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Design and parametric study of an Organic Rankine cycle using a scroll expander for engine waste heat recovery

Yiji Lu[a,*], Anthony Paul Roskilly[a], Andew Smallbone[a], Xiaoli Yu[b], Yaodong Wang[a]

[a] *Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle NE1 7RU, UK*
[b] *Department of Energy Engineering, Zhejiang University, Hangzhou, 310027, China*

Abstract

This paper reports the design and investigation of a small scale Organic Rankine cycle using a targeted scroll expander to recover both coolant and exhaust energy from a diesel fuelled internal combustion engine. The designed system could potentially be used to recover both the heat source energy into electricity using simple control of the mass flow rate of the working fluid. Results indicated that under the optimal conditions this ORC system can generate 1 kW power under the full load operational condition of a 6.5 kW engine. Moreover, the corresponding rotation speed of the scroll expander is about 4000 rpm, which means the expander could be adapted with conventional generator to produce electricity at relatively reasonable cost.

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Keywords: Organic Rankine cycle, Scroll expander, Engine waste heat recovery, Coolant and exhaust energy

1. Introduction

The Organic Rankine cycle (ORC) has been widely recognized as one of the most promising technologies to improve the overall energy efficiency and reduce CO_2 emissions of the Internal Combustion Engine (ICE) [1]. A well designed ORC waste heat recovery system recovering exhaust energy of the ICE can be developed with around 2 to 5 years payback period through fuel saving [2, 3]. Several researchers pointed out the coolant energy contains about 30% of the fuel energy, which could be potentially utilized in the ORC waste heat recovery system of the ICE to improve the ORC system efficiency and reduce the payback period of the overall cost with a proper designed system [3-5]. However, the available heat loads from the coolant and exhaust systems are variable over the various operational conditions of the ICE, this requires the development of advanced control strategy to balance two heat sources or result to complex design of ORC system such as a dual-loop ORC system [6-9]. Therefore, the parametric study of the ORC system to recovery both coolant and exhaust energy under various ICE operational conditions is important to optimal system performance and selection of system components. Moreover, the selection of expansion machines is critical for the ORC system performance [1]. For small scale applications, scroll expanders are recognized as the optimal expansion candidate because of its high reliability, relatively high isentropic efficiency and

* Corresponding author. Tel.: +44 (0) 191 208 4827
E-mail address: yiji.lu@ncl.ac.uk; luyiji0620@gmail.com (Y. Lu)

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broad availability [10-13]. In this study, the design of a small scale ORC waste heat recovery system using a targeted scroll expander to recovery both coolant and exhaust energy from ICE is reported. The parametric study on the ORC system under variable heat source ratio of coolant and exhaust energy from the ICE using a targeted scroll expander has been conducted in order to evaluate the performance and provide essential data for the selection of components.

