

Exergy Analysis of Organic Rankine Cycle and Electric Turbo Compounding for Waste Heat Recovery

Mohd Hanif Mat Muhammad¹, Aman Mohd Ihsan Mamat^{1*}, Wan Saiful-islam Wan Salim²

¹ Automotive Research and Testing Centre (ARTeC), Faculty of Mechanical Engineering, Universiti Teknologi MARA Shah Alam, Selangor, Malaysia

² Faculty of Mechanical and Manufacturing, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia

* Email: amanihsan@salam.uitm.edu.my

Abstract

With such tough legislation on current emission standards, car manufacturers are focusing on increasing the efficiency of their engines with the development of advance waste heat recover (WHR) technology. Organic Rankine Cycle (ORC) and Electric Turbo Compounding (ETC) system have a good potential to be used as exhaust energy recovery. This paper compares the exergy availability and losses between the ORC and the ETC. In this particular study, exhaust data from the Proton 1.6L CamPro CFE turbocharged engine was used. This particular engine already has a main turbocharger, making the added WHR as a secondary recovery system to further increase the engine efficiency. Both systems are coupled to a 1 kW electric generator for ease of comparisons. At first the available exergy is calculated for both WHR technologies. Exergy losses from rotating the generator are analysed to finally determine the thermal efficiency of the overall system. Exergy calculation is simplified to only account for chemical and physical exergy since kinetic and potential energy are negligible in comparison. Available exergy for ORC was significantly high which went up to 12.5 kW with the exergy losses recorded at 9.7 kW. The ETC achieved only 5 kW but had a small loss at 8×10^{-3} kW. Average thermal efficiency of the ORC systems was 10.7% compared to ETC which was 58.7%. It can be concluded that the complexity of the ORC system contributes to its downfall where multiple components increase its exergy losses compared to the simplistic design of an ETC.

Keywords: Waste heat recovery; exergy; Organic Rankine Cycle electric turbo compounding.

1. Introduction

In the current trend of concern for less polluting vehicles, severe standards for fuel consumption and emissions have been put in place. Euro 6 requirements are limited to 1 g/km of carbon monoxide (CO) and 0.080 g/km of nitrogen oxide (NO_x) [1]. With such tough legislation, car manufacturers are focusing on increasing the efficiency of their engines with the development of advance waste heat recover (WHR) technology [2, 3]. Current development is focusing on three main technologies of WHR; Organic Rankine Cycle (ORC), Thermoelectric Generator (TEG) and Electric Turbo-Compounding (ETC).

ORC uses the exhaust gas to heat up an organic fluid recover using an evaporator. This heated fluid expands inside a turbine which is coupled to an electric generator. By using an evaporator, the system does not interfere with the backpressure of the exhaust systems. This technology has reported an improvement as much as 11% in brake specific fuel consumption (BSFC) in a heavy duty direct injection engine [4]. ORC is widely used in large engine because of its complex architecture [5]. This results in a heavy system and occupies a bigger space in overall system integration which is not suitable for small vehicles. Choice of organic fluid inside the ORC is very dependent to heat source which is also toxic to human; therefore, it makes its maintenance very difficult. TEG is based on the Seebeck effect. A current is generated in a semiconductor with each side being exposed to different temperature. With the high temperature of the exhaust gas, the material electric current is generated. The advantage of this setup is that

there is no increase in the pumping loss. The technology however has low conversion and requires a large surface area to achieve good energy recovery. Stobart et al. reports that 4.7% of fuel savings can be achieved [6]. Another study found that the energy recover barely offsets the additional cost of the system and is not enough to justify the cost [7]. In current state, the TEG cost is around \$10/(W/K) and a significant amount of research and development is necessary to reach a viable value [8]. Thus, it makes it unsuitable for commercialization in its current state.

For electro-turbocompounding, an electric generator is attached to the turbine assembly to generate electricity. Two different setups can be found; in the first setup, the generator is mounted in the middle of the main turbocharger. When the exhaust gas energy is more than the turbocharger working zone, the generator will recover the extra energy for storage. Then when energy from the exhaust gas is not enough to spin the turbine, the stored energy is then used to spin the shaft turning the generator into an electric motor. This setup has recorded an overall engine efficiency of 5% [9]. Another setup is attached to the electric generator directly to the turbine omitting the compressor. The energy recover can be used for example to help the engine by directly assisting the output shaft. A study has shown that this kind of approach increases the overall engine efficiency by 3% [10]. Additionally, ETC has a more compact architecture but due to its setup, it increases the back pressure in the exhaust pipe.

