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An experimental investigation on a recuperative Organic Rankine Cycle (ORC) system for electric power generation with low-grade thermal energy

L. Li[a], Y.T. Ge[a]*, X. Luo[b], S.A. Tassou[a]

[a]RCUK National Centre for Sustainable Energy Use in Food Chains (CSEF), Institute of Energy Futures, Brunel University London, Uxbridge, Middlesex, UB8 3PH, UK

[b]National Key Laboratory of Science and Technology on Aero Engines Aero-thermodynamics, The Collaborative Innovation Centre for Advanced Aero-Engine of China, Beihang University, Beijing, 10191, China

Abstract

In this study, a small-scale recuperative Organic Rankine Cycle (ORC) system capable of generating electric power using low-grade thermal energy was setup and experimentally investigated at different operating conditions. The experimental setup consisted of typical recuperative ORC system components, such as a turboexpander with high speed electricity generator, plate recuperator, finned-tube air cooled condenser, ORC fluid pump and plate evaporator. R245fa was used as the working fluid in the recuperative ORC system due to its zero ozone depletion potential (ODP) and appropriate thermophysical properties for ORC system. The working fluid was evaporated in a plate evaporator by hot thermal oil flow which was circulated and heated by exhaust flue gases of an 80kWe microturbine CHP unit. The test rig was fully instrumented and extensive experiments were carried out to compare and examine the influences of various important parameters including heat source temperature and ORC pump speed etc. on the performances of ORC systems with and without recuperator integration. The test results are essential in understanding the system operations and can contribute significantly to optimal system design, component selections and controls.

Keywords: R245fa recuperative Organic Rankine Cycle; recuperator; heat source temperature; ORC pump speed; system performance.

* Corresponding author. Tel.: +44(0)1895266722; fax: +44(0)1895256392.
E-mail address: Yunting.Ge@brunel.ac.uk

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1. Introduction

Globally, the extensive consumption of fossil fuels in different energy systems has been leading to severe problems including atmospheric pollution, excessive CO_2 emissions and energy resource shortages. Consequently, there is an urgent obligation to generate more power with low grade renewable energy such as biomass, geothermal, waste heat from power plants and industrial processes and applicable thermodynamic power cycles such as Organic Rankine Cycles (ORCs) [1]. The ORC technologies are based on the same operating principle of steam Rankine cycle for power generation, but instead organic working fluids such as R245fa are used in cycles. When applied into a low grade heat source, the system with ORC is expected to generate power with higher efficiency and more cost effectiveness than that of steam Rankine cycle [2].

From many studies, a recuperator is normally installed in an ORC system to save thermal energy from the heat source and thus increase the thermal efficiency of the cycle [3, 4]. However, when a low-grade heat source is applied, the feasibility of recuperator integration in an ORC system is dependent on a number of issues including types of working fluids, applications and operating conditions. The applicable ORC working fluids can be classified as wet, isentropic or dry based on respective shapes of saturated vapor [5]. For these ORC working fluids, different degrees of superheating are required if a recuperator is integrated in each ORC system. This will ensure some significant degrees of superheating at expander outlet so as to preheat liquid working fluid from pump outlet. These can be demonstrated by some previous research outcomes. When the superheats at evaporator were properly maintained and dry working fluids were applied, the ORC system thermal efficiencies could be greatly improved [6, 7]. Otherwise, even a dry ORC working fluid such as R236ea was used, the installation of a recuperator in the system could not improve the system performance under a given waste heat source condition [8]. On the other hand, as a different application, an experimental investigation was carried out on a low-temperature solar recuperative Rankine cycle system using working fluid R245fa and a flat plate collector was used as an evaporator to gather solar thermal energy [9]. The test results demonstrated that using a recuperator in the ORC system could not increase the system thermal efficiency. This was because the preheating by the expander exhaust through the recuperator lowered the solar collector efficiency and thus the overall system thermal efficiency. Another disadvantage of recuperator integration in an ORC system is the caused pressure increase at the expander outlet due to fluid pressure drop through the heat exchanger, which will affect negatively the expander efficiency. The pressure drop through the recuperator however is subject to the working fluid flow rate and therefore ORC pump speed and system operating states which need to be further investigated experimentally.