2. Design of the system

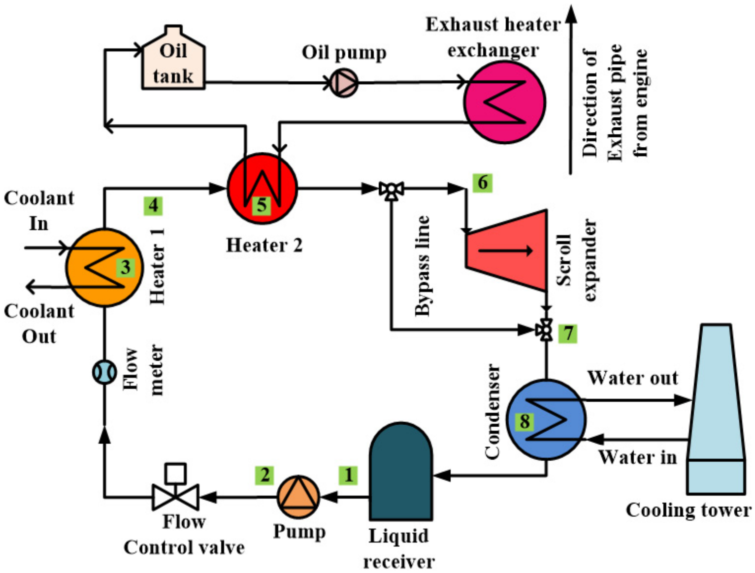


Fig. 1. Schematic diagram of the ORC system

The ORC system employed here includes two heaters, a scroll expander, condenser, liquid receiver and pump as shown in Fig 1. The coolant water from the ICE is supplied to Heater 1, which heats up the working fluid in two phase condition. The energy from the exhaust is recovered using a heater exchanger located on the exhaust pipe. Thermal fluid is used to transfer the exhaust energy from exhaust heater exchanger to Heater 2, where the working fluid is heated up to the designed working condition to start the expansion process inside the scroll expander. Because the existing of liquid fluid flows into the scroll expander will damage the expansion machine, a bypass line is designed to protect the expander when the desirable working conditions have not been reached. The exhaust heat of the scroll expander is rejected to the environment through the condenser, which is connected to a cooling tower. A liquid receiver is located at the inlet of the pump in order to maintain sufficient liquid ORC working fluid pumped to the ORC system.

The working conditions of the ORC working fluid can be represented by the $T-s$ diagram as indicated in Figure 2. The pump firstly pumps the working fluid from point 1 to point 2, which is an isentropic process. The heater 1 recovers the heat from the coolant energy while the heater 2 recovers the heat from the exhaust energy, which can be represented as process 2-4 and process 4-6, respectively. The evaporating temperature of the working fluid is designed at 80 °C to meet the heat source temperature of the coolant energy. The working conditions of the working fluid at the inlet of the expander start from the vapour saturated line to superheated region. The expansion process inside the expander is shown as line 6-7 as isentropic expansion process. The working fluid selected in the system is R245fa, which is a type of dry working fluids and can effectively prevent the ORC working fluid reaches two phase condition inside the expansion machine to protect the expander.

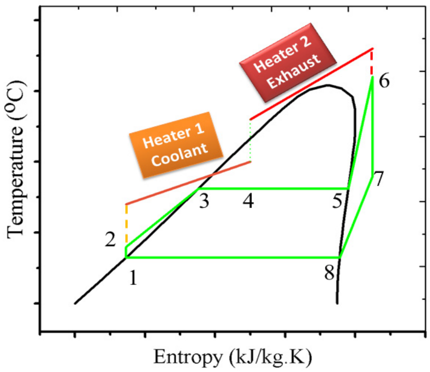


Fig. 2. $T-s$ diagram of the ORC system

3. Methods and case study

A 6.5 kW YANMAR ICE with the model number YTG6.5S is selected in this study. Ringler et al. pointed out that the ratio of the recoverable heat from the coolant and exhaust energy ranges from 1.5 to 0.5[14]. The previous study of the authors and other researchers study also support this point [6-9, 15, 16]. The recoverable wasted heat of this ICE can therefore be plotted as Fig 3, which has considered the real experimental results obtained by Yu on the 6.5 kW YANMAR ICE under 10%, 25%, 50%, 75% and 100% load @ 2400 rpm[17].

In the ORC system, heat provided to Heater 1 can be calculated by

$$\dot{Q}_{Heater1} = \dot{m}\cdot(h_4 - h_2) = \dot{Q}_{coolant}\cdot\eta_{Heater1} \qquad (1)$$

Heat provided to Heater 2 can be written as,

$$\dot{Q}_{Heater2} = \dot{m}\cdot(h_6 - h_4) = \dot{Q}_{exhaust}\cdot\eta_{Heater2} \qquad (2)$$

The efficiency of all the heat exchangers ($\eta_{Heater1}, \eta_{Heater2}$) is set at 80%.
The mass flow rate is defined by,

$$\dot{m} = \frac{N}{60}\cdot\frac{V_{SV}}{v_{su}} \qquad (3)$$

where N is the rotation speed, V_{SV} is the swept volume of the targeted scroll expander and v_{su} is the specific volume at the inlet of the expander.

