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Experimental study on a small-scale R245fa organic Rankine cycle system for low-grade thermal energy recovery

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Abstract

This work conducted an experimental investigation of a small-scale organic Rankine cycle (ORC) system at designed operating and control conditions for low-grade thermal energy recovery application. In the ORC system, R245fa was selected as working fluid while a turboexpander (turbine) with a high speed and permanent magnet synchronous electricity generator was installed to produce electric power and two-plate type heat exchangers were designed as an evaporator and condenser. The effects of condenser cooling water temperatures and R245fa superheat at the turbine inlet on the system performance were measured and analyzed. Practically, to ensure safe operation of the ORC expander, the R245fa superheat at the expander inlet is controlled to remain constant. The experimental results showed that at constant heat source parameters (temperature and flow rate), the turboexpander power output and cycle efficiency increased with lower cooling water temperatures. Under the specified test condition ranges, the maximum turboexpander power generation could achieve 5.405 kW when the cooling water temperature and the pressure ratio were set at 23.0°C and 7.3 respectively. On the other hand, at certain cooling water temperatures, the superheat at the expander inlet exerted a negative impact on the turboexpander and system performances when the evaporating pressure was kept constant. Ultimately, the superheat was found to be an important control parameter to ensure efficient and safe system operation.

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Keywords: R245fa organic Rankine cycle; turboexpander; heat sink temperature; superheat temperature

1. Introduction

In the last few decades, there has been extensive waste thermal energy discharged into the atmosphere in various forms of industrial waste or exhaust flue gases from engines and turbines. This is accumulating towards serious risks of global warming, environmental pollution and fossil fuel crises. Meanwhile, inexhaustible renewable energy such as solar, geothermal, biomass energies can be utilized around the

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world. Notably, these waste heat and renewable sources are categorized mostly into low grade thermal energy [1], with organic Rankine cycles (ORCs) being the most appropriate thermodynamic power cycles for their conversion into electricity [2, 3].

From many studies, selecting a proper organic working fluid for an ORC system is one of the important tasks for high efficiency operation, safety, low cost and smaller environmental impact etc. [4-6]. Nonetheless, it is difficult to find an ORC working fluid that can meet all of these criteria. Accordingly, four working fluids Benzene, Toluene, p-Xylene, R113 and R123 were investigated in an ORC system in terms of thermal efficiency and irreversibility. The results showed that p-Xylene had the highest thermal efficiency while R113 and R123 had the least irreversibility in recovering a low temperature thermal energy [7]. In addition, a mixture of working fluids has been studied in attempt to improve ORC system performance and reversibility for low grade thermal energy conversions [8]. The results indicated that the use of suitable zeotropic mixtures as working fluids may lead to better system performance. In terms of components, the expander is key for the ORC system, and can determine system efficiency and cost effectiveness. Therefore, various experimental investigations have been carried out to evaluate and compare system performance when different expanders were applied. Compared with the scroll [9] and screw [10] expanders, the turboexpander offered many advantages in terms of smaller size, compact structure, lower cost and higher efficiency [11, 12]. However, the turbine inlet superheat needs to be controlled to ensure its dry operation as it will affect system performance.

Subsequently, the effects of R245fa superheat controls at different operating conditions, especially at changed heat sink temperatures, need to be further investigated. Therefore, in this study, a small-scale R245fa ORC system experimental bench with a nominal $5kW_e$ power output was designed, fabricated and experimented. The effects of heat sink temperatures and superheat at the turbine inlet and system performance have been measured and analysed. The research outcomes have significant impact on ORC system design and control system optimization.

2. Experimental system and facilities

Schematic diagrams of the tested ORC system and its corresponding T-S diagram are shown in Fig 1(a) and (b) respectively. The test rig comprised mainly of an oil boiler, oil pump, plate evaporator, turboexpander with generator, water cooled plate condenser, liquid receiver, R245fa pump, water pump, cooling tower and individual control with data acquisition device etc. For a clearer demonstration, various photographs of system components were purposely selected and shown in Fig 2.