A review of the previous literature reveals that large information can be found on theoretical research of comparisons between basic ORC and recuperative ORC systems. However, the experimental comparisons for both systems need to be further investigated, especially in different operational and control parameters. These include the heat source temperatures and ORC liquid pump speeds. Accordingly, in this paper the construction and instrument of a small scale R245fa recuperative ORC experiment system were explained in which thermal oil and ambient air were used as heat source and sink respectively. The effects of recuperator installation, liquid pump speeds and heat source parameters on the expander and system performances were examined experimentally. The experimental investigation can provide a significant insight to understand the recuperative ORC system performances and therefore optimize the recuperative ORC system designs and operations.

2. Experimental facility and methodology

A schematic diagram with installed measurement instruments of a recuperative ORC test rig is illustrated in Fig. 1. The test rig comprised of a number of system main components including an 80 kWe CHP unit, oil pump, thermal oil heated plate evaporator, turboexpander with generator, plate recuperator, finned-tube air cooled condenser, liquid receiver, liquid pump, controls and data acquisition device etc. For a clearer demonstration, some photographs of the system and components were purposely selected and shown in Fig. 2.

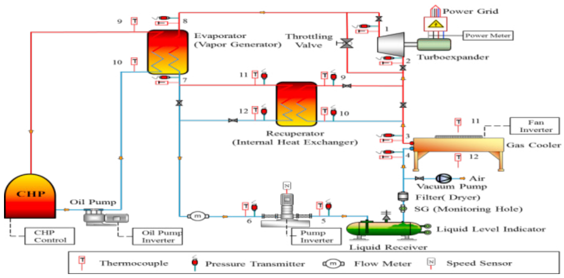

Fig. 1. Process flow diagram with the relative sensors position of a recuperative ORC test rig.

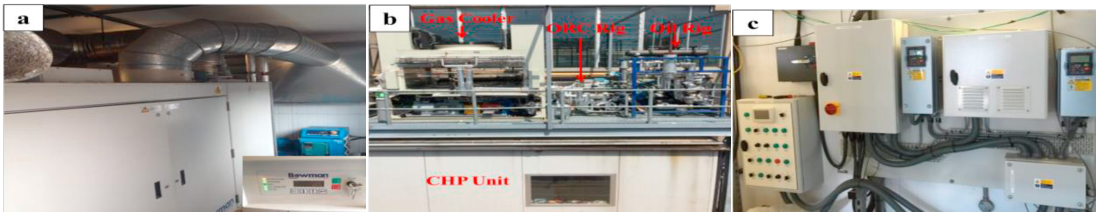

Fig. 2. Photographs of the system. (a) 80kWe CHP unit, (b) from view of whole system, (c)Recuperative ORC main control system.

The plate evaporator was heated indirectly by exhaust flue gases of the 80 kWe CHP unit (Fig. 2a) through a thermal oil circuit (Fig. 2b) and a thermal oil boiler installed inside the CHP exhaust. The thermal oil flow rate was controlled by a variable speed oil pump while its temperature was modulated by the CHP power output controls [10]. The turboexpander was integrated with a high speed and permanent magnet synchronous generator with rated rotation speed up to 18,000 rpm. The electricity power generated by the generator was connected and transmitted into the campus electric grid by means of a smart inverter and transformer. The smart inverter in turboexpander system, provided by ABB, allowed the generator speed to be monitored and matched with the electric power generated so that the turboexpander could operate safely. In parallel to the turboexpander, a by-pass valve was installed to bypass the R245fa flow completely when necessary. To examine the effect of recuperator integration in the ORC system, two two-way valves were installed respectively on both hot and cold sides of the recuperator. After the recuperator, a finned-tube air cooled condenser was installed. The air flow rate of the condenser was controlled by its variable speed fan while the air inlet temperature was modulated by mixing warm exhaust and cold ambient air flows through a number of recircular fans installed on two sides of the condenser outlet. The whole recuperative ORC control system is shown in Fig. 2c. In addition, the test rig was fully instrumented with calibrated sensors, flow and power meters, as shown in Fig. 1. The names, types ranges and accuracies of these instruments are also listed in Table 1.

