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Research Paper

Experimental study on Organic Rankine cycle for low grade thermal energy recovery

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HIGHLIGHTS

- A small scale ORC experiment system for waste heat recovery was built and tested.
- A turbine expander without oil lubricant was coupled with a synchronous generator.
- R245fa and the environmentally friendly HFE7100 were selected as the working fluids.
- The influences of the operation parameters on overall system performance were discussed.

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ABSTRACT

A small scale Organic Rankine cycle experiment system capable of generating electric power using a low temperature heat source was built and experimental study was conducted. A single stage axial turbine expander coupled with a permanent magnet synchronous generator was used, where no lubricant oil was used. R245fa and the new environmentally friendly HFE7100 were selected as the working fluids in the experimental system. The influences of the evaporating pressure, pressure drop and mass flow rate on overall system performance were discussed. The maximum electric output generated by the turbine expander was 1979 W for R245fa, while the maximum electric power output was 1027 W for HFE7100.

1. Introduction

The world energy consumption had increased more than 40% in the last few decades [1], which caused seriously economic and environmental problems. More than 30–40% of fuel energy was wasted from the exhaust and just 12–25% of the fuel energy converted to useful work [2]. Research related to waste heat recovery has drawn increasing attention in recent years. Waste heat recovery not only reduces the demand of the fossil fuels, but also reduces the greenhouse gases and helps to provide a more sustainable environment for the future. It has been argued that low grade waste thermal energy, below 200 °C, represented a viable resource of a growing interest because of its abundance [3]. Organic Rankine cycle (ORC) is one of the promising low grade thermal energy recovery technologies due to its small scale and its potential integration in future distributed generation systems. ORC has been used to all kinds of low-temperature heat sources including geothermal energy, solar energy, waste heat energy and biomass energy [4].

It could be found from the literature that there are some experimental researches on ORC, but only a few on the evaporation temperature below 100 °C. Quoiin et al. [5] carried out experimental study on the ORC system which used R123 as the working fluid and a scroll expander, and reported an expander isentropic efficiency in the range of 42–68% under an expander pressure ratio of 2.7–5.4. Kang [6] conducted experiments to analyze the operational characteristics and performance of the ORC system by using a radial turbine. The results showed that the maximum average cycle, turbine efficiencies and electric power were found to be 5.22%, 78.7% and 32.7 kW, respectively at an evaporator temperature of 82 °C. An experimental investigation of an ORC power plant was carried out by Borsukiewicz-Gozdur [7]. R-227ea was used as the working fluid and the electric efficiency was around 4.88%. Lee et al. [8] investigated the dynamic behaviors of a 50 kW ORC system subject to the operating conditions of the condenser.

Some ORC systems combined with solar heating water system were investigated. Wang et al. [9] built a low temperature solar ORC system to investigate the performance of system with the typical weather using R245fa as working fluid. Both the evacuated solar collector and the flat plate solar collector were used in the system, and a rolling-piston expander was mounted in the system. They [10] also built another experimental system consisting of a flat plate

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collector, a throttling valve, a pump, an air cooled condenser and a regenerator to investigate the performance of a low temperature solar ORC system. They found that the introduction of a recuperator did not improve the ORC thermal efficiency obviously. Pei et al. [11] constructed a kW-scale ORC system with a turbine using R123 and a preliminary test on the constructed system showed that the ORC system electric efficiency was about 3.0%. In a solar cogeneration ORC with a scroll expander, a system efficiency of 3.47% was achieved at an output power of 676 W [12]. In order to remove the power consumed by the pump, Yamada et al. [13] used two scroll expanders with directional valves instead of a pump in the ORC, and a continuous power of 20 W was achieved.

Among these experimental studies, most expanders were scroll expanders or screw expanders, and only a few ORC systems were equipped with the generator. In fact, the expander and the generator were critical components in a relatively efficient and cost effective ORC system. Qiu et al. [14] reviewed various expansion machines, but no experiments and comparisons among different types of expanders were covered. Bao et al. [15] discussed the operation characteristics of all types of expanders. Cho et al. [16] designed a small-scale radial-type turbine and supersonic nozzles to regulate the fluctuation of the available thermal energy. Some researchers [6,14,15,17] argued that the turbo-expander was widely used for large-scale output power and the scroll expander was used for small-scale output power. Nevertheless, it was shown that the majority of the ORC expanders employed recently for ORC applications have suffered from key problems, mainly excessive working fluid leakage, thermal losses, low isentropic efficiency and high cost [5,18–20]. And the turbo expander offered many advantages, such as its compact structure, small size, stability, superior and efficiency, and the majority of commercial ORC plants use it [6,11,21]. In the present paper, a compact small scale turbo expander integrated with a synchronous generator was used in our ORC system. Due to the expander and generator built into a whole body, there is no leakage.