By developing this different technology, car manufacturer hopes to be able to comply with the emission standard. To look at which WHR technology has a better efficiency, a study of exergy efficiency for each technology is compared. Here the TEG is not con-

sidered since the technology is still not commercially viable. The comparison is made between ORC and ETC for 1 kW of energy recovery through electric generator.

2. Exergy Analysis

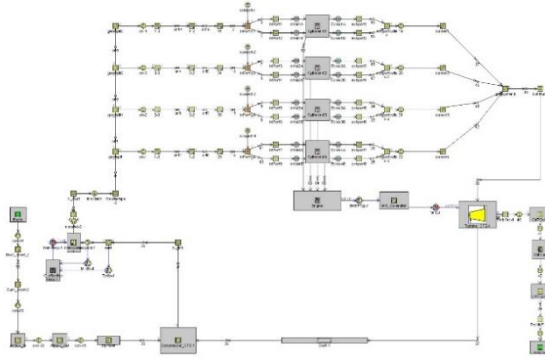


Fig. 1: Proton 1.6L CamPro CFE engine model

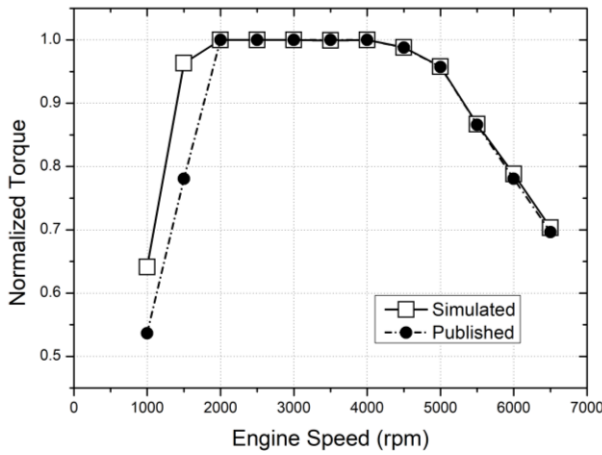


Fig. 2: Torque data comparisons of engine model and Proton 1.6L CamPro CFE datasheet

In this particular study, Proton 1.6L CamPro CFE turbocharged engine was used. Specification of this engine is given in Table 1. The engine was modelled in GT-POWER software based on the model developed and validated by Ismail, et al. [11]. Final engine model is shown in Fig.1. The model is based on a Proton CamPro engine with an added turbocharger with wastegate. Engine model was compared to the published engine data [12]. The model gives an output of the engine torque with an average an accuracy of 72.6% for all engine speeds and 99% between 2000-6500 rpm, which is the region of interest explained later in the paper. Data comparison of the developed model and the published data is shown in Fig.2.

Table 1: Proton 1.6L CamPro CFE engine specifications

Combustion system	4-stroke, in-line, gasoline PFI
Capacity	1.6 litres
Compression ratio	9.0
Bore x stroke	76mm x 86mm
Induction system	Single-stage turbocharger
Maximum torque	205 Nm @ 2000-4000 rpm
Maximum power	103 kW @ 5000 rpm
Intake cam profile	≤ 220° (duration) / 7.51 mm (valve lift)
Exhaust cam profile	2° BTDC @ 0.15 mm lift

Since both architectures recovered the downstream exhaust energy from the main turbocharger, the exergy analysis was evaluated from the output of the main turbocharger to the electric generator. Total blow down was preliminary calculated by differentiating the pressure between inside the exhaust and the ambient. It shows that the 1 kW energy is only available at 2000 rpm (1.49kW) and above, which determines the region of interest for the study. Exergy analysis of an ORC is compared to an ETC in order to deter-

mine the most efficient method to recover the available remaining energy from the upstream turbine. Fig.3 and Fig.4 show the installation of the ORC and the ETC to the Proton 1.6 CFE engine architecture. Both architectures are attached to a 1 kW electric generator.