Table 1. Range and precision of the main measurement instruments.

Measured Parameter	Device type	Measuring range	Accuracy
Mass flow meter	Twin tube type	0~6500 kg/h	±0.15%
Temperature	Type-K thermocouple	(-10)~1100 ºC	±0.5 ºC
Pressure	RPS	0~25bar	±0.3%
Pump rotation speed	Laser speed sensor	50~6000RPM	±0.75%
Electric power	Digital multimeter	1mW~8kW	±0.8%
Ambient air velocity	Hot wire anemometer	1.27~78.7m/s	±0.15m/s

3. Results and analysis

After the test rig was setup, a series of experiments were conducted to evaluate the performance of the ORC at different heat source (thermal oil) temperatures and running speeds of ORC pump for both scenarios of with and without recuperator. The thermal oil temperatures control range was between 135°C to 166 °C by modulating the CHP system power outputs, while the speed of the ORC pump was varied between 580 to 779 RPM by changing the pump motor frequencies. Meanwhile, the rest of control parameters were kept constant.

3.1. The effect of the heat source temperature swing

For this particular test, the effect of heat source (thermal oil) temperature on the ORC system performance was examined. The design parameters of the test are listed in Table 2.

Table 2. The operating conditions of thermal oil temperature swing for R245fa ORC systems with and without recuperator.

Recuperator of system In/Out	Oil temperature °C	Oil flow rate kg/s	R245fa pump speed RPM	Condenser air velocity m/s	Ambient air temperature °C
In	154~166	0.36	680	3.67	18.5
Out	135~160	0.65	680	3.67	17.0

For the system with recuperator, the temperatures of oil outlet, turbine inlet and outlet and evaporator inlet experienced increases along with higher heat source temperature, as shown in Fig. 3(a). However, the temperatures of condenser inlet and outlet, pump outlet did not change much. For the system without recuperator, the changes in temperature of evaporator and condenser inlets were exactly opposite, as shown in Fig. 3(b). In addition, the cycle point pressures and the pressure ratios of turbine inlet and outlet on both systems increased with higher heat source temperatures, as shown in Fig. 3 (c) and (d). The pressure ratios of the turbine in the system with recuperator were much lower than those in the system without recuperator.

