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ORC units driven by engine waste heat – a simulation study

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Abstract

ORC (organic Rankine cycle) technology is promising in industry for utilizing low-grade heat to generate electricity. It is acknowledged that in an internal combustion engine, only a small amount of primary fuel energy can be effectively used for the power generation, and the other part of the energy lost through exhaust gas, cooling of elements and overcoming friction. The heat in exhaust gas and cooling system (jacket water) can be used as a heat source to drive ORC units for power generation. In this way, the energy lost can be recovered to generate extra power. In this study, Ricardo Wave software was used to investigate the amount of waste heat available from a 1-cylinder diesel engine and THERMOLIB toolbox in SIMULINK was used to simulate and evaluate the performance of a small ORC unit designed for the application. The simulation results from the engine and ORC models were validated against experimental data from other researchers. Two different heating methods to the ORC were used: a) directly driven by the exhaust gas and jacket water (EG-JW); b) thermal oil (TO) was used to collect the waste heat from the engine exhaust gas; the heated thermal oil together with jacket water were then used to drive the ORC. It was found that the performance of the ORC was improved and it was more stable when using TO under different engine running conditions than that directly driven by EG-JW.

Keywords: engine; waste heat; ORC; simulation; thermal oil.

1. Introduction

Waste heat recovery is a popular topic nowadays because of energy crisis and environment issues. ORC is a common technology in recovering low-grade heat. Compared with the traditional Rankine cycle, the choices of working fluids for ORC are multitudinous, such as halocarbon and hydrocarbon refrigerants. ORC systems with different configuration are widely used in industry. Because the required temperature of the heating source of ORC is relative low, it is promising to utilize various natural low-temperature heat resources and industrial waste low-grade heat. The natural heat source for ORC can be solar heat, underground geothermal heat, direct combustion of biomass as well as engine exhaust gas. Solar energy based ORC systems adopt concentrating solar power (CSP) technology to supply heat for ORC. The conversion (from solar to electrical power) efficiency can reach 6.2% utilizing R245fa as working

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fluid [1], and the generated electricity can meet around 32% of the electricity demand of a typical UK family. Masheiti, S.et al [2] used IPSEpro software to simulate ORC powered by geothermal source and compared the performance of different actuating mediums. The results showed that R245fa had better performance than R134a and it was found that in the evaporator, the pinch temperature difference of R245fa was higher than that of R134a. The heat from biomass incineration can be utilized in some CHP (combined heat and power) plants, and because of abundant resources of biomass, they are cost-effective. Due to the primary energy utilization factors of internal combustion engines are restricted by their cycles, more than 60% of the energy from the combustion of the fuels are wasted in the form of waste heat in exhaust gas and cooling water. Therefore, ORC systems are valuable to utilize the waste heat from engines to save energy and improve the overall thermal efficiency of the engines. The temperature of engine exhaust gas increases with the rise of engine loads, and elevated temperature may damage many refrigerants because most of them have a relative low decomposition temperature. Thermal oil(s) can be used in ORC [3] to protect the working fluid from decomposition by collecting and storing heat from engine exhaust gas and keep the temperature under designed and controlled ranges. In this way, the ORC system can be operated stably in different engine conditions. Although there is numerous research in this area, there is not an ORC system which can be used in practice. Therefore, it is necessary to carry out further research into this area. The aim of this study is to investigate the performance of an ORC unit designed and used to harvest the waste heat from a diesel engine generator, using R245fa as the working fluid and driven by waste heat from the engine cooling water and exhaust gas directly and indirectly by thermal oil.