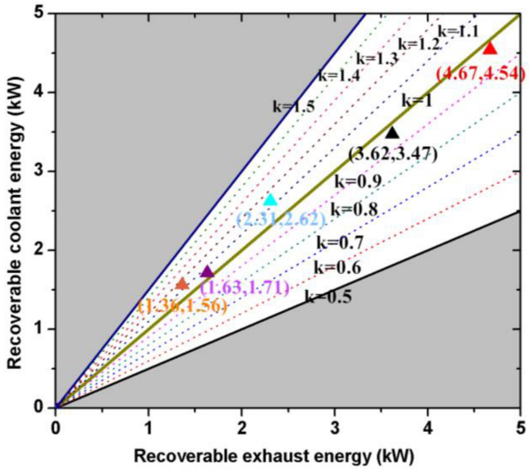


Fig. 3. Recoverable coolant and exhaust energy from a 6.5 kW Yanma engine

$$\dot{W} = \dot{m}\cdot\left[(h_{su} - h_{d\_s}) + (P_{d\_s} - P_{ex})\cdot v_d\right] = \dot{m}\cdot(h_6 - h_7)\cdot\eta_{expander} \qquad (4)$$

The power obtained from the scroll expander can be written as equation (4)[12], where h_{su} is the specific enthalpy at the inlet of the scroll expander, h_{d_s} is the designed exhaust specific enthalpy of the scroll expander after isentropic expansion process.

In order to calculate the designed condition of the scroll expander such as swept volume and volume expansion ratio, a geometric study of the scroll of the expander has been conducted. The comparison of the shape obtained from the geometric model and the real picture of the fixed scroll of the expander has been indicated in the center of Figure 4. The working principle of the scroll expander during the expansion process under four different crank angles is shown in Figure 4. The physical parameters of the geometric model and calculated parameters such as swept volume and volume expansion ratio of the scroll expander have been listed in Table 1.

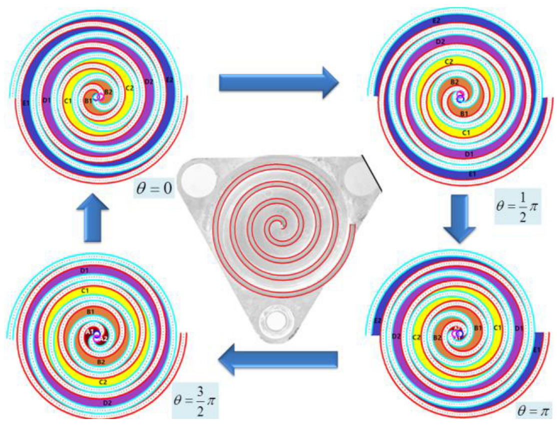


Fig.4. Expansion process of the scroll expander under different crank angle

The mass flow rate of the designed ORC system has a linear relationship with the coolant energy of the ICE, which has the benefit of easily control of the system to meet various heat source ratio of the two heat source energy. When the coolant/exhaust heat ratio is 1.5, the working condition at the inlet of the expander is on the vapor statured line. And with the increase of exhaust energy the condition at the inlet of the expander moves to superheated region.

The working condition of the point 4 can therefore be calculated by equation (5).