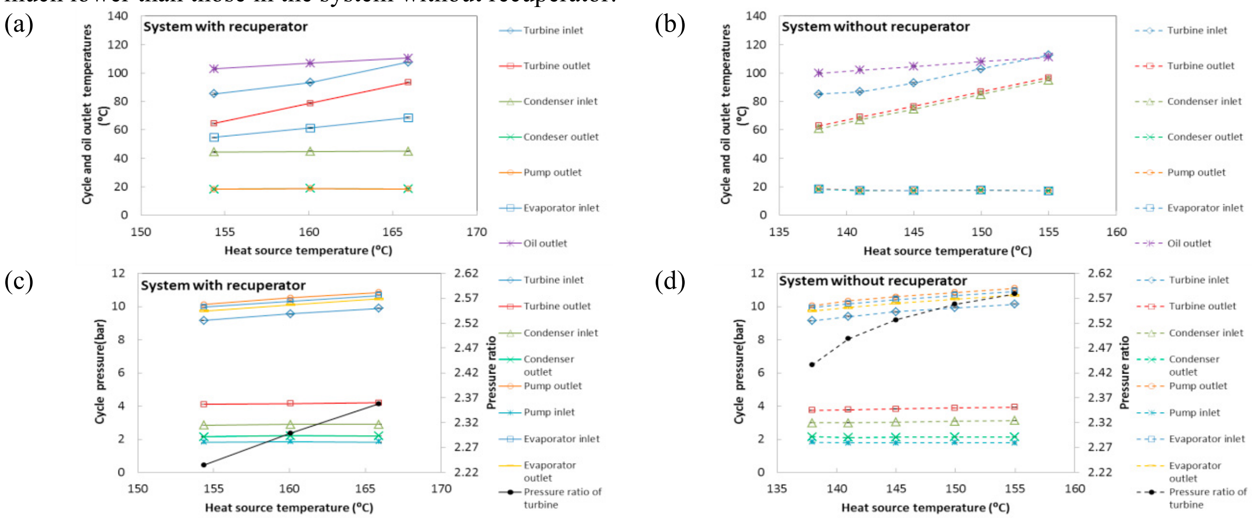

Fig. 3. Variations of cycle point and thermal oil outlet temperatures (a, b) and cycle point pressures and pressure ratios (c, d) with heat source (thermal oil) temperatures on system with and without recuperator.

To clarify, the efficiencies of the turbine isentropic (η_{is}), turbine overall (η_t), system thermal (η_{the}) and system overall (η_{over}) are defined and calculated as:

$$\eta_{is} = \frac{h_1 - h_2}{h_1 - h_{2,is}}\,;\ \eta_t = \frac{W_t}{\dot{m}_f (h_1 - h_{2,is})}\,;\ \eta_{the} = \frac{(h_1 - h_2) - (h_6 - h_5)}{h_8 - h_7}\,;\ \eta_{over} = \frac{W_t - W_{pmp}}{Q_{in}} \quad (1)$$

In the above equations, W_t (kW), W_{pmp} (kW) , $\dot{m}_f$ (kg/s) and Q_{in} (kW) are the measured turbine power generation, R245fa pump power consumption, R245fa mass flow rate and heat input respectively; the h is enthalpy (kJ/kg) and the subscript numbers correspond to the diagram in Fig 1 while "is" means isentropic expansion process.

For the system with recuperator, the turbine power outlet, ORC pump power input, evaporator heat input, condenser heat output, turbine isentropic and overall efficiencies and system thermal and overall efficiencies of both the systems increased along with higher heat source temperatures, as shown in Fig. 4. However, compared to the system without recuperator, the system with recuperator need to have much higher heat source temperatures.

(a) (b)

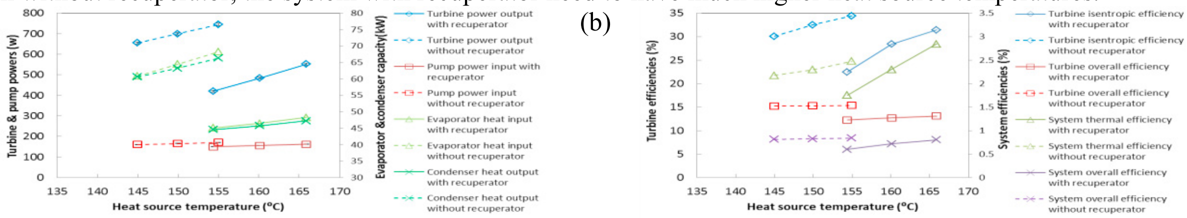

Fig. 4. Variations of turbine and pump powers and evaporator and condenser capacities (a) and turbine and system efficiencies (b) with heat source (thermal oil) temperatures on system with and without recuperator.

3.2. The effect of the ORC pump speed swing

As shown in Fig. 1, a liquid pump was installed after the liquid receiver. The pump speed could be controlled so as to modulate the ORC fluid mass flow rate and pressure at the turbine inlet. In order to examine the effect of variable pump speed on the system performance, a test matrix of the ORC pump speed swing was designed for the system. The parameters of the test matrix are listed in Table 3.

Table 3. The operating conditions of pump speed swings for R245fa ORC systems with and without recuperator.