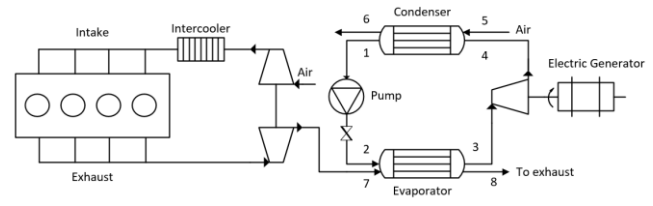


Fig. 3: Waste heat recovery using turbocharger and ORC

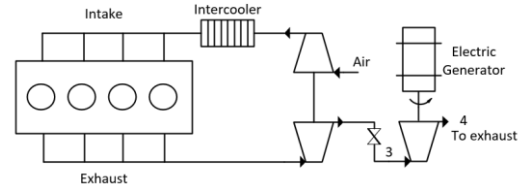


Fig. 4: Waste heat recovery using turbocharger and ETC

Exergy is the maximum useful work at a specified state that can be obtained from the system [13]. In an exergy analysis, rate of change in exergy is studied to determine the location of inefficiencies in a system. Exergy in a flow rate system consists of kinetic ($\dot{E}_k$), potential ($\dot{E}_p$), physical ($\dot{E}_{ph}$) and chemical exergy ($\dot{E}_{ch}$) as shown in Eq.(1) [14]. Assumptions and simplification of exergy calculations for this study are that kinetic ($\dot{E}_k$) and potential ($\dot{E}_p$) exergy are negligible compared to physical ($\dot{E}_{ph}$) exergy [15]; and chemical exergy ($\dot{E}_{ch}$) for organic fluid is only taken into considerations since non organic chemical exergy is negligible [16, 17].

$$E = \dot{E}_k + \dot{E}_p + \dot{E}_{ph} + \dot{E}_{ch} \quad (1)$$

Where for ideal gas,

$$\frac{\dot{E}_{ph}}{\dot{m}} = h - h_0 - T_0 \left[s - s_0 - R \ln \left(\frac{P}{P_0} \right) \right] \quad (2)$$

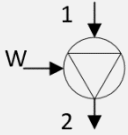
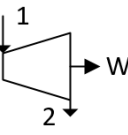
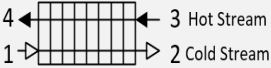
And chemical exergy for organic substance is defined as follow:

$$\frac{\dot{E}_{ch}}{\dot{m}} = \frac{e_{ch}^0}{M} \left[\frac{T_0}{298.15} \right] + \frac{\Delta H_0}{M} \left[\frac{T_0 - 298.15}{298.15} \right] \quad (3)$$

In this particular study, chemical exergy is only calculated for the mixture of ammonium hydroxide (NH_4OH) as the working fluid for ORC. Since the mixture contains 25% organic fluid, only the chemical exergy of ammonia (NH_3) is calculated and is multiplied by 0.25 to account for its mass flow rate contribution as in Eq.(4). The thermodynamic properties of NH_4OH were based on study used by Razif, et al. [18] and Tillner-Roth and Friend [19]. Value of e_{ch}^0 was referred to the study made by Szargut [20].

$$\frac{\dot{E}_{ch\text{NH}_4\text{OH}}}{\dot{m}} = 0.25 \left(\frac{e_{ch\text{NH}_3}^0}{M} \left[\frac{T_0}{298.15} \right] + \frac{\Delta H_{0\text{NH}_3}}{M} \left[\frac{T_0 - 298.15}{298.15} \right] \right) \quad (4)$$

Table 2: Exergy rate of each element

Component	Pump	Turbine	Heat Exchanger
Schematic			
Used exergy (E_i^u)	$E_2 - E_1$	W	$E_2 - E_1$
Available exergy (E_i^a)	W	$E_1 - E_2$	$E_3 - E_4$

The analysis used the topological approach where each element is mapped and the exergy of its nodes at the interconnection is calculated [21, 22]. This study focuses on the overall system which looks at the overall exergy loss and exergy efficiency. Exergy loss of the system is defined as losses associated in each element as shown in Eq.(5). Exergy efficiency of each element i , is defined as the used exergy (E_i^u) over the available exergy (E_i^a) of the element i as in Eq.(6) [23]. The overall system exergy efficiency is given in Eq.(7). Available and used exergy for each component can be determined using the equation in Table 2. Component exergy analysis is evaluated but not presented since the study is only interested in the final exergy efficiency of the systems.