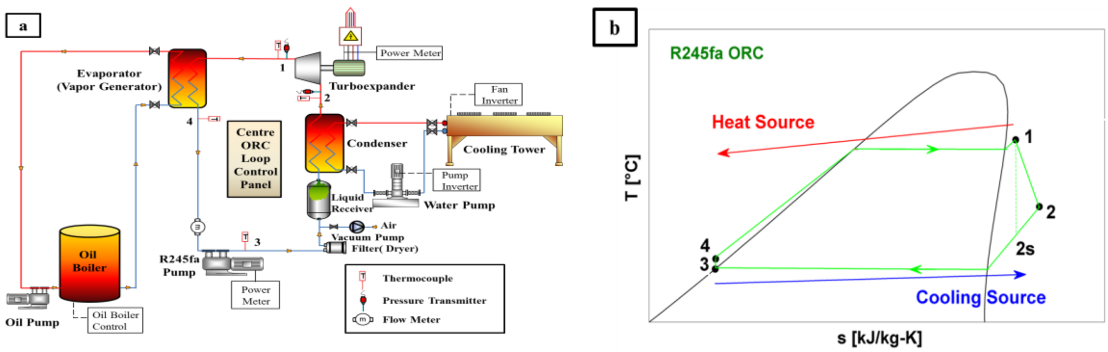


Fig. 1. (a) schematic diagram of the experimental system; (b) T-s diagram

Fig. 2. Photographs of ORC system components (a) oil boiler and the controller; (b) cooling tower; (c) turboexpander.

In the test rig, the heat source to the ORC system was from hot thermal oil flow through the evaporator, which was heated and controlled by the oil boiler and circulated by the oil pump. The ORC working fluid was then heated from subcooled state point 4 to superheated point 1 in Fig 1 (b). The high speed and permanent magnet synchronous electricity generator was driven by the superheated R245fa vapour flowing through a single stage axial turboexpander at a rated revolution speed of up to 18,000 rpm. Meanwhile the electricity generated by the generator was transmitted into the electric grid of the research workshop by means of a smart inverter and a transformer. The smart inverter provided by ABB allowed a generator speed matched and monitored by the electric power produced. In the plate condenser, R245fa low pressure superheat vapor from the turboexpander exit at state 2 was condensed to a subcooled liquid at state 3. The subcooled liquid was collected and stored in the liquid receiver and then pumped back by a diaphragm pump to the plate evaporator at state 4 to continue another operation cycle. The R245fa pump was connected with a frequency drive inverter to control its rotational speed and thus modulating the R245fa flow rate, evaporating pressure and superheat at the turbine inlet in the ORC system. For the heat sink loop, the condensing heat from the plate condenser was rejected to the cooling water which was thereafter cooled down by the integrated cooling tower. Three propeller air fans with variable speed controls were installed above the cooling tower and the cooling water temperature could be controlled by the different propeller air fan speeds.

To ensure efficient and safe operation, all the dedicated sensors and meters for measuring the temperatures, pressures, flow rates and electric powers were installed at various positions in the ORC system as shown in Fig.1 (a). All the signals were transmitted by an ORC system programmable logic controller to a computer for instant data logging. The controller was then able to dynamically modulate the ORC system parameters based on feedback signals in response to any changed external working conditions.

3. Results and discussions

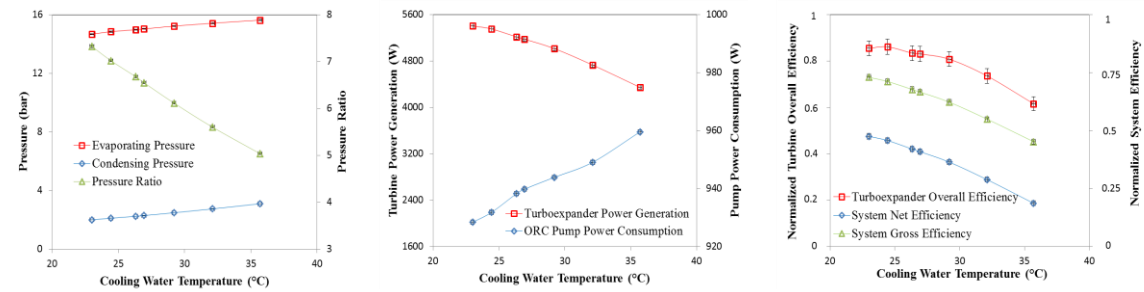
In order to achieve the targets, a test matrix as listed in Table 1 was planned to evaluate the performances of the turboexpander and ORC system at different heat sink temperatures and superheats at the expander inlet while thermal oil parameters (temperature and flow rate) and cooling water flow rate were both kept approximately constant. Due to the reliability and simplicity of the tested system, the stationary conditions are maintained for at least 20 min for all operating tests.

