

Application of Rankine Cycle to Passenger Vehicle Waste Heat Recovery - A Review

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ABSTRACT

Rankine cycle (RC) is a thermodynamic cycle that converts thermal energy into mechanical work, which is commonly found in thermal power generation plants. Recently, there are many studies focusing on applying Rankine cycle to recover low-grade waste heat. On-road vehicles, which convert around one third of the fuel energy into useful mechanical energy for propulsion, are moving energy conversion systems that generate considerable waste heat. It was found from many research studies that Rankine cycle has a great potential to be applied to harvest waste heat from automobiles. However, different from other low-grade waste heat sources, vehicles have limited space for the RC system integration and the waste heat is relatively unstable. In the current paper, the efforts in the past few decades related to applying RC to on-road vehicles, specifically passenger cars, are reviewed. Characteristics of the waste heat sources on vehicles and the constraints put on the automotive RC application are identified. Rankine cycle architectures, system components, and working fluids suitable to different vehicle types are summarized to provide a guideline for the future RC system design for automobiles. In the end, an insight into the application of Rankine cycle to vehicle waste heat recovery (WHR) is provided.

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INTRODUCTION

In 2012, the Obama administration announced vehicle fuel-efficiency standards which require all the U.S. auto fleet, including cars and light trucks, to reach 54.5 mpg on average by model year 2025. All the OEMs are scrambling to improve the fuel efficiency step by step in order to meet the fuel economy requirements and more stringent emissions regulations. Due to the inefficiency of the internal combustion engine, around 60-70% of the fuel energy is wasted in the form of heat.

It has been estimated that the thermal efficiency of a modern IC engine is limited to 20-40% while 33% of the fuel energy from a typical medium-size passenger vehicle is carried away by exhaust gases and 29% is carried away by engine cooling water in urban traffic conditions. Depending on engine type and operating conditions, the IC exhaust gas temperature usually varies from 500 to 900 °C and engine cooling water temperature is around 100 °C. It is reported that for a typical light duty 4 cylinder spark ignition engine, the waste energy carried by the exhaust gas ranges from 4.6 to 120 kW and cooling water heat ranges from 9 to 48 kW [1], which makes the exhaust gas and engine cooling heat very attractive for energy recovery.

There are a few technologies that have been researched on for waste heat recovery (WHR), which include thermoelectric generator (TEG), turbocharger, six-stroke cycle internal combustion engine, Rankine Cycle (RC), etc. The RC system has been identified as a promising solution to harvesting part of this waste energy from vehicles as regenerated mechanical or electrical power [2, 3, 4, 5]. A RC system includes four main components: 1) an evaporator, 2) an expander, 3)

a condenser, and 4) a pump; refer to Figure 1. The pump drives the working fluid to circulate through the loop and the evaporator utilizes the waste heat to vaporize the working fluid. The fluid vapour expands in the expander and turns the thermal energy into mechanical power output. Then the expanded vapour flows through a condenser to turn back into liquid phase, completing the cycle.

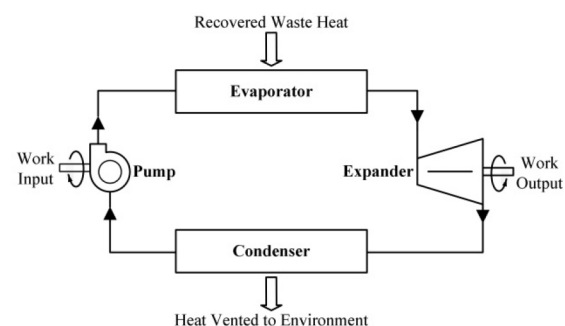


Figure 1. Schematic of the RC system layout.

The first study examining the application of RC to an automotive application was reported in the 1970s [6], and since then extensive work has been done to investigate the feasibility of applying RC to automobiles (with a primary focus on heavy-duty diesel engine trucks [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]). Generally a 10~15% fuel efficiency improvement was reported for the application to diesel engine truck. The focus of this study is to review the latest research on RC application to passenger vehicles. The architectures of the RC system, researches that have been done on RC passenger vehicle applications so far, expander selection, suitable working fluids and RC system

vehicle integration are summarized which would provide a guideline for the future RC system design for passenger vehicles. In the end, a thought on the application of Rankine cycle for passenger vehicle waste heat recovery is provided.

