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A combination of thermoelectric generator and organic Rankine cycle for both waste heat recovery and engine oil warm-up in a passenger car

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ABSTRACT

Thermoelectric generator (TEG) and organic Rankine cycle (ORC) are both promising waste heat recovery technologies, which have different advantages and disadvantages in operating temperature, size and efficiency. A combination of TEG and ORC systems forming a TEG-ORC system has the possibility to complement each other achieving a win-win situation. The paper proposes a combined TEG-ORC system applied in passenger cars for both waste heat recovery and engine warm-up. This bifunctional TEG-ORC system has a novel layout utilizing components that already exist in a passenger car to reduce the size of system. To evaluate the performance of TEG-ORC, a semi-empirical model is developed. The fuel saving potential of the vehicular TEG-ORC system along the world light vehicle test procedure (WLTP) is estimated. The results indicate that 0.13% and 3.19 % of fuel saving potential are respectively achieved in the fast engine warm-up and waste heat recovery compared to the baseline vehicle without the TEG-ORC system.

Keywords: thermoelectric generator, organic Rankine cycle, engine warm-up, waste heat recovery, passenger car

1. INTRODUCTION

Interest in waste heat recovery for vehicle application has flourished in recent years. The potential of thermoelectric generator (TEG) and organic Rankine cycle (ORC) integrated in vehicles has been demonstrated with a number of prototypes [1, 2]. TEG and ORC systems both have their own characteristics, challenges and complementary advantages in operating temperature, size and recovery efficiency. Herein, a combination of TEG and ORC systems forming a TEG-ORC system has the possibility to complement each other achieving a win-win situation.

This paper presents a study of a novel combination of TEG with an ORC in a passenger car. The integration layout for the proposed TEG-ORC system is different from previous studies [3,4]. Another novelty of this work is that the TEG-ORC combination concept is investigated for the first time in a passenger car application. Considering the limitation of space, the integration layout of TEG-ORC system is kept as simple as possible and utilizes components that already exist to reduce cost, weight, and complexity. The performance evaluation of the TEG-ORC system in this paper is comprehensive and profound. Unlike most of previous literatures which only conducted a simple estimation of electric power output, the fuel saving potential of the TEG-ORC system is estimated in vehicle running the world light vehicle test procedure (WLTP).

2. DESCRIPTION OF TEG-ORC SYSTEM

A 2L-gasoline and D-segment passenger car is selected as reference car for this study. For the waste heat recovery in passenger vehicle application, maximizing the recovered energy is not the only objective. System complexity, component volume and weight are also big concerns. Based on this principle, a baseline scenario and a novel layout of TEG-ORC system are both presented in Fig 1. The added components for the TEG-ORC system have been highlighted in Fig 1 (b). The specifications of the TEG-ORC system and reference vehicle are shown in Appendix A.

It can be seen from Fig 1 (b) that the hot side and cold side of TEG are respectively integrated in the exhaust line

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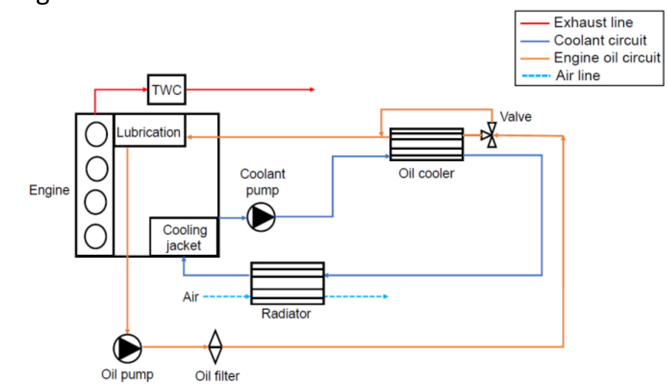
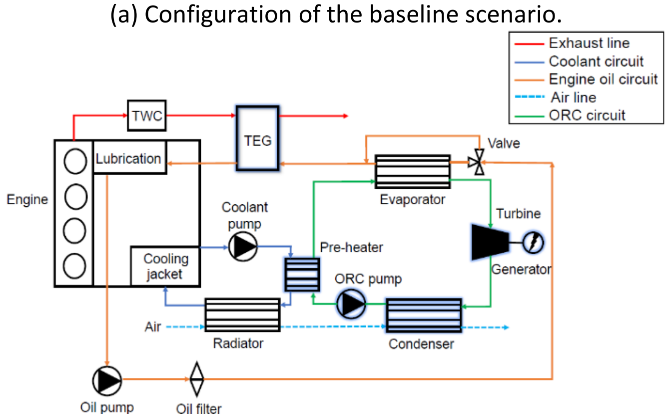
and engine oil circuit. To avoid in influence on the performance of three-way catalytic (TWC), the hot side of TEG is installed downstream of TWC, whose temperature is above the decomposition temperatures of most organic fluids. Therefore, the TEG system broadens the temperature range for an ORC system. For the cold side of TEG, the original engine oil pump circulates the engine oil through the cold side of TEG avoiding adding extra fluid loops or pumps. In this layout, TEG absorbs heat directly from exhaust gas and releases a portion of the absorbed heat into the engine oil circuit, which not only recovers exhaust energy to electricity but also fastens the engine oil warm-up process at cold start stage.