2. Methodology
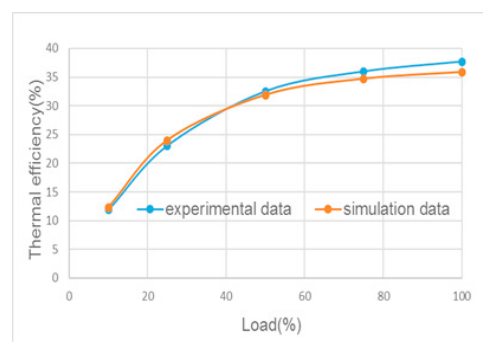
2.1. Engine modelling and model validation

An investigation into available waste heat in cooling water and exhaust gas from a diesel engine (YANMAR TF120M) was carried out in this study. The engine model was built in Ricardo Wave, 1-D engine simulation software and it is developed by Ricardo Company and can be used for gas dynamics simulation. The YANMAR engine simulated is a 1-cylinder diesel engine with a fixed engine speed of 2400 r/min. The main parameters of the engine are shown in Table 1. The modelling of the engine includes module selection, connection and parameters setting. The core module of an engine model is cylinder junction and the main engine parameters can be set in the cylinder panel. Besides, a diesel Wiebe combustion model and a Woschni heat transfer model were applied in the process of modelling. There are five engine loads set for the engine model to run, i.e. 10%, 25%, 50%, 75% and 100% engine loads. The simulation results from Wave software were validated against experimental data from our Swan Centre as shown in Fig.1.
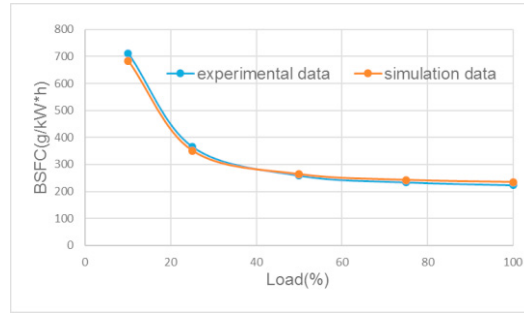
Table 1. Engine parameters.

Bore	92 mm	Fuel consumption	2.8 litres per hour
Stroke	96 mm	Displacement	0.638 litres
Cooling system	Radiator	Fuel type	Diesel
Continuous power output	10.5 hp/7.72 kW	Rated output	12 hp / 8.82 kW
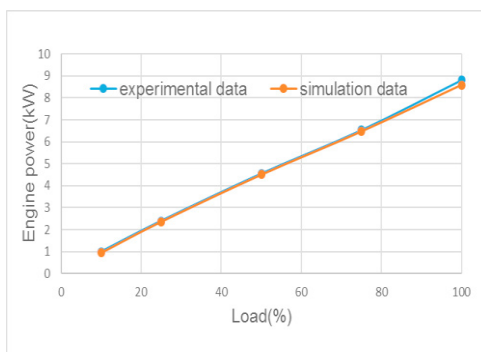
(a)

(b)

(c)

Fig. 1. Engine model validation: (a) Engine power; (b) Thermal efficiency; (c) Brake specific fuel consumption (BSFC).

2.2. ORC model validation

THERMOLIB is a thermodynamic process simulation software or toolbox in SIMULINK/MATLAB which includes many blocks with various functions. It has an addible database containing chemical and physical properties of different substances to support process simulation. The software was used to simulate ORC systems in this study. The amount of heat in cooling water and exhaust gas from the engine simulation results was used as the heat that the ORC system can achieve from the engine. Before constructing the ORC powered by engine waste heat, the model was validated to provide a reliable ORC model. The ORC system is shown in Figure 2. It had two heat exchanger blocks, a turbine block and a pump block and refrigerant R245fa was selected as working fluid.
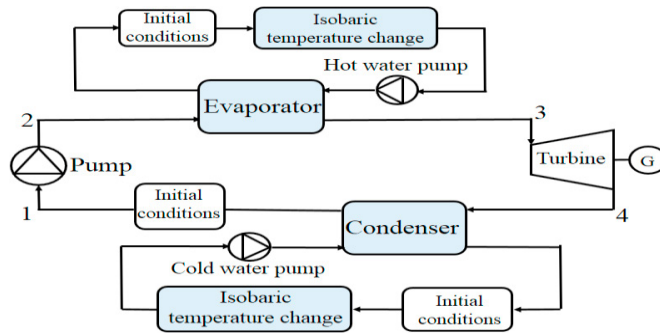

Fig. 2. The ORC model in THERMOLIB for validation.