RC STRUCTURES FOR PASSENGER VEHICLE APPLICATION

For automotive application, the RC system is usually installed downstream of the catalyst to avoid influencing emission control by extending the time for catalyst to reach light-off temperature at cold start and to utilize the extra energy produced by pollutant conversion within the catalyst. As to the architecture of RC systems, Lecompte et al. [31] conducted a thorough review of organic Rankine cycle architectures for general WHR. However, heat sources on vehicles are different from other typical industrial heat sources, which are stable and no space limitation for the RC system. To be technically feasible for vehicle RC application, the cycle system should be kept as simple as possible and utilize components that already exist in the vehicles in order to reduce the added expense, weight and complexity of the system. Besides, the temperature ranges of the two main heat sources on vehicles are significantly different which requires special treatment. In this section, the commonly used structures of RC system for passenger vehicle application are summarized.

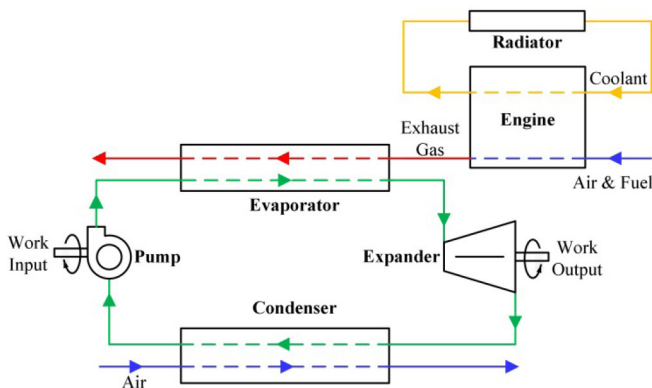


Figure 2. Structure 1 of the RC system for application to passenger vehicles.

The most common and simple structure is shown in Figure 2. It utilizes the exhaust gas as the only heat source to evaporate the working fluid. The second structure design is shown in Figure 3. In this design, another heat exchanger (recuperator) is added before the evaporator, using the steam from the expander to preheat the working fluid. The third very common structure is shown in Figure 4. Different from structure 2, waste heat from engine coolant is used to preheat the working fluid. The regenerative preheating of structure 2 requires a very complex liquid-gas heat exchanger with high exchange surfaces, while the preheater in structure 3 only requires a simple liquid-liquid heat exchanger. For some working fluids, e.g. organic fluids, structure 2 with recuperator is needed in order to cool down the vapor from expander to reduce the cooling load of the condenser.

There have been contradicting conclusions about the effect of preheating using engine coolant on the RC system efficiency. Based on Vaja and Gambarotta's work [32], the RC system with a preheater (structure 3) allows a net increase in power output, compared to structure 1, of 10% to

35%, depending on which working fluid is chosen. Alberto Boretti [33, 34] also showed a 8.2% fuel economy improvement using engine coolant to preheat the RC cycle, compared to a 6.4% improvement when only exhaust gas is used to boil the working fluid. Arias et al. [35] also compared the combined exhaust and engine coolant heat recovery system, structure 3, with the exhaust only structure, structure 1. It was found that the additional power recovered from the engine coolant system was 20W out of a total 2140W, which is around 1% improvement. It was argued that the reason why it is not advantageous to build combined engine coolant and exhaust gas waste heat recovery system is due to the constraint imposed on the engine coolant temperature, around 100 °C, is not a good match for the working fluid preheating. Duparchy et al. [36] also analyzed the waste heat recovery potential for engine cooling water and exhaust gas from both energy and exergy points of view. It was found that the proportion of thermal energy carried by exhaust gas is comparable with that dissipated by engine cooling water, which means these two sources are roughly equivalent from the energy point of view. However, exhaust gas shows a much greater recovery potential in terms of exergy. The main reason why opposite conclusions were drawn from different studies is that different working fluid is selected for the RC system. Vaja and Gambarotta's work [32] and Alberto Boretti [33, 34] adopted organic fluids, e.g. benzene, R11, R134a and 245fa, while Arias et al. [35] and Duparchy et al. [36] selected water as the working fluid. These organic fluids have moderate evaporating temperature and low evaporation latent heat, compared to a higher boiling point and higher latent heat of water. Therefore, for organic fluids, the preheating energy ranges 30% to 50% of the total obtained energy while it is only about 10% for water [1].

