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Research paper

Design, construction, and preliminary results of a 250-kW organic Rankine cycle system

Ben-Ran Fu*, Yuh-Ren Lee, Jui-Ching Hsieh

Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Hsinchu 31040, Taiwan

HIGHLIGHTS

- A 250-kW ORC system using turbine expander was studied for waste heat recovery.
- The experimentally maximal net power output was 219.5 ± 5.5 kW.
- The experimentally maximal system thermal efficiency was 7.94%.
- The turbine isentropic efficiency was 63.7% with a rotational speed of 12,386 rpm.
- The system responded very rapidly as the heat source temperature changed.

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ABSTRACT

This study involved designing and constructing a 250-kW organic Rankine cycle system, consisting of a pump, preheater, evaporator, turbine, generator, condenser, as well as hot and cooling water circulation systems. Refrigerant R245fa was used as a working fluid. The design operating pressure levels of the preheater/evaporator and condenser was 1.265 MPa and 0.242 MPa, respectively. Under design conditions, the net power output was 243 kW and the system thermal efficiency was 9.5%. The preliminary experimental results under off-design conditions showed that the average net power output was 219.5 kW with a fluctuation of ±5.5 kW during prolonged operation. The maximal net power output and system thermal efficiency were 225 kW and 7.94%, respectively. Under this condition, the isentropic efficiency of the turbine was 63.7% with a rotational speed of 12 386 rpm, and the back-work ratio was 6.7%. In addition, the results of the dynamic testing demonstrated that the present system responded very rapidly as the heat source temperature changed. The experimental results also demonstrated that the system thermal efficiency and net power output increased linearly with an increasing heat source temperature. However, the effect of the heat source temperature on the turbine efficiency was not obvious.

1. Introduction

An organic Rankine cycle (ORC) is identical to a steam Rankine cycle, except that it employs organic fluids with a low boiling point as working fluids to generate power from low-temperature heat sources [1]. ORC is considered to be one of the most economical and efficient methods for converting low-grade thermal energy, such as that derived from waste heat recovery, geothermal and solar thermal sources, biomass combined heat and power (CHP), and ocean thermal energy into electricity [2,3]. Previous studies on ORCs have applied various perspectives and research tools, including conducting technical-economic-market surveys [1,4], developing methods for selecting working fluids [5], reviewing application of scroll expanders for ORC systems [6], evaluating waste heat recovery from a power plant [7], onboard ships [8], and at data centers [9], as well as proposing proof-of-concepts [10], optimal control strategy models [11], quasi-dynamic models [12]. In addition, relevant studies have assessed the effect of the optimal pinch-point temperature range of evaporators on system performance [13], conducted prototype testing [14–16], and performed statistical analysis of ORC-related patent data [17] and off-design performance analysis [18,19]. This section reviews several previous experimental studies on the ORC systems in detail.

* Corresponding author.
E-mail address: brfu@mx.nthu.edu.tw (B.-R. Fu).

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Nomenclature

E_{sys}	thermal efficiency of the ORC system (%)
E_{tur}	isentropic efficiency of the turbine (%)
m_W	mass flow rate of the hot water (kg/s)
s	mass specific entropy (kJ/kg K)
T	temperature (°C)
$T_{C,in}$	inlet temperature of the cooling water (°C)
$T_{C,out}$	outlet temperature of the cooling water (°C)
$T_{W,in}$	inlet temperature of the hot water (°C)
$T_{W,out}$	outlet temperature of the hot water (°C)
W_{net}	net power output of the system (kW)

Manolakos et al. [20] experimentally evaluated the performance of a low-temperature solar ORC system for reverse osmosis (RO) desalination using R134a as the working fluid and scroll expander. In their experiments, the expander had a maximal efficiency of 65%, power output of 2.05 kW, and ORC efficiency of 4%. In addition, Manolakos et al. [21] presented on-site experimental results of a solar ORC system combined with an RO system. However, the maximal efficiencies of the expander and the ORC system were approximately 45% and 1.75%, respectively.

Lemort et al. [22] and Quoilin et al. [23] have experimentally investigated an ORC prototype with an open-drive oil-free scroll expander and R123 as the working fluid. In their experiments, the maximal isentropic effectiveness of the expander was 68%, and the shaft work of the expander was between 0.4 and 1.82 kW. The maximal system efficiency was 7.4%. In addition, they determined that the deviation between the experimental and predicted results of the proposed model was only approximately 5%.

Wang et al. [24] reported on the experimental results of an on-site micro-scale solar ORC system using R245fa and R245fa/R152 mixtures as the working fluids. The maximal power output and ORC efficiency were 7.2 W and 5.59%, respectively. Their results demonstrated that the ORC efficiency was considerably improved by using R245fa/R152 mixtures rather than using pure R245fa.