(a) Configuration of the baseline scenario.



(b) Configuration of the TEG-ORC system.

Fig 1: Comparison of layouts between the baseline scenario and TEG-ORC system.

As can be seen from Fig 1 (b), the ORC system with only one fluid loop is integrated with both coolant circuit and engine oil circuit. Compared with highly varied exhaust temperature, the temperatures of both engine oil and coolant circuits are lower but more stable. Therefore, this integration is able to avoid the decomposition of organic fluid and keep the ORC system running safe and stable. The coolant loop pre-heats the working fluid of ORC before the evaporator at the pre-heater. The original oil cooler is adopted as evaporator minimizing the number of added components. Since the ORC replaces the coolant circuit for engine oil cooling and the added pre-heater also cools down the coolant circuit, the cooling load on the radiator is largely relieved. Herein, a radiator with smaller size compared to the original one can be adopted, which offers space for the added condenser in the front cooling package. Compared with the previous TEG-ORC systems [3, 4], this novel layout of TEG-ORC system has fewer added components and reduces the size of original engine cooling system, offering space feasibility for the TEG-ORC integration in passenger cars.

A brief description of TEG-ORC system operation is given below. At the start-up stage of vehicle, TEG begins to recover exhaust heat as soon as the engine starts. While the ORC shuts down and its evaporator is bypassed through valve. The heat rejected by the TEG at its cold side warms up the engine oil. When the temperature of engine oil raises above its maximum optimal temperature 383 K, the ORC begins to work and the valve switches from bypass branch to evaporator branch. When the engine oil temperature falls below 363 K, valve switches back to bypass branch again and ORC stops.

3. SEMI-EMPIRICAL MODEL DEVELOPMENT

3.1 Model structure

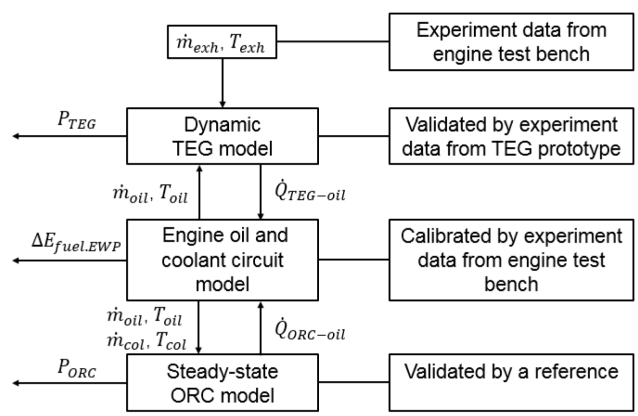


Fig 2: The model structure and variables for the semi-empirical model.

To estimate the performance of the proposed TEG-ORC system along a driving cycle, a semi-empirical model is developed. The model is made up by three sub-models: a dynamic TEG system model, an engine oil and coolant circuits model, and a steady-state ORC model. The model structure and variables are shown in Fig 2. As can be seen, the three sub-models are only separated conceptually, as they depend on and interact with each other. The engine oil and coolant circuits model governs the heat transfer in the engine oil circuits, from the

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absorption of heat from TEG ($\dot{Q}_{TEG.oil}$) to the rejection of heat to ORC ($\dot{Q}_{ORC.oil}$). The warm-up effects of fuel saving ($\Delta E_{fuel.EWP}$) is also predicted by the engine oil and coolant circuits model based on engine maps. The dynamic TEG model developed and validated in our previous paper [5, 6] calculates the electric power output of TEG (P_{TEG}) based on the mass flow rates and temperatures of exhaust ($\dot{m}_{exh}$ and T_{exh}) and engine oil ($\dot{m}_{oil}$ and T_{oil}). The ORC adopts a steady-state model that computes the net power output of ORC (P_{ORC}) according to the mass flow rates and temperatures of engine oil and coolant ($\dot{m}_{col}$ and T_{col}).

