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# Evaluation of automotive waste heat recovery for various driving modes

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ABSTRACT

A computational study was performed to determine an optimum position of a superheater used in an automotive WHR (waste heat recovery) system integrated with a 3.3 L V6 gasoline direct injection engine, and the results were validated through an experimental study. Regardless of utilizing only half of the exhaust mass flow, the superheater mounted close to the exhaust manifold was found to be able to recover approximately 3.8 kW more waste heat from the exhaust of the particular engine. Based on the result, the optimum layout of a dual loop Rankine system for an automotive waste heat recovery was developed, and the automotive waste heat recovery rate was assessed for many driving test modes widely adopted in various regions of the world. The temperature and the mass flow rate of the engine exhaust increased as the load and speed of engine increased; thus, the technology is more suitable for vehicles that mostly run in either highway or city. In conclusion, the dual loop Rankine system is more advantageous for vehicles driven in the United State or Europe in terms of improving fuel economy of engine.



## 1. Introduction

Although there have been tremendous efforts on green energy technologies, the global energy use is still weighted heavily toward fossil fuel combustion. Worrisome issues such as fossil fuel depletion threating to global economy and climate change due to $CO_2$ emission never seem to fade away. According to a study reported recently, the transportation sector is responsible for 27% of the total greenhouse gas emission [1], and light-duty vehicles including passenger cars lead to 59% of the total fossil fuel consumption followed by Heavy-duty vehicles accounting for 23% [2]. Therefore, many countries have continued to enhance regulations on fuel efficiency of automobiles and greenhouse gas emission. In particular, European countries have relatively stringent greenhouse gas legislations that strongly encourage $CO_2$ emission from automotive engine to be reduced from 139.8 g/km in 2012 to 93 g/km in 2020 [3].

In response to the regulations, recently EV or HFCV (electric or hydrogen fuel cell vehicles) have been actively researched and developed; however, electric cars still suffer from short driving range due to low energy density of Li-ion battery, lack of infrastructure of charging station, and slow battery charging time. FC (Fuel cell) technology is also not mature sufficient for practical HFCV application owing to operation problems associated with electro-catalysis in direct FCs and even more critical problems in hydrogen storage. Those technical issues must be overcome before this vehicle is commercially viable, and both electric and FC cars hardly look like promising near-term solution for fully replacing conventional IC (internal combustion) engine. Many organizations including the IEA (International Energy Agency) have predicted that the IC engine would still occupy in most of the powertrain market even in more than 40 years [4]. Thus, technologies such as VVT & VVL (variable valve timing & lift), cylinder deactivation, ISG (integrated starter/generator) systems, turbocharging, direct fuel injection, engine downsizing to improve the thermal efficiency of conventional IC engine are recognized as an important and realistic task. Fabio et al., developed a computational model to investigate the VVL profile that could improve fuel economy [5]. Flierl et al., discussed the effect of the cylinder deactivation on fuel consumption benefits and indicated applicable regime of the strategy over the whole engine map [6]. Wang et al., showed that potential fuel economy improvement could be achieved through torque distribution control in an integrated starter generator hybrid electric

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car [7]. Lecointe et al., presented around 15% lower specific fuel consumption with 1.8 L direct injection engine in combination with a turbocharger compared to that with 3 L naturally aspirated engine [8].

While continuous efforts on such technologies have been made to improve fuel economy of powertrains, automotive WHR (waste heat recovery) system has newly emerged in the past decade. Currently available IC engine has less than 30% chemical fuel into tank to wheel conversion efficiency, and thus more than 60% is loss through exhaust gas and the cooling system. If some portion of the waste heat (e.g. ~15%) could be recovered by the WHR system, the thermal efficiency of the IC engine can be eventually improved up to around 5%, which is very attractive achievement since none of aforementioned technologies have shown remarkable improvement in terms of fuel economy of vehicles [9].

The waste heat from automotive engine could be harvested largely using two approaches, namely thermoelectric generation and Rankine cycle. The TEM (thermoelectric module) is a small device that converts waste heat directly into electrical energy based on a phenomenon called the Seebeck effect. Since the TEM can be easily mounted in transportation system, it is considered more feasible system for WHR of automotive engines. However, the high cost of TEM material is still prohibitive for commercialization. Therefore, more efforts should be given on the development of a cost-effective and energy efficient TEM module [10,11].