$$\varphi = \sum_{i=0}^n \varphi_i = \sum_{i=0}^n E_i^{in} - E_i^{out} \quad (5)$$

$$\eta_{exergy}^i = \frac{E_i^u}{E_i^a} \quad (6)$$

$$\eta_{exergy}^{total} = \frac{E_{total}^u}{E_{total}^a} \quad (7)$$

Pressure and temperature of the exhaust gas were obtained from the engine model in GT-Power at the exit of the main turbocharger before the catalytic converter. For the ORC, the internal mass flow rate was controlled to maintain 1 kW at the output of the generator. The ORC was operated at 0.1 MPa on the evaporator side and 1 MPa on the condenser side. This ORC design was based on a study conducted by Razif, et al. [24]. The evaporator and condenser capacity varies with the requirement to maintain ORC internal pressure. Here, the condenser is cooled down using air at ambient temperature. Thermal efficiency of the ORC model is coherent with other findings [15, 24]. For the ETC, the inlet pressure is controlled to maintain a 1 kW output in the generator as well. Isentropic efficiency of the pump and turbine are set at 85% and 80% effectively. Ambient temperature is at 298 K for 0.1 MPa.

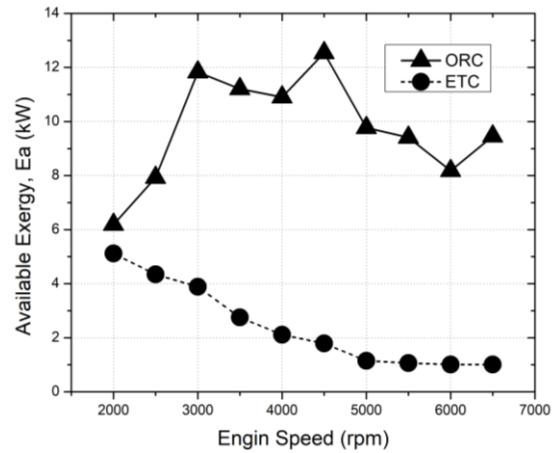
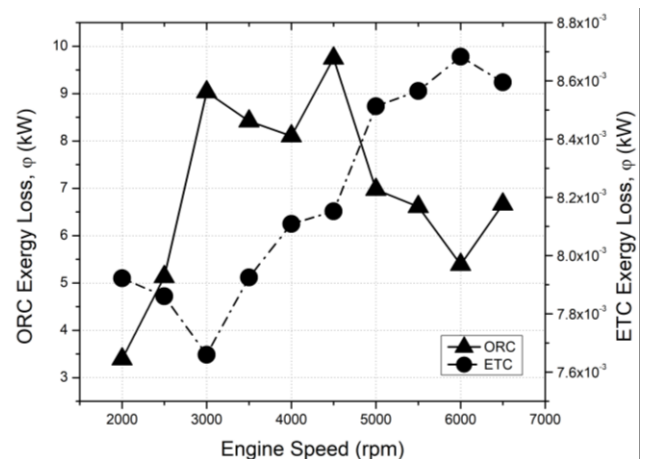
3. Results and Discussions

In Fig.5, it can be observed that the available exergy is higher at most engine speed for the ORC compared to ETC. Available exergy (E_a) for the ORC varies from 6.2 to 12.5 kW in a nonlinear manner. Whereas the ETC has a more linear form ranging from 1.5 kW at the highest rpm to a maximum of 5 kW at the lowest rpm. At high rpm, exhaust gas has higher pressure which should have more exergy availability to the ETC. But in order to maintain a continuous 1 kW of electric generation, the mass flow rate was adjusted for the ETC at the turbine inlet. As a result, the available exergy declined at higher rpm due to a decrease in temperature and mass flow rate. On the other hand, the ORC is more capable of absorbing the exhaust gas energy as there is no restriction to bypass the excess flow from the exhaust gas. With more components including pumps and evaporator, the ORC has more contributors for the total final available exergy.

Fig.6 shows the comparisons of exergy losses (φ) between the two WHR technologies. The losses in ORC are higher compared to the

heat transfer [25]. In addition, existence of multiple components in the ORC system also adds up to the total losses in exergy. Exergy loss in ETC is negligible (maximum of 8×10^{-3} kW) compared to ORC which recorded a maximum value of 9.7 kW.

Research has shown that exergy loss in ORC is proportional to temperature variation and the other way around with variation of pressure [26]. At lower rpm, both the temperature and pressure in the exhaust gas increase but the exergy losses in ORC still increase since it is more sensitive to temperature variation. Medium to high rpm, the pressure of exhaust gas maintains to increase and temperature starts to decline which leads to a drop in value of exergy losses in the ORC. Because of the simplicity of the ETC, the losses are negligible. Exergy coming in to the system is more or less the same with exergy going out of the system.