Recuperator of system In/Out	Oil temperature °C	Oil flow rate kg/s	R245fa pump speed RPM	Condenser air velocity m/s	Ambient air temperature °C
In	156.1	0.366	580~731	3.67	18.0
Out	131.1	1.08	630~779	3.67	17.0

At higher ORC pump speeds for system with recuperator, the temperatures of thermal oil outlet, turbine inlet and outlet and evaporator inlet all experienced various decreases, but the temperatures at condenser inlet and outlet, and pump outlet experienced somewhat increases, as shown in Fig. 5(a). In contrast, the changes in temperatures of evaporator and condenser inlets on system without recuperator were exactly opposite, as shown in Fig. 5(b). In addition, the ORC mass flow rate and cycle point pressures all increased with higher ORC pump speeds, but the pressure ratios of turbine inlet and outlet were decreased in both systems, as shown in Figs. 5(c) and (d).

(a) (b) (c) (d)

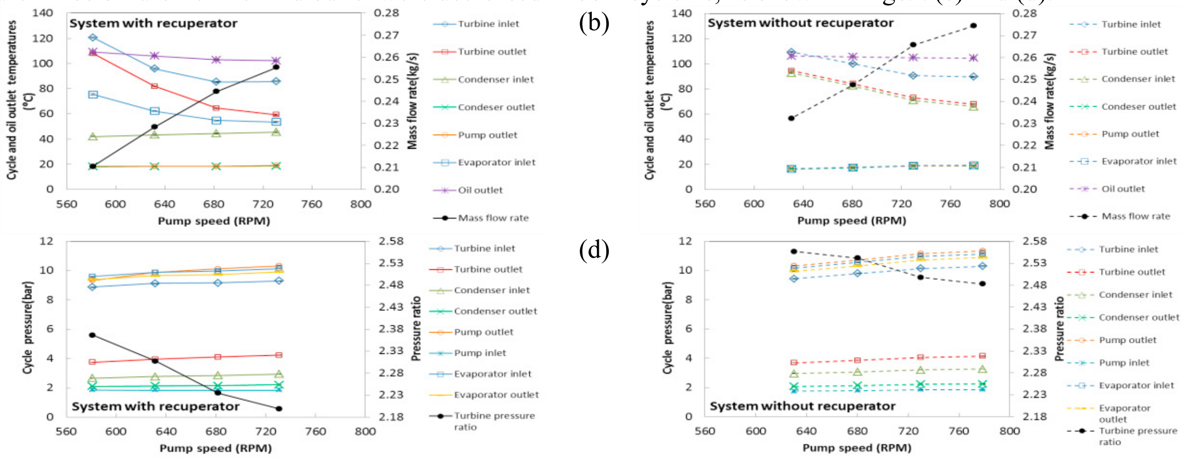

Fig. 5. Variations of cycle point, thermal oil outlet temperatures and ORC mass flow rates (a, b) and cycle point pressures and pressure ratios (c, d) with ORC pump speeds on system with and without recuperator.

At higher ORC pump speeds for the system with recuperator, the ORC pump power input, condenser heat output, evaporator heat input and turbine overall efficiency experienced different increases, but the turbine power output, turbine isentropic efficiency and system thermal and overall efficiencies experienced somewhat decreases, as shown in Fig. 6. Generally, the performance parameters for the system with recuperator were lower than those of system without recuperator. In addition, due to a larger pressure drop and thus a higher pressure at the turbin outlet in the system with recuperator, the pressure ratio was much lower than that of system without recuperator.