To date, small scale Rankine cycle is considered more suitable approach for the automotive WHR system regardless of numerous barriers such as bulky size, weight increase and deteriorating combustion efficiency due to increasing back pressure [12]. Ringler et al., insisted that WHR system based on Rankine cycle could be the most effective for heat recovery, and it was revealed that a steam power cycle (e.g. one loop Rankine cycle) could recover 10% of waste heat from engine exhaust at high speed driving mode [9]. They also found that two loop Rankine cycles capable of harvesting waste heat from coolant as well as engine exhaust was more efficient concept than the one loop cycle. Yamaguchi et al., performed an experimental study to prove the fuel economy improvement using a Diesel-Rankine Combined Cycle, and they observed 2.6% improvement in brake specific fuel consumption at full load condition [13]. Katsanos et al., used diesel heavy duty engine integrated with Rankine system to investigate the waste heat recovery rate and proved that the system efficiency could be considerably improved [14]. Zhu et al., proposed an in-cylinder WHR system and found that the fuel economy of turbocharge diesel engine could be improved up to 3.2% according to their numerical study [15]. Wang et al., applied 2-loop Rankin cycle to a gasoline engine to harvest waste heat from the engine out exhaust and coolant [16]. He et al., also installed Rankine base WHR system to a gasoline engine and performed energy balance and exergy analyses for evaluating the WHR rate [17]. Since the working fluid using in the Rankine cycle affects the system overall efficiency, numerous research have been accomplished on the choice of working fluid. A study indicated that R245fa was the best applicable working fluid for WHR application of the diesel engine in terms of thermodynamic performances, environmental impacts and safety levels [18]. It was also used for recovering heat from both engine exhaust and coolant of a small gasoline engine in hybrid car [19]. This study revealed that the fuel consumption rate could be reduced up to 6.4%, and the overall efficiency was approximately 3.4%. A supercritical WHR Organic Rankine Cycle model was proposed, and the system performance was assessed for various circuit layouts related to the recuperator position as well as working fluid selection [20]. In addition, a parametric study was carried out using genetic algorithm for analyzing the effects of evaporation pressure, superheat degree and condensation temperature on the WHR system performances of a diesel engine [21]. Peralez et al., proposed an effective control method for WHR system and showed that the heat recovery rate increased when a superheater of the WHR system was effectively controlled using PID (proportional integral derivative) control [22]. Such countless efforts contribute to exciting progresses in the area of automotive WHR technology over the past decade. Nevertheless, there are still many challenges facing the design of the automotive WHR system. The main goal of this study was primarily to investigate the optimum position for a superheater of WHR in unspacious engine room and access the heat recovery rate of WHR system for various driving test cycles widely adopted in different regions of the world.

## 2. Experimental and computational approaches

Among WHR technologies, Rankine system is known as the best one in terms of the waste heat recovery rate. However, the system complexity is a serious concern when it comes to the system installation in unspacious engine room of automobiles. In particular, an issue on the optimum position for installing only one superheater (e.g. heat exchanger) in V-type gasoline engine has arisen. The V-type engine is more common for engine having high displacement volume, and it usually has two exhaust manifolds connected in the engine head. The exhaust gas temperature around exhaust valves can be reached up to around 900 °C at high speed and wide open throttle condition. However, the hot exhaust quickly cools down as the gas travels through the tailpipe from the engine combustion chamber. The higher temperature of the exhaust is obviously desirable for the higher temperature gradient between the source and working fluid. When considering cost effectiveness and space availability of engine room, only one superheater is allowed to be installed close to one of exhaust manifolds. In this case, the superheater can recover the waste heat from only half of mass flow of engine exhaust as shown in Fig. 1(A), namely “design I”, and then it joins with the other half flow before going through the boiler. The concept takes advantage of high temperature of exhaust for heat recovery with the superheater. Fig. 1(B), namely “design II” illustrates the other option installing the superheater at a junction where two exhaust streams join together so that the waste heat can be recovered from all gas flow although the temperature of the exhaust is somewhat lower at the inlet of the superheater than that in “design I”.

Experimental study was carried out to compare two conceptual layout of WHR system integrated with a gasoline engine in terms of WHR rate and thermal efficiency of the system. A basic Rankine cycle employing water as working fluid was fabricated and coupled with a 3.3 L V6 GDI (gasoline direct injection) engine. The specifications along with two shell and tube type heat exchangers (e.g. superheater, boiler) are listed in Table 1. Engine speed and load were selected on the basis of actual vehicle operating conditions (i.e. 60, 80, 100, and 120 km/h) and controlled using an EC dynamometer (EC-80, MEIDEN Co.). The engine operating conditions are tabulated in Table 2. The flow rate and temperature of the exhaust along the tailpipe from the exhaust manifold were measured using a mass flow meter (CMF 010, Emerson Electric Co.) and K-type thermocouples, respectively. The temperatures of the engine coolant (90 ± 2 °C), intake air (25 ± 2 °C), and engine oil (100 ± 2 °C) were maintained using independent heat exchangers to minimize unexpected engine power change. The maximum pressure and temperature of the steam power cycle were controlled to be fixed at 25 bars and 300 °C, respectively. The mass flow rate of the working fluid should be varied according to the engine operating conditions; however, the flow rates were controlled as high as possible to generate superheated steam at the exit of the superheater. The maximum flow rate was 0.3 L/min at a vehicle speed of 120 km/h.