Table 2. Model validation.

Parameters	Data from paper	Simulation data	Parameters	Data from paper	Simulation data
P_1 [bar]	2.02	2.02	P_3 [bar]	9.95	9.96
T_1 [°C]	33.8	33.5	T_3 [°C]	89.7	89.5
P_2 [bar]	9.99	9.99	P_4 [bar]	2.17	2.17
T_2 [°C]	35.8	35.8	T_4 [°C]	38.4	40.1
X_3 [-]	0.915	0.913	$\dot{m}$ [kg/s]	0.052	0.052

The heat exchanger block in THERMOLIB was modelled by using effectiveness-NTU (the number of transfer units) method [4]. The heat exchanger block named evaporator and condenser were to simulate the process of evaporation and condensation of the working fluid. A heat exchanger block has two pairs of inlet and outlet ports to simulate the heat transfer between two fluids with different temperatures. In the evaporator block, one pair of the inlet and outlet

ports was connected to a flow of hot water, and the other pair of ports was linked with the main loop of ORC. In the condenser block, one pair of inlets and outlets was linked with a flow of cooling water, and the other pair was also connected to the main loop of the ORC. When the initial conditions including hot and cold-water temperature were settled, other parameters of the ORC can be calculated by THERMOLIB. The simulation results validated against experimental data from the publication [5] were shown in the Table 2.

2.3. The modelling of ORC powered by engine waste heat

After the model was validated, an ORC powered by engine waste heat can be constructed in THERMOLIB, as shown in Fig. 3.
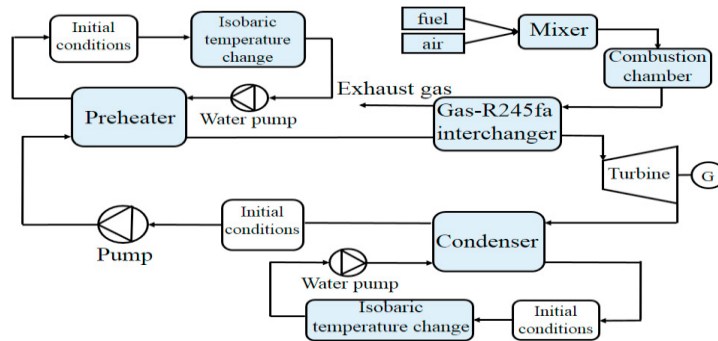

Fig. 3.ORC directly powered by engine waste heat.

The working fluid was respectively preheated and evaporated by the jacket water and exhaust gas. A source of fuel and air were mixed before entering a combustion chamber block. The combustion chamber block in THERMOLIB was used to simulate the combustion of fuel and air in the engine cylinder. The mass flow rate of exhaust gas equals to the total flow rate of fuel and air entering the engine cylinder and the temperatures of the gas equals to the results from Ricardo Wave simulation. Ricardo Wave can also calculate the values of exhaust gas temperature at different engine loads. The mass flow rate and temperature of exhaust gas can also be computed by simulation programme at the outlet of the combustion chamber in THERMOLIB to simulate different engine conditions. When the outlet gas of the combustion chamber had the same mass flow rate and temperature with engine exhaust gas, corresponding engine condition can be simulated.
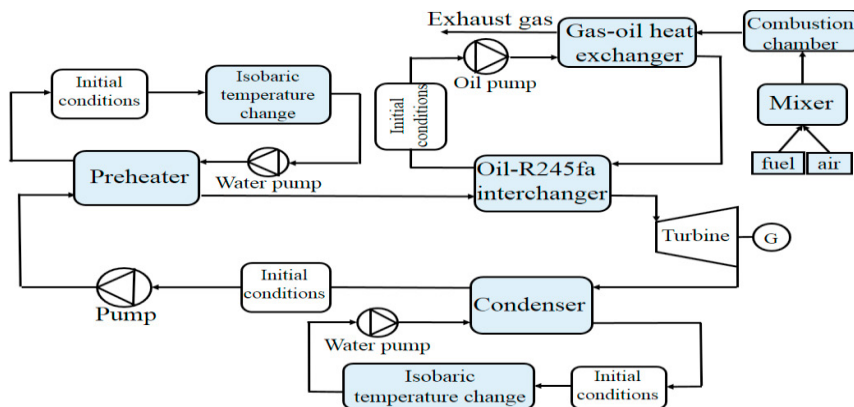

