heat exchanger analysis showed that the steam heat source can be applied to this system. The isothermal heat exchange and high heat transfer coefficient at the two-phase region of the steam showed a large overdesign for the current application. We tested the ORC system using a steam generated from an incineration plant. The temperature and pressure of the steam were 143.5°C and 302 kPa. We showed that the ORC system originally developed for the hot water heat source could be used for the steam heat source without any major system changes.

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Keywords: Organic Rankine cycle, site test, different heat sources, waste heat recovery

* Corresponding author. Tel.: +82 515102324; fax: +82 51557866.
E-mail address: kckim@pusan.ac.kr

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1. Introduction

In many energy consumption areas, the thermal efficiency has been improved up to its achievable maximum using available economic technologies [1]. However, there is still a room for further improvement using other technologies which are not fully mature yet or still uneconomic. Organic Rankine cycle (ORC) is one of the potential candidates for this purpose because ORC was already commercialized [2] and has a typical payback period of 6-12 years depends on the heat source temperature [3]. Energy price and application area can change the economics. About 40-90 ORC units were globally introduced every year [4]. However, the application area is limited to the field which can be operated stably. This is because the economic performance of the ORC system is a bit ambiguous to invest and is greatly influenced by operation hours and partial-load operation. When the ORC system is used as the main engine such as geothermal and biomass power plants, the operation hour is long and the system can be driven by almost full load so that the system has a sufficient economics to install. Some bottoming systems also have a good economic performance if the parent system shows a stable and patterned operation like ORC for a steel arc furnace and internal combustion engines for continuous power production. However, the waste heat does not occur only in stable sources. Therefore, it is needed to find a way to increase the economic performance by decreasing the system cost, improving the partial-load performance, increasing the operation hours and others.

The most fundamental factor for the economics is its initial cost which accounts for 70-80% of the total investment cost [5]. The ORC cost showed a power law tendency for the system size [6] but the cost has been unchanged recent time because the reduced cost of main components was offset by an additional cost from new regulations [7]. Energy price also plays an important role in the system economics, but they are not controllable. Maintenance cost is another important factor for the economics due to the high cost of mechanics and the production loss during the shutdown. Therefore, systems with less maintenance cycles are preferred. Financial cost has little impact on the system economics. In comparison, improving the total electricity production can be a key for the fine economics. ORC operated at partial-load by controlling the pump and turbine speeds but this not provides the exergy optimized operation. For optimum operation, it is necessary to control the system characteristics for the relation of the mass flow rate and pressure ratio, which mainly depends on the turbine. The turbine can be optimized for the fluctuating heat source [8]. A variable inlet guide vane can improve the partial-load performance [9]. Multiple expanders in parallel also provide a similar performance improvement in the partial-load condition [10].

In this study, we propose a new concept for improving system total electricity production: mixing different heat sources. In this system, the ORC system can continue to run changing the heat source depending on its availability. The heat source can be the same or different type. Considering chemical plants, we designed a system that can use both the pressurized hot water and the steam. The ORC system was designed for the hot water heat source and it was tested with a steam heat source.

2. The hot water ORC for the steam heat source

The proposed ORC system increases the operation hours by choosing one of the heat sources based on its availability. In this study, steam and pressurized hot water were used as the heat source options.

The ORC system, especially the evaporator, needs to be designed for one of the two heat sources. A system suitable for one heat source can be over-designed or under-designed for another heat source because steam and water have different heat transfer characteristics and coefficients. The optimal design of a system using various heat sources will require a thermoeconomic analysis considering a detailed state of the heat sources. We studied an ORC system designed for the hot water heat source (we call it as a hot water ORC or hot water mode) without considering the specific economics to investigate the technical feasibility of the concept. The hot water ORC can directly use the steam heat source (a steam ORC or steam mode) without an additional evaporator overdesign due to a high heat transfer coefficient of the phase change of the steam when a sufficient amount of the heat is supplied.

There are some considerations in steam mode because the steam has different heat transfer characteristics in the evaporator. First, the evaporator outlet temperature of the working fluid can be overheated beyond the acceptable limit due to the evaporator overdesign in the steam mode when a high-pressure steam (superheated steam) is supplied. Steam Rankine cycle systems, which have similar problems due to unstable steam flow from the boiler, are solving these problems by installing control valves at both the inlet of the evaporator for the steam and the outlet of the