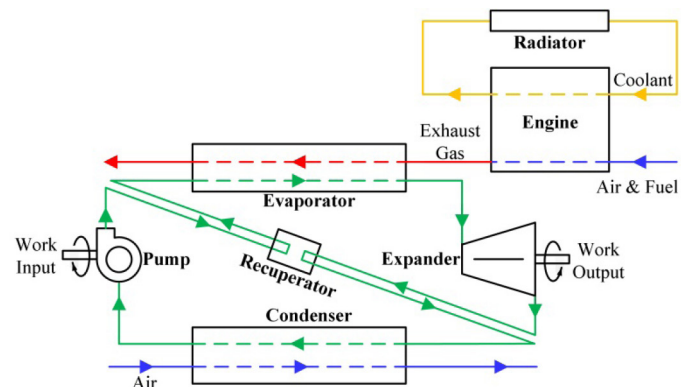


Figure 3. Structure 2 of the RC system for application to passenger vehicles.

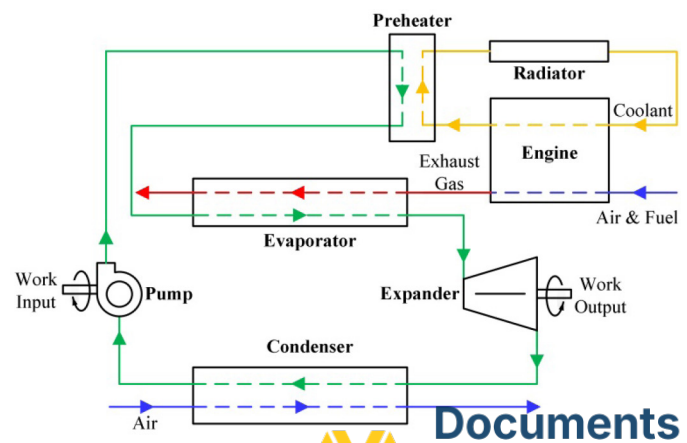


Figure 4. Structure 3 of the RC system for application to passenger vehicles.

To utilize the engine waste heat, two more options could be considered. The first option (structure 4) is shown in Figure 5, which was proposed by Arias et al. [35]. Instead of using engine coolant to preheat the working fluid, the engine block, which has higher temperature, is used to partially evaporate the working fluid. For this structure, complete evaporation of the working fluid inside the engine block should be prevented. A design parameter, e.g. quality, was recommended to be selected and given a value as an intermediate state in the boiling process, so that two-phase mixture would flow out of the engine block and into the evaporator to complete the boiling and superheating process by exhaust gas [35].

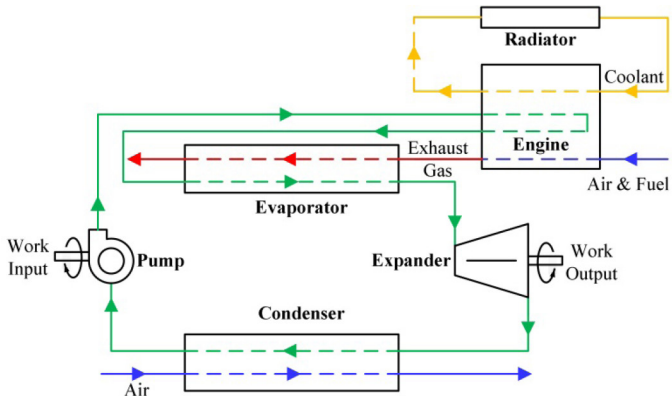


Figure 5. Structure 4 of the RC system for application to passenger vehicles.