For the test swing of cooling water temperatures, when the thermal oil (heat source) temperature and flow rate were controlled constantly at 139°C and1.09kg/s respectively, the variations of condensing and evaporating pressures, turbine pressure ratio, turbine power generation, pump power consumption, turbine overall and system efficiencies were measured and shown in Fig 3 (a), (b) and (c).

Table 1. Test matrix for the R245fa ORC system

Test swing	Superheat at turbine inlet (K)	Cooling water temperature (°C)	Cooling water flow rate (kg/s)
Cooling water temperature	2.92	23-35.7	3.4
Superheat at turbine inlet	2.92-32.86	29.9	4.53

3.1. The influence of the heat sink temperature on system and turboexpander performances



(a) (b) (c)

Fig. 3 System and turboexpander performances with heat sink temperature

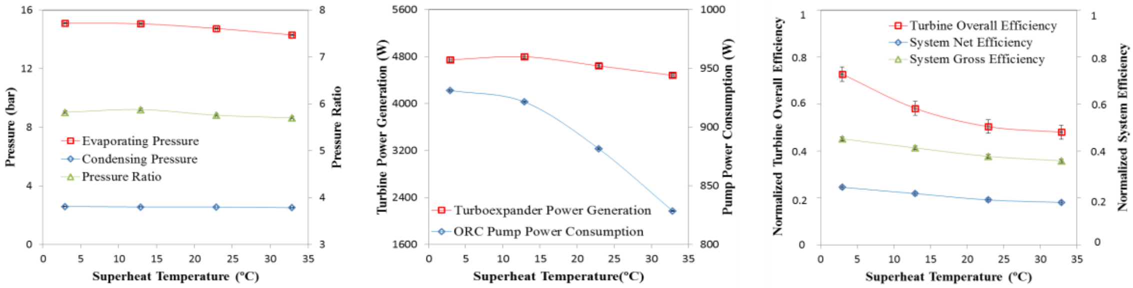
To clarify, the efficiencies of the turboexpander overall (η_t), system net (η_{net}) and system gross (η_{gro}) are defined and calculated as:

$$\eta_t = \frac{W_t}{\dot{m}_f (h_1 - h_{2,is})} \quad ; \quad \eta_{net} = \frac{W_t - W_{pmp}}{Q_{in}} \quad ; \quad \eta_{gro} = \frac{h_1 - h_{2,is}}{h_1 - h_4} \tag{1}$$

In the above equation, 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 T-S diagram in Fig1 (b) while 'is' means isentropic expansion process.

As depicted in Fig 3(a), the condensing and evaporating pressures both increased but the pressure ratio through the turboexpander decreased with higher cooling water temperatures. The increase of condensing pressure is due to the mechanism of heat transfer at the plate condenser. The higher cooling water temperature increases the condensing temperature and thus the condensing pressure. This will directly result in an increase in the turboexpander outlet pressure and affect turbine efficiency. As to the resultant higher evaporating pressure, this is due to the turboexpander characterisation and heat transfer mechanism at the plate evaporator (working fluid density change in the evaporator). The release resistance was increased when the turboexpander operated at a higher outlet pressure which would thus lead to an increased turboexpander inlet pressure. The higher evaporating pressure is equivalent to the higher evaporating temperature and working fluid density in the plate evaporator. However, the increased rate of the condensing pressure was larger than that of the evaporating temperature such that the pressure ratio decreased with higher cooling water temperatures. The lower pressure ratio would decrease the power generation from the turbine as shown in Fig 3(b). On the other hand, since R245fa is a dry working fluid, the higher evaporating temperature would increase the superheat at the evaporator outlet (turbine inlet). It is worth noting that pump speed was used to control the superheat. A higher superheat due to increased condenser cooling water temperature would need amplified pump speeds to maintain constant superheat. The higher pump speed would therefore increase the fluid mass flow rate and thus pump power consumption as indicated in Fig 3(b). Under the specified test condition ranges, the maximum turboexpander power generation could achieve 5.405 kW when the cooling water temperature and the pressure ratio were set at 23.0°C and 7.3 respectively. The decreased turbine power generation and increased pump power consumption with the higher cooling water temperature would further decrease the net power generation and therefore the system net efficiency (normalized), as depicted in Fig3 (c). Simultaneously, the reduced pressure ratio and turbine power generation resulted in a decrease in gross turbine and system efficiencies (normalized).