**Fig. 5:** Comparison of available exergy between ORC and ETC**Fig. 6:** Exergy losses in ORC and ETC

Due to its high losses, the exergy efficiency of the ORC is low as compared to ETC which is mainly above 3500 rpm as shown in Fig.7. ETC exergy efficiency is the highest at 6000 rpm with 99.3%. At low rpm, both systems are equivalent in terms of exergy efficiency. Since the study is set to recover a continuous 1 kW of energy, the ORC is at a disadvantage since it has high available

ORC using different organic fluid [17]. The exergy efficiency can be increased up to 36% by using modified ORC to include turbine bleeding or regenerative ORC [15, 25]. Since ORC has higher available exergy, it is possible to use larger capacity electric generator. Thus, it increases its exergy efficiency by increasing the used exergy.

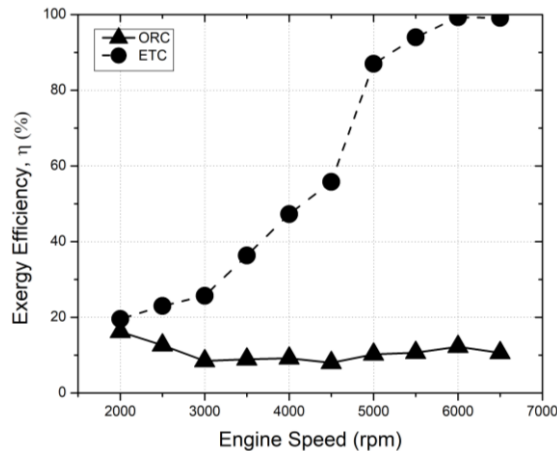


Fig.7: Exergy efficiency comparison between ORC and ETC

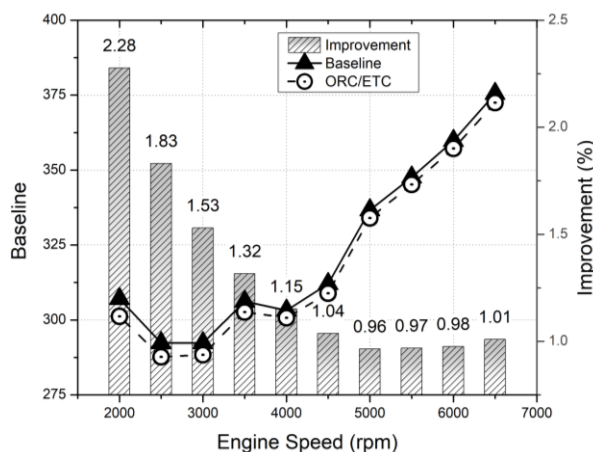


Fig.8: Comparison of BSFC between the baseline Proton 1.6 CFE engines with the additional 1 kW recovered

By increasing the power output of an engine, the brake specific fuel consumption can be reduced. With the additional continuous 1 kW recovered by the electric generator, this will assist the engine with additional power. From Eq.(8), it can be shown that by increasing the power for the same amount of fuel, the BSFC will increase. Here the power is the total of engine brake power with the recovered power through the electric generator. In Fig.8, the additional energy from the electric generator reduces the overall BSFC. Maximum improvement is recorded at 2000 rpm with 2.28%. Less improvement can be seen at higher rpm due to higher fuel flow rate. The average BSFC improvement is 1.31%. With the BSFC improvement, we can benefit from better emission in general.

$$BSFC = \frac{\text{Fuel Flow Rate}}{\text{Power}} \quad (8)$$

4. Conclusion

A lot of energy is still available from the downstream exhaust gas. Due to its different characteristic at different rpm, not all energy can be recovered efficiently. Using ETC will reduce exergy losses in general and has a simpler system. Here the ETC has a maximum of 99.3% exergy efficiency with an average 58.7% for a constant 1 kW of recovery. ORC operation depends highly on its

choice of fluid. Increasing its efficiency requires sophisticated setup with many parameters to be optimized at the same time. Incorporating a bigger electric generator will help increase the ORC efficiency and BSFC but component losses are still high compared to ETC. Recovering using electric generator is a better option since it is considered as an exergy efficient component and is easier to maintain. However, electric generator efficiency is not always optimised due to the exposure to the high heat of operations. Heat from the exhaust gas coupled with the internal heat generated from high speed operation reduces electromagnetic induction inside the electric generator and reduces its efficiency.

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