Many studies [15,22–24] showed the selection of working fluids was very important for the ORC system performance. Rayegan et al. [25] developed a procedure to compare the thermodynamic properties of working fluids under similar working conditions. Hung et al. [26] presented that slopes and shapes of the saturated vapor curves of the fluids primarily affected system efficiency by analyzing the effects of various working fluids. Aljundi et al. [27] analyzed the effects of using alternative dry fluids on the efficiency of the ORC and compared them with other refrigerants. Recently, research work [28] focused on analyzing multi-component mixtures of working fluids in order to better match the heat and cold sources.

In this experiment study, R245fa and HFE7100 were chosen as working fluids. R245fa was selected as a working fluid for its appropriate evaporation pressure, overpressure on the condenser and comparatively high thermal efficiency. HFE7100 was also chosen as the working fluid to be compared with R245fa. Tsai et al. [29] carried out an environmental risk assessment of Hydrofluoroether (HFE) fluids and concluded that Hydrofluoroether (HFE) fluids could be an applicable substitute to Hydrofluorocarbon (HFC) and hydrochlorofluorocarbon (HCFC) fluids in the ORC systems due to their environmental friendly aspect especially HFE7000, HFE7100, HFE7200 and HFE7500. Reid [30] carried out the experiment investigation on the use of HFE-7000 as a working fluid in a Rankine cycle under a low-grade heat source (100 °C). HFE7100 is clear, colorless, low odor and non flammable fluid with zero ozone depletion potential and very low global warming potential. Its boiling temperature is around 61 °C, larger than boiling temperature of R245fa which is at 15.3 °C.

In the present study, a compact small scale ORC system with a nominal 5 kW of electric power was constructed. A single stage axial turbine expander with an integrated turbine-generator design was used in the ORC system. A new environmentally friendly HFE7100 was also employed as the working fluid in the experimental investigation besides R245fa. The effect of evaporation pressure, pressure drop and mass flow rate on the overall ORC system performance was discussed. And the influence of R245fa and HFE7100 on the system performance was compared.

2. Experimental system and facilities

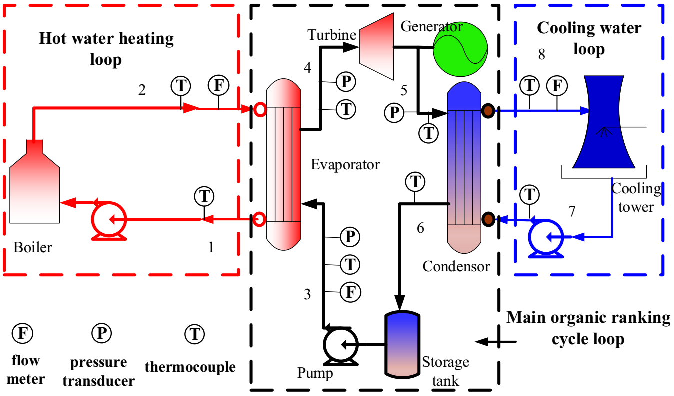
A schematic diagram of the ORC experimental system was given in Fig. 1. The system consisted of three main loops: hot water heating loop, cooling water loop and the main ORC loop. Fig. 2 showed the photographs of experiment apparatus.

2.1. Hot water heating loop

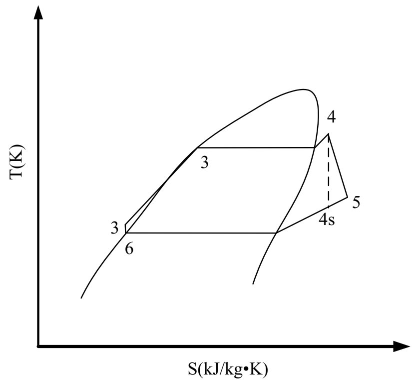
The external heat input source, three boilers fueled with diesel oil, provided heat input to the ORC system through supplying hot water to heat up the ORC fluid at the level of the system evaporator. The maximum temperature of water was controlled below 100 °C.

2.2. Cooling water loop

The counter flow closed circuit cooling tower was used in ORC system. It dissipated the heat load into the ambient air via a heat exchanger coil, which created two separate fluid circuits: an external circuit and an internal circuit. Spray water circulated over the coil and mixes with the outside air in opposite direction in the external circuit. The circuit cooling water circulated inside the coil in the internal circuit. During the cooling operation, heat went from



(a) Schematic diagram of the ORC system



(b) T-S diagram

Fig. 1. Schematic diagram of the ORC system and T-S diagram.