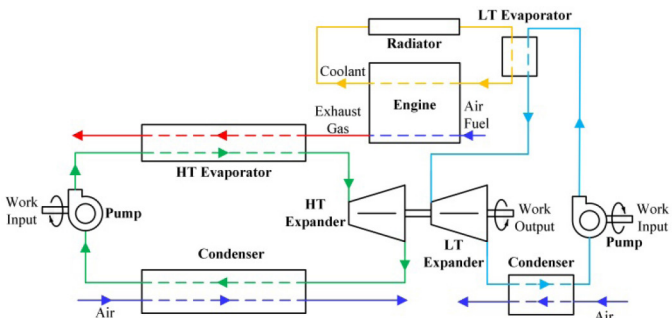


Figure 6. Structure 5 of the RC system for application to passenger vehicles.

The second option (structure 5) is to build separate system loops and use different working fluids to match the specific characteristics of engine coolant and exhaust gas, see Figure 6. The first generation

waste heat recovery system developed by BMW [37] adopted a similar dual circuit system, in which water was used as the medium in the high-temperature (HT) loop and ethanol as working fluid in the low-temperature (LT) loop. The dual loop system can utilize the full potential of the waste energy with the disadvantage of large system volume and system complexity.

Another RC system which integrated with engine cooling is shown in Figure 7. This system minimized the number of required components by adopting an evaporative engine cooling structure and a refrigerant as the working fluid, so that the engine functioned as an evaporator and the existing radiator worked as a condenser. The only extra component added to the system is an expander for power conversion. However, this structure requires a modification of the existing engine cooling system, while the current engine cooling technology is quite mature and widely taken and has been using 50/50 water ethylene glycol as the coolant for decades.

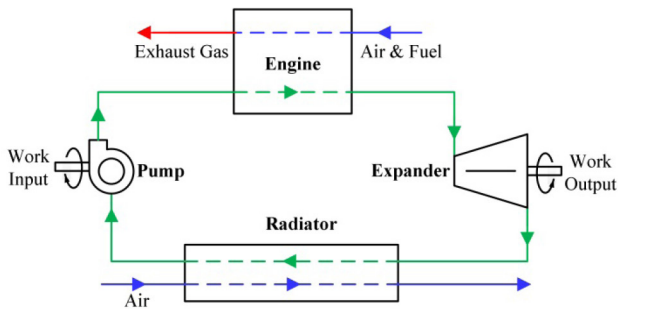


Figure 7. Structure 6 of the RC system for application to passenger vehicles.

Table 1 summarizes the pros and cons of the six different RC structures. For the structure design of the RC passenger vehicle application, maximizing the recovered energy is not the only objective. System complexity, component volume and weight, and the resulted extra cost added to the vehicles and the payback period are also big concerns, which make the current review paper necessary for automotive engineers and researchers. In the following section, some typical applications of RC system to passenger vehicles to date are reviewed and summarized.

Table 1. Comparisons between different RC structures.

	Pros	Cons
Structure 1	Simple structure	Only recover exhaust gas waste heat
Structure 2	Reutilize waste heat of vapor from expander; Reduce the cooling load of the condenser	An extra liquid-gas heat exchanger
Structure 3	Recover part of waste heat from engine coolant	An extra liquid-liquid heat exchanger
Structure 4	Recover waste heat from engine more efficiently	Modification of engine block
Structure 5	Maximize the energy recovered from both engine coolant and exhaust gas;	Complex system
Structure 6	Simplest structure Same coolant for engine cooling and RC system.	Significant redesign of the engine and engine cooling system

APPLICATION TO PASSENGER VEHICLES TO DATE

In this section, the studies on RC application to passenger vehicles reported in open literature are reviewed and summarized. Two improvements in efficiency were commonly used in the literature to show the impact of the RC system to the vehicle efficiency, one of which is *Thermal Efficiency* defined by

$$\eta_{th} = \frac{W_{RC}}{\dot{m}_{fuel} \cdot LHV} \quad (1)$$

in which W_{RC} is net power out of the RC system, $\dot{m}_{fuel}$ is the fuel consumption rate and LHV is fuel low heating value. The other definition is *Mechanical Efficiency*, which is the ratio of the net power output of the RC system and the effective power produced by the engine, P_e ,

$$\eta_m = \frac{W_{RC}}{P_e} \quad (2)$$

Assuming one third of the total fuel energy is transferred to mechanical power output, which is a typical value for modern internal combustion engine, then

$$\eta_{th} \approx \eta_m / 3 \quad (3)$$

In the current review paper, all the reported fuel economy improvement values are converted to either thermal efficiency or mechanical efficiency for consistence and easy comparison.