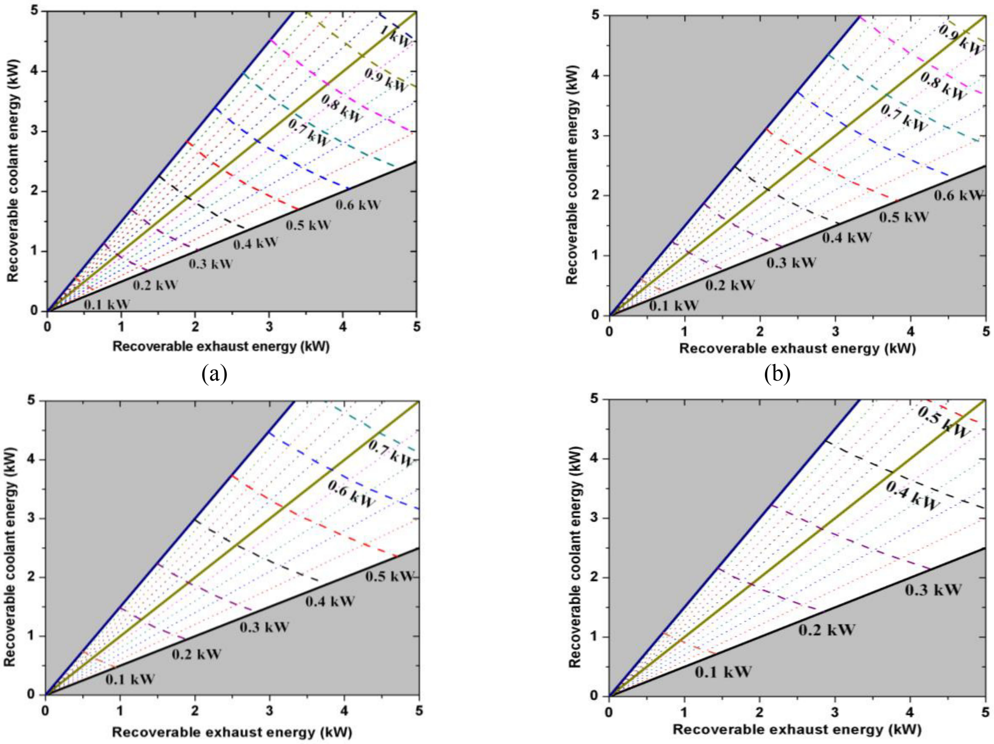
$$(h_4 - h_2)/(h_5 - h_4) = 1.5 \quad (5)$$

Table 1
Parameters of the scroll

Name	Value
Scroll height	22.4 mm
Scroll turns	4
Radius of gyration	3.0 mm
Radius of the basic circle	2.23 mm
Thickness of the scroll	4.0 mm
Pitch of the scroll blade	14.0 mm
Start angle of the involute	51.43 ^{o}
Swept volume	11.82 cm^3

4. Results and discussion

The thermodynamic analysis of the designed ORC system has been conducted and the power theoretical achieved from the system under various coolant/exhaust energy ratios when four different heat sink temperatures are plotted in Figure 5. Results indicate that the highest power obtained from this waste heat recovery system is about 1 kW when the heat sink temperature is at 20 ^oC. When this system is used in some places the heat sink temperature is quite high, the ORC system could produce about 0.5 kW at the full load condition of the 6.5 kW ICE.



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

Fig. 5. Evaluation on power performance of the ORC system under various coolant/exhaust heat ratio where the heat sink temperature at (a) 20 ^oC, (b) 30 ^oC, (c) 40 ^oC, (d) 50 ^oC