Fig. 4. ORC powered by thermal oil and jacket water.

The engine exhaust gas had hot temperature especially at high engine loads and when the heating source temperature is beyond the decomposition temperature of the working fluid, the stability of the system will be affected. In this case,

a thermal oil cycle was used to collect the waste heat from the exhaust gas and stored in it; the temperature of the oil was then lowered down to protect the working fluid from directly transferring heat with high-temperature gas, as shown in Fig. 4. The thermal oil cycle circuit included a gas-oil heat exchanger, an oil-refrigerant (R245fa) heat exchanger, a thermal oil container to store the oil and an oil pump.

2.4. Parameters setting

The heat exchangers applied in the two ORC systems above were divided into liquid/liquid type (including preheater and the oil-R245fa heat exchanger) and gas/liquid type (including the gas-oil and gas-R245fa heat exchangers). The coefficient of the overall heat transfer rate of liquid/liquid type interchanger was set to 2000 W/K and that of gas/liquid type was set to 100 W/K according to THERMOLIB user manual. The isentropic efficiency of turbine and pump block were set according to reference [6]. The working fluid in the two ORC systems both were R245fa.

3. Results and discussion

The results are shown in Figure 5 – 8. In Figure 5, the temperature of thermal oil was changed from 94.6 to 125 °C; and the temperature of exhaust gas was changed from 230.8 to 548.2 °C when the engine generator loads varied from 10% to 100%. Thermal oil temperature at each engine load was below the decomposition temperature of R245fa. Although the oil temperature was much lower than the exhaust gas temperature, the heat transfer coefficient between thermal oil and R245fa was much higher than that between exhaust gas and liquid, so the oil-R245fa heat exchanger had higher heat transfer rate than the gas-R245fa heat exchanger.
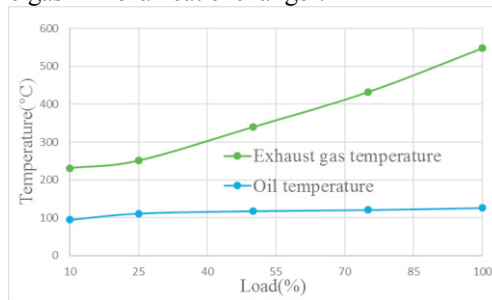

Fig. 5.   Exhaust gas and oil temperature.
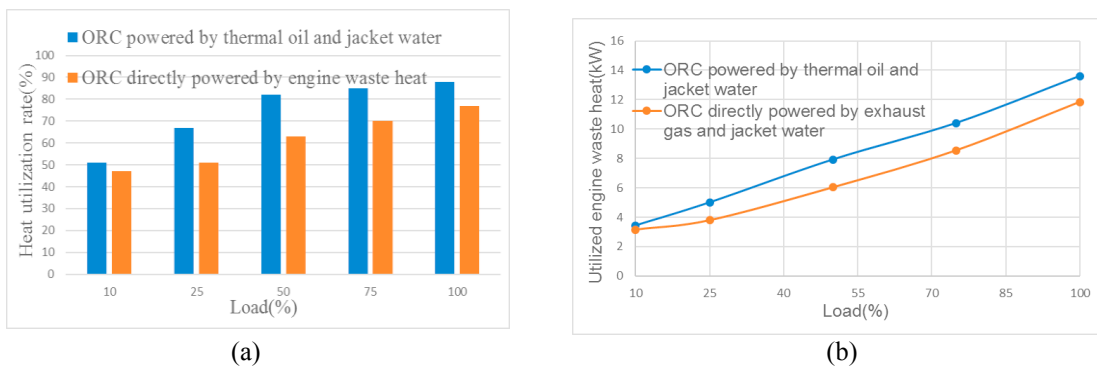