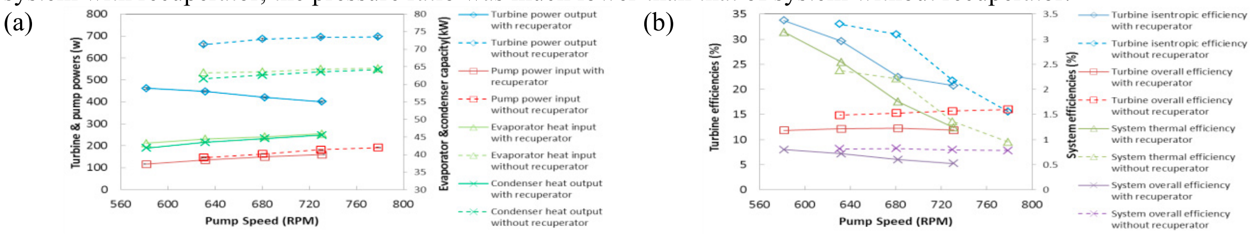

Fig. 6. Variations of turbine and pump powers and evaporator and condenser capacities (a) and turbine and system efficiencies (b) with ORC pump speeds on system with and without recuperator.

4. Conclusions

With the rapid development of economy and technology, as the most active factor of productivity, small scale recuperative ORC systems play an important role in the low grade industry waste heat recovery applications. However, the operation, control and optimisation of recuperative ORC systems and experimental comparisons between basic and recuperative ORC systems need to be further investigated. In this paper the utilization of industry waste heat by means of a small scale R245fa recuperative ORC system was studied with an experimental setup. The system was studied on the effects of two important operating parameters including heat source temperature and ORC pump speed. Also, the comparisons of experimental results between the recuperative ORC system and its basic form have been investigated. It was found that at a fixed working fluid speed and constant heat sink parameters, the performances of both the recuperative and basic ORC systems could be enhanced with increased heat source temperatures. However, due to the maximum working fluid temperature limitation at the turbine inlet, the heat source flow rates couldn't be maintained constants for both systems such that the temperature ranges were also varied. These led to less efficiency for the system with recuperator at those specific test conditions. The pressure drop from the recuperator had also contributed to the decrease of system efficiency. On the other hand, at a constant heat source and sink parameters, the higher R245fa pump speed could further reduce the thermal efficiency of both systems.

References

[1] Li L, Ge YT, Luo X, Tassou SA. Experimental investigations into power generation with low grade waste heat and R245fa Organic Rankine Cycles (ORCs). Applied Thermal Engineering. 2017;115:815-824.
[2] Badr O, Probert SD, O'Callaghan PW. Selecting a working fluid for a Rankine-cycle engine. Applied Energy. 1985;21:1-42.
[3] Colonna P, Casati E, Trapp C, et al. Organic Rankine Cycle Power Systems: From the Concept to Current Technology, Applications, and an Outlook to the Future. Journal of Engineering for Gas Turbines and Power. 2015;137:100801-100801-19.
[4] Li L, Ge Y, Luo X, Tassou S. Thermodynamic analysis and comparison between CO2 transcritical power cycles and R245fa organic Rankine cycles for low grade heat to power energy conversion. APPLIED THERMAL ENGINEERING. 2016;106:1290-1299.
[5] Saleh B, Koglbauer G, Wendland M, Fischer J. Working fluids for low-temperature organic Rankine cycles. Energy. 2007;32:1210-1221.
[6] Meinel D, Wieland C, Spliethoff H. Effect and comparison of different working fluids on a two-stage organic rankine cycle (ORC) concept. APPLIED THERMAL ENGINEERING. 2014;63:246-253.
[7] Mago PJ, Chamra LM, Srinivasan K, Somayaji C. An examination of regenerative organic Rankine cycles using dry fluids. Applied Thermal Engineering. 2008;28:998-1007.
[8] Dai Y, Wang J, Gao L. Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery. Energy Conversion and Management 2009;50: 576–582.
[9] Wang JL, Wang XD, Zhao L. An experimental study on the recuperative low temperature solar Rankine cycle using R245fa. Applied Energy. 2012;94:34-40.
[10] Ge YT, Tassou SA, Chaer I, Suguartha N. Performance evaluation of a tri-generation system with simulation and experiment. Applied Energy. 2009;86:2317-2326.