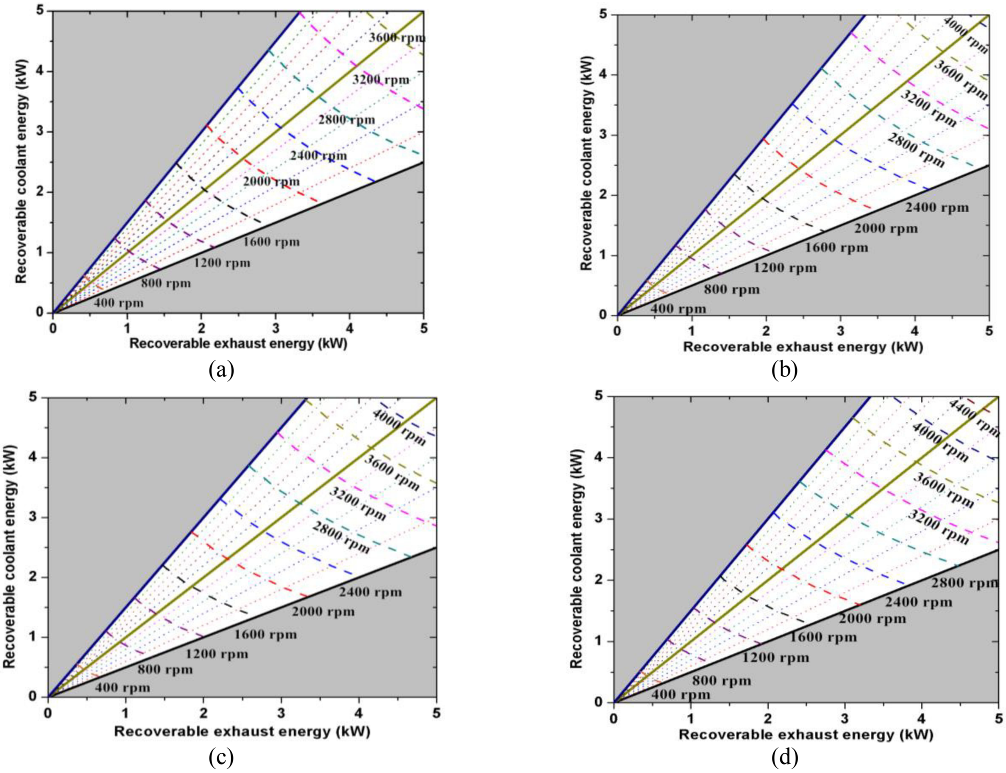


Fig. 6. Evaluation on rotation speed of the scroll expander of the ORC system under various coolant/exhaust heat ratio where the heat sink temperature at (a) 20 ^{o}C, (b) 30 ^{o}C, (c) 40 ^{o}C, (d) 50 ^{o}C

The relationship between the rotation speed of the targeted scroll expander under various coolant/exhaust energy ratio of the 6.5 kW ICE are drawn in Figure 6, when the heat sink temperature are at 20 ^{o}C, 30 ^{o}C, 40 ^{o}C and 50 ^{o}C. The results show the highest rotation speed of the scroll machine is about 4000 rpm, which means the designed ORC system can potentially use this scroll machine to be integrated with conventional generator to produce electricity rather than use high speed generator. The cost of this designed ORC system can be relatively lower than the ORC system using a turbine type of expansion machine, which requires a special made high speed generator to produce electricity.

5. Conclusions

In this study, the design of a small scale ORC waste heat recovery system to recovery both coolant and exhaust of a 6.5 kW ICE has been reported. The evaluation of this proposed waste heat recovery system using a targeted scroll expander as the expansion machine under various coolant/exhaust heat ratio of the ICE has been conducted in order to provide the parametric data of this system. Results indicate that the system can potentially produce 1 kW power at the ICE full load condition when the heat sink temperature is at 20 ^{o}C. The rotation speed of the scroll expander under the designed conditions were evaluated and the highest rotation speed of the scroll expander is around 4000 rpm, which means the scroll expander could be easily adapted with conventional generator to produce electricity under the designed condition to recover both coolant and exhaust energy from the ICE. Further optimization study, experimental investigation on the rig and economic analysis of the ORC system for the waste heat recovery from ICE are essential and will be reported in the future.

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Biography

Dr Yiji Lu, born in June 1989, is currently a research associate in Newcastle University. He graduated from Shanghai Jiao Tong University in 2011 for his bachelor degree, he conducted his M.Phil. and Ph.D. in Newcastle University in 2012 and 2016. His Ph.D. program was fully sponsored by EPSRC and was awarded the '2015 Chinese Government Award for Outstanding Self-financed Students Abroad' from China Scholarship Council. His research interests include but not limited to advanced waste heat recovery technologies, engine thermal management, chemisorption cycles and expansion machines for power generation system. He has been regularly invited to review the manuscripts for the scientific journals including Applied Energy, Applied Thermal Engineering, Energy (the international Journal), and Energy for Sustainable Development.