3.2 Experimental setup

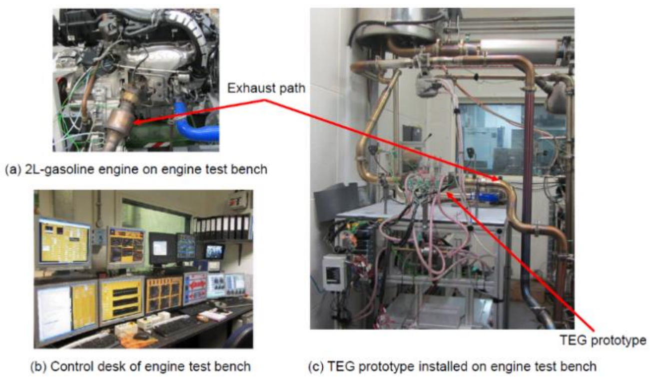


Fig 3: Experimental test setup on the engine test bench.

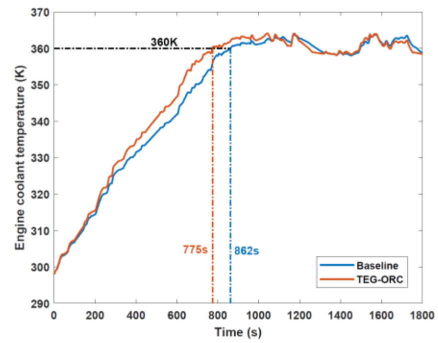
Some essential empirical parameters of the semi-empirical model need to be validated with experiment data. A vehicle equipped with this novel layout TEG-ORC is not available, so there is no experimental data for a complete TEG-ORC system. Thus, both experimental and published data of subsystems or components are used to calibrate and validate the sub-models shown in Fig 2. The majority of the data has been collected from an engine test bench shown in Fig 3 (a) and (b), which is the same engine as the reference vehicle. Connected with a dynamometer, the 2L-gasoline engine is able to simulate in different driving cycles. The TEG prototype is installed downstream of the TWC of the gasoline engine shown in Fig 3 (c), which is the same as the proposed TEG-ORC system. The engine related data (exhaust, engine oil and coolant) and TEG related results (power, voltage and current) are obtained from the engine tests and TEG prototype engine tests, respectively.

Semi-empirical models have been extensively used for the performance prediction of waste heat recovery technologies [7]. Compared to the purely empirical investigations costing a great amount of time and money, the semi-empirical model provides a more cost-effective investigation for the novel TEG-ORC system. With each sub-model validated against experimental data and references, this semi-empirical model is suitable for both predicting and describing this TEG-ORC performance in the driving cycle.

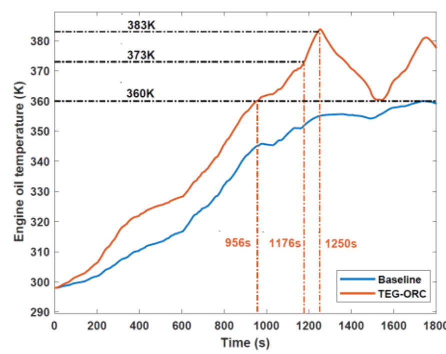
4. RESULTS AND DISCUSSION

4.1 Engine warm-up performance

4.1.1 Engine warm-up time reduction



(a) Comparison of warm up characteristics of engine coolant for baseline scenario and TEG-ORC system.



(b) Comparison of warm up characteristics of engine oil for baseline scenario and TEG-ORC system.

Fig 4: Comparison of warm up characteristics of engine coolant and oil in the WLTP.