| (a) | (b) |

Fig. 6 Waste heat utilization: (a) Heat utilization rate; (b) Utilized waste heat from the engine

As shown in Fig. 6, the ORC system with thermal oil cycle had higher heat utilization rate than the system with no thermal oil cycle at corresponding engine load because higher heat transfer rate of oil-R245fa than that of gas-R245fa. The generator efficiency of the two ORC both were assumed to be 0.75 according to reference [7]. As shown in Figure 7, power output and electricity generated of the ORC system increased from 0.126 kW to 1.271 kW, and from 0.095 kW to 0.953 kW with the increase of engine loads because more working fluid (R245fa) was evaporated with more

heat input at high engine loads. Figure 8 showed that the thermal efficiency of engine alone was around 35% at engine full load, while with the ORC system, the whole system efficiency was improved to more than 40%, which increased by around 6%.
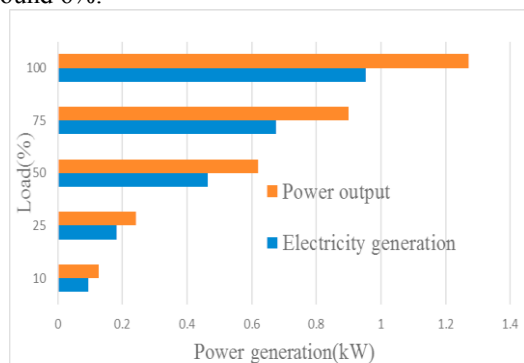

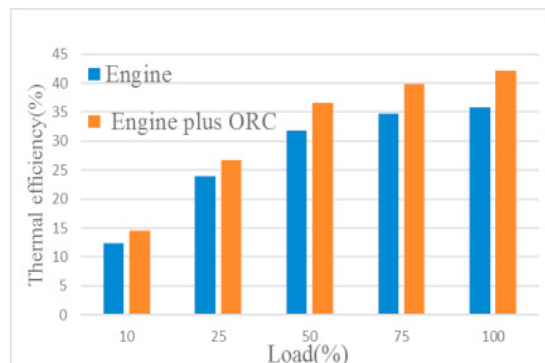Fig.7. Power generation of ORC powered by thermal oil and jacket water. Fig.8. Thermal efficiency of engine plus ORC system.

4. Conclusions

Heat utilization, power output and thermal efficiency of a micro ORC under different engine conditions were explored in this study. Different heat source (i.e. heat directly from the engine jacket water and exhaust gas and indirectly from thermal oil) showed different performance, which is mainly because gas-liquid and liquid-liquid type heat interchangers have different heat transfer coefficient. The ORC powered by thermal oil and jacket water had better and stable performance than the ORC directly driven by engine exhaust gas and jacket water.

- The temperature of thermal oil can be controlled in a small temperature range and went up with the increase of engine load.
- The heat utilization of thermal oil and jacket water powered ORC was higher than the engine exhaust gas and jacket water powered ORC because better heat transfer between thermal oil and R245fa than that between exhaust gas and R245fa. The heat utilization rate increased with the growth of engine load.
- The power output of thermal oil and jacket water powered ORC can reach 1.27 kW at 100% engine load. Higher heat utilization rate and higher heat input resulted in higher power output.
- The thermal energy utilization efficiency of the engine plus thermal oil and jacket water powered ORC system increased by 6% at engine full load than the engine alone.

Acknowledgements

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