Wang et al. [25] designed and constructed a low-temperature solar ORC system using R245fa as the working fluid and a rolling-piston expander. In their experiments, the average shaft power output and isentropic efficiency of the expander were 1.73 kW and 45.2%, respectively. They achieved a maximal ORC efficiency of 12.9%.

Pei et al. [26] experimentally examined a kW-scale ORC system using a turbine and R123 as the working fluid. The results showed that the isentropic efficiency of the turbine was 62.5%; the ORC efficiency was 6.8% at a temperature difference of 70 °C between the heat source and heat sink, and the power output was 1.36 kW.

Qui et al. [27] constructed and tested a micro-scale biomass-fired CHP system with an ORC. Their experimental results showed that the micro-CHP system with an ORC generated 0.861 kW and 47.26 kW in electricity and heat, respectively, and the corresponding efficiencies of the expander and ORC were 53.92% and 3.78%, respectively. Consequently, the overall biomass CHP efficiency was 78.69%.

Zheng et al. [28] proposed a kW-scale rolling-piston expander for a low-temperature ORC system using R245fa as the working fluid and conducted a running test of the proposed ORC system. The experimental results showed that the expander operated at 350–800 rpm with a maximal power output of 0.35 kW when the heat source temperature was below 90 °C. The maximal isentropic efficiency of the expander and cycle efficiency were 43.3% and 5%, respectively.

Declaye et al. [29] experimentally investigated an ORC system using R245fa as the working fluid and a scroll expander. They demonstrated a maximal isentropic efficiency of the expander and shaft power of 75.7% and 2.1 kW, respectively. A maximal cycle efficiency of 8.5% was reached at evaporating and condensing temperatures of 97.5 and 26.6 °C, respectively.

Twomey et al. [30] reported on the dynamic performance of a small-scale solar cogeneration system with an ORC using R134a as the working fluid and a scroll expander. The results demonstrated a maximal isentropic efficiency of the expander of 59% with a corresponding ORC efficiency of 3.47%. In addition, the maximal power output was 0.676 kW.

Hsu et al. [16] experimentally investigated the effect of inlet pressure and the pressure ratio in the expander on the performance of a 50-kW ORC system using a screw expander and R245fa as the working fluid. The results showed that for a given pressure ratio, higher inlet pressure resulted in both higher isentropic efficiency of the expander and higher system efficiency under an over-expansion condition, but resulted in lower isentropic efficiency of the expander and system efficiency under an under-expansion condition. In their experiments, the maximal power output was 50 kW and the system thermal efficiency was 10.5%.

Jradi and Riffat [31] experimentally examined a small-scale tri-generation system, consisting of an ORC-based (using a scroll expander and HFE7100 as the working fluid) CHP unit and a combined dehumidification and cooling unit. They demonstrated that this combined system provided approximately 9.6, 6.5, and 0.5 kW for heating, cooling, and electric power, respectively. Under a maximal electric power output condition, the isentropic efficiency of the expander was 74.2% and the corresponding cycle efficiency was 5.64%.

Avadhanula and Lin [32] proposed empirical models for a screw expander based on the experimental data of a 50-kW ORC system using R245fa as the working fluid. The experimental results showed that the pressure ratio, volume ratio, and power output of the ORC system were 2.70–6.54, 2.54–6.20, and 10–51.5 kW, respectively. In addition, their proposed models predicted the system power output accurately, namely within ±10% and ±7.5% of experimental values for the polytropic exponent model and isentropic work output model, respectively. The maximal isentropic efficiency of the expander was nearly 70%, but no information of the ORC efficiency was provided.

Klonowicz et al. [33] designed and constructed a small-scale turbine with a rotational speed of 3264 rpm for an ORC system using R227ea as the working fluid. In addition, they presented the numerical and preliminary testing results of the system. The experimental power output was 9.9 ± 0.2 kW, and the corresponding electrical efficiency was 53 ± 2%. However, the ORC efficiency was not provided. In addition, the predicted system efficiency exhibited a high consistency with the experimental result.

Chang et al. [34] experimentally investigated an ORC system with a scroll expander and R245fa as the working fluid. The maximal shaft power output and electricity power output were 1.74 and 1.375 kW, respectively, at a temperature difference of 60.6 °C between the heat source and heat sink. The maximal system efficiency of the ORC system was 7.77%.

Zhang et al. [35] reported on the experimental results of an ORC system with a single-screw expander and R123 as the working fluid for waste heat recovery from the exhaust of a diesel engine with a maximal horsepower of 336 kW. The results demonstrated that the maximal ORC power output was 10.38 kW. In addition, the ORC efficiency and overall system efficiency were 6.48% and 43.8%, respectively, resulting in 250 kW of diesel engine output. Using the ORC improved the overall efficiency of the diesel engine by approximately 1.53%.