Fig 4 shows the temperature difference of engine coolant and oil in the WLTP between the baseline scenario and TEG-ORC system. The optimal temperature ranges for the coolant and engine oil are respectively 365 $\pm$5 K and 378 $\pm$5 K [8]. It can be seen from Fig 4 (a) that the engine coolant of TEG-ORC reaches its optimal temperature at 775 s, which is about 1.5 minute faster than the baseline. This is due to the stop using coolant to warm up oil in the TEG-ORC system, leading a higher warm up rate of coolant. The temperature difference is more significant in the comparison of engine oil. As shown in Fig 4 (b), the maximum engine oil temperature for the baseline can only reach 360 K at the end of WLTP,

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which is still about 10 K below its optimal temperature. In comparison, the engine oil temperature of TEG-ORC system raises faster reaching 360 K in 956 s, which is around 14 minutes earlier than the baseline. The optimal temperature of engine oil can be reached at 1176 s. Such difference shows that using the exhaust from TEG to warm up engine oil is more effective than the conventional layout of baseline scenario using engine coolant. At 1250 s, the ORC starts to work and absorbs the heat from engine oil causing its temperature fluctuating between 360-383 K.

4.1.2 Fuel saving potential from fast engine warm-up

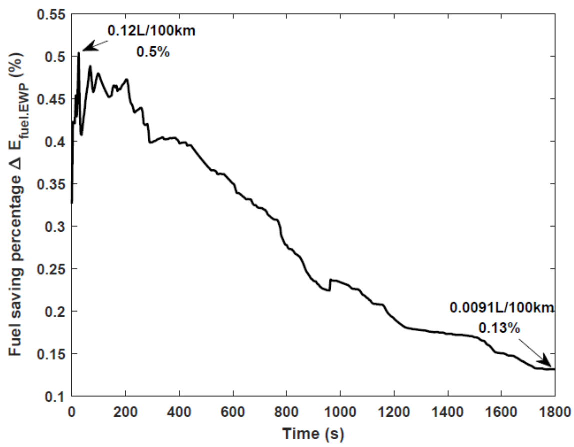

Fig 5: Fuel saving percentage changing in the WLTP.

As shown in Fig 5, the fast engine warm-up of TEG-ORC system saves 0.0091 L/100km fuel with 0.13% of fuel saving at the end of WLTP compared to the baseline scenario. However, the fuel saving percentage varies during the WLTP. A maximum 0.5% of fuel saving is observed at the beginning of WLTP. This is due to the much higher viscosity of engine oil at lower temperature leading to a particularly high friction loss. Therefore, even a small temperature raising of engine oil at the beginning of cold start can lead to a significant engine efficiency improvement. When the engine oil temperature raises, its impact on the FMEP reduces. It can be seen that the fuel saving percentage reduces with time. This result highlights the need for a faster engine warm-up at the very beginning of driving cycles.

4.2 Waste heat recovery performance

4.2.1 Electric power outputs from waste heat recovery

Fig 6 shows the electric power outputs of the TEG-ORC system. It can be seen that the TEG begins to work when the engine starts. Its power output shows a quick response and fluctuates with the driving conditions. In the first three phrases of WLTP (0-1477s), P_{TEG} is below 200 W. This can be explained by the relatively less thermal energy at the exhaust due to the frequent stops at first three phrase of WLTP. P_{TEG} increases in the last extra-high-speed phrase (1477-1800 s) and a maximum power output 412 W is achieved when the vehicle runs continuously with high speed. The ORC system begins to operate at 1250 s with a constant 460 W electric net power output. As can be seen, the ORC system effectively increases the total net power output during its operation. A maximum of 872 W is achieved when TEG and ORC operate together in the last 550 s of WLTP.

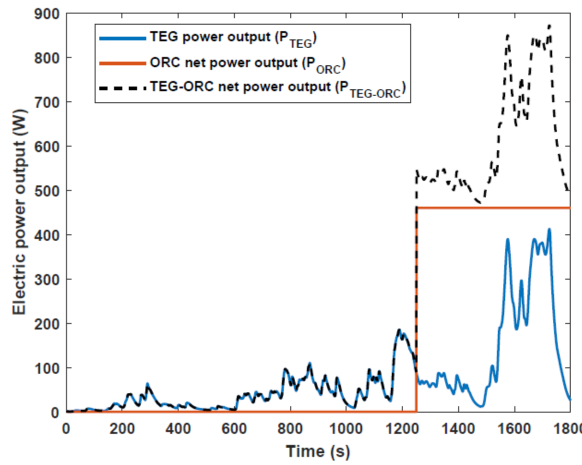

Fig 6: Electric power output of the TEG-ORC in the WLTP.