The first RC application to a small passenger vehicle was reported in 1993 by Oomori and Ogino [38] from Toyota Motor Corp. The adopted system structure is structure 6, as shown in Figure 7. Based on the study, approximately 3% of the engine output power was recovered from the engine waste heat at an ambient temperature of 25 °C, which means a thermal efficiency improvement of around 1%.

Chammas and Clodic [1] conducted a rough estimation of fuel efficiency improvement for RC application to hybrid vehicles (HV). In their work, analysis was conducted from the energy balance perspective. Different working fluids, e.g. water, R-245ca and isopentane, and different technical options, e.g. high pressure steam Rankine bottoming cycle, low pressure steam Rankine cycle, organic Rankine cycle, etc., are compared. It was estimated that using the available heat exchanger and expander technologies, steam RC can offer up to 4% thermal efficiency improvement while organic RC can provide up to 5% thermal efficiency improvement since the heat released by the engine cooling circuit can be better recovered by organic fluids besides the waste heat from exhaust gas.

In the following year, Arias, Shedd and Jester [35] conducted theoretical analysis of different structures of Rankine cycle system for waste heat recovery from a hybrid vehicle. Three different RC structures, structure 1, 3 and 4, were compared. It was found that

structure 4 was the most efficient RC system and approximately 5.5% of the total inlet energy and 7.5% of the total waste heat can be recovered when engine block is used as the preheater and the exhaust gas is used to super-heat the working fluid.

In 2007, Honda R&D Co., Ltd [39, 40] reported an application of a RC system to a hybrid vehicle. To realize a compact design for vehicle installation and high efficiency, densely layered multi-plate fins were adopted in the boiler and the unit was integrated with the engine cylinder head to minimize the heat loss and system size. According to the vehicle testing and numerical modelling, the thermal efficiency was increased from 28.9% to 32.7% at 100km/h constant cruising speed.

In 2008, BMW [37, 41] unveiled their first generation turbosteamer to use the potential waste heat from the inefficient internal combustion engines. A dual-circuit system was developed to utilize the waste heat from both the engine coolant and the exhaust gas, with ethanol and water as the working fluids in the two circuits respectively. An additional 10-15% power output, which is approximately 5.7% thermal efficiency improvement, was achieved. However, due to added weight, high system complexity and space restrictions, the first generation turbosteamer is generally not feasible for mobile applications.

The second generation turbosteamer [42], which simplified the system by only utilizing the waste heat from the exhaust gas to enable efficient vehicle integration, was reported in 2012. This second generation system can reduce the mechanical engine load by approximately 6%, which is around 2% thermal efficiency improvement. BMW claimed that a higher fuel efficiency improvement can be reached with an intelligent heat management optimized for waste heat recovery. Some modelling works from BMW [43, 44] followed, which underlined the importance of including vehicle integration effects when the fuel efficiency improvement is estimated and foresaw an even higher fuel saving potential in hybrid-electric vehicles.

He et al. [45, 46] conducted a steady-state experiment on a dual loop waste heat recovery system for internal combustion engine, which is similar to structure 5. The difference is Kalina Cycle (KC) is used to harvest waste heat from engine cooling loop instead of Rankine cycle. Different working fluids for the RC loop were compared and a cycle thermal efficiency of 18-26% was achieved, depending on RC fluid selection and evaporation temperature, which indicated a thermal efficiency improvement of 12-17.3% if 2/3 of the total fuel energy is assumed to be wasted by engine coolant and exhaust gas. However, the proposed combined cycle is more feasible for naval engine application than passenger vehicles considering the system complexity and space requirement.

Alberto Boretta [33, 34] studied the potential application of Rankine cycle to a 1.8 L naturally aspirated hybrid vehicle. The waste heat recovery from exhaust gas and engine coolant increase the fuel efficiency by up to 6.4% and 2.8% respectively and up to 8.2% combined with corresponding averaged values to be 3.4%, 1.7% and 5.1% for steady operation. For transient operation, the integrated