3.2. The influence of the superheat temperature on system and turboexpander performances



(a) (b) (c)

Fig. 4 System and turboexpander performances with superheat temperature

For the test swing of superheat at the turbine inlet, when the thermal oil (heat source) temperature changed from 137°C ~142°C and flow rate was controlled constantly at 1.09kg/s, the variations of condensing and evaporating pressures, turbine pressure ratio, turbine power generation, pump power consumption, turbine overall and system efficiencies were measured and shown in Fig 4 (a), (b) and (c).

As depicted in Fig 4(a), the constant condenser cooling water temperature and flow rate led to nearly constant condensing temperatures or pressures considering the heat transfer mechanism of condenser. To increase the superheat at the turbine inlet, the R245fa pump speed had to be lowered, which would thus lead to decreased evaporating pressure and pump power consumption as shown in Fig 4(a) and (b) respectively. As depicted in Fig 4 (a), the decreased evaporating pressure would decrease the pressure ratio of turbine when the superheat increased. Similar trends could be found for the turbine power generation to turbine pressure ratio with a superheat increase, as demonstrated in Fig4 (b). The decreased turbine power generation and reduced R245fa pump power consumption with higher superheat at turbine inlet would cause a slight reduction in the net power generation of the system. However, the increased heat source (thermal oil) temperature from 137°C to 142°C needed greater heat input to the system, which could therefore further reduce system net efficiency(normalized), as shown in Fig 4(c). Similar to Fig 3(c), the decreased pressure ratio and turbine power generation caused the decreased turbine overall efficiency (normalized) and the system gross efficiency (normalized).

4. Conclusions

There are many low-grade industrial waste heat and renewable energy sources worldwide that can be utilized to generate power so as to diminish extensive consumption of fossil fuels. An organic Rankine cycle (ORC) with working fluid of R245fa is now commonly used in low-grade power generation systems. An expander is an important component in an ORC system and can assume many different types including turbine, scroll, reciprocating or screw. When a turbine is utilized in an ORC system, a dry inlet condition or some extent of superheat at the turbine inlet needs to be controlled to protect turbine operation. This can be achieved by modulating the ORC pump speed at different operating conditions.

The superheat controls however could affect the system and turbine performances which were investigated experimentally by this paper on a small-scale ORC test rig and the following research outcomes were obtained:

- At constant heat source parameters (temperature and flow rate), superheat at turbine inlet and condenser cooling water temperature, both condensing and evaporating pressures and ORC pump power consumption increased with higher condenser cooling water temperatures. Meanwhile, the increased cooling water temperature led to a decreased pressure ratio of turbine, turbine power generation, turbine overall efficiency, system gross and net efficiencies.
- At constant heat source flow rate and heat sink parameters (temperature and flow rate) but increased heat source temperatures, the condensing pressure remained almost unchanged with increased superheat at the turbine inlet. Simultaneously, the increased superheat at the turbine inlet would decrease the evaporating pressure, pressure ratio of turbine, turbine power generation, pump power consumption, turbine overall efficiency and system net and gross efficiencies.

Ultimately, to improve system and turbine efficiencies and ensure safe operation, both superheat at turbine inlet and condenser cooling water temperature need to be controlled or maintained as low as possible.

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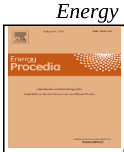

Biography

Dr. Yunting Ge is a Reader in the College of Engineering, Design and Physical Science at Brunel University London. Dr. Ge has 20+ years of research, application and development experience in refrigeration, energy conversion technologies and built environment controls and has published over 80 research papers in these fields.