4.2.2 Fuel saving potential from waste heat recovery

The fuel economy benefit of the TEG-ORC system could be compromised through a number of integration effects. Added weight, increased exhaust backpressure and increased pump power shown in Appendix A are the three main integration effects considered in this study. In our previous study [5], a method using modified quasi static simulation (QSS) toolkit [9] to evaluate the integration effects on fuel saving potential of TEG is developed. The same method is adopted here.

Fig 7 shows the fuel saving potential of TEG-ORC with and without considering the three integration effects. With all the integration effects taken into consideration, the fuel saving for the TEG-ORC system in the waste heat recovery is 3.19% in the WLTP. Because of the three integration effects the saving potential is decreased from 0.28 L/100km (4.27%) to 0.21 L/100km (3.19%). The contributions of the three integration effects to the decrease of fuel saving percentage are also presented in Fig 7. The added weight of TEG-ORC system is identified as the biggest reduction of fuel saving, which contributes to 73% of the reduction of fuel saving potential. In comparison, the increased exhaust gas backpressure and pump power both have relatively less significant effects

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on the fuel saving potential, which respectively occupies 13% and 14% of the fuel reduction from integration effects.

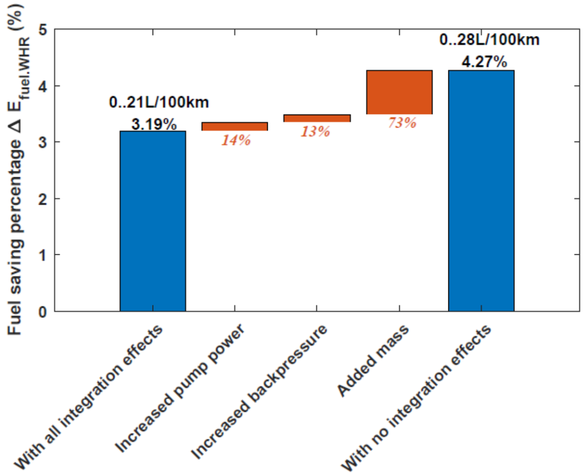

Fig: 7 Fuel saving potential of TEG-ORC system in the WLTP with and without integration effects.

5. CONCLUSIONS

This work describes a bifunctional TEG-ORC system with a novel layout applied in a passenger car for both engine warm-up and waste heat recovery. The performance of this proposed TEG-ORC system in terms of engine warm-up and waste heat recovery are both evaluated by a semi-empirical model. The simulation results show that the warming up time for both engine coolant and oil has been effectively reduced and 0.13% of fuel saving potential has been obtained for this fast engine warm-up. As for the waste heat recovery performance, a maximum 872W of net power is achieved when the TEG and ORC work together. The fuel saving potential of waste heat recovery is estimated by taking three integration effects into consideration, showing that 0.21 L/100km of fuel saving can be achieved in the WLTP. Among the three integration effects, the added weight is identified as the main effect compromising the fuel saving potential.

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APPENDIX A

The thermoelectric modules (TEMs) are recently developed s skutterudite TEMs [10] The structure of the TEG system is shown in Fig A1

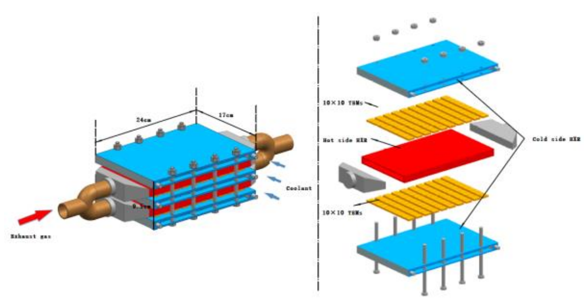

Fig A1: Structure and parameters of the TEG system [3-4].

Specification for the reference car and TEG-ORC system

Total mass of the vehicle	1520 kg
Frontal area	2.26 m^2
Tyre radius	0.326 m

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Drag coefficient	0.29
Engine maximum power	150 kW
Engine maximum torque	282 Nm
Total mass of TEG	15 kg
Total mass of ORC	20 kg
Increased backpressure	0.1-0.2 kPa
Increased pump power	10 W
Total number of TEMs	400
Average heat exchange rate in evaporator	3.4 kW
Condensing temperature	308 K
Superheat temperature	2 K
Supercooling temperature	2 K

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