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A review and future application of Rankine Cycle to passenger vehicles for waste heat recovery

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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 have been 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 is found from prior research that the Rankine Cycle has great potential in automobile waste heat harvesting applications. However, in contrast with other low-grade waste heat applications, vehicles have limited space for the RC system integration, and the waste heat is relatively unsteady. In this work, the efforts in the past few decades to apply RC to on-road vehicles, specifically passenger cars, are reviewed. Characteristics of the waste heat sources found in vehicles and the constraints put on the automotive RC application are identified. Rankine Cycle architectures, system components, and working fluids suitable to different applications are summarized, which provides a guideline for future RC system design in automobiles. Lastly, a new concept and case study into the future application of Rankine Cycle to vehicle waste heat recovery (WHR) is provided.

1. Introduction

In 2012, vehicle fuel-efficiency standards were announced by the Obama administration that require all US cars and light trucks to reach 54.5 miles per gallon on average by model year 2025 [1]. As a result, automobile manufacturers are working to improve fuel efficiency in order to meet current and future fuel economy requirements plus emissions regulations. Vehicle fuel efficiency is logically related to the efficiency of the internal combustion engine, where approximately 60–70% of fuel energy is wasted in the form of heat.

It has been estimated that the thermal efficiency of a modern internal combustion (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 33% is carried away by engine cooling water in urban traffic conditions [2]. Depending on the engine type and operating conditions, the IC exhaust gas temperature usually varies from 500 to 900 °C and the 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 [3], which makes the exhaust gas and engine cooling heat very attractive for energy recovery.

Several technologies have been investigated for waste heat recovery (WHR) including thermoelectric generators (TEG), turbochargers, six-stroke cycle internal combustion engines, the 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 [4–7]. A RC system includes four main components: 1) an evaporator, 2) an expander, 3) a condenser, and 4) a pump; refer to the flow loop of a typical RC system in Fig. 1. The pump drives the working fluid to circulate through the loop, and the evaporator utilizes a waste heat source to vaporize the working fluid. The fluid vapor expands in the expander and converts thermal energy into mechanical power output. Then, the expanded vapor flows through a condenser to turn back into liquid phase, thus completing the cycle.

The first study examining the application of RC to an automotive application was reported in the 1970 s [8], 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 [9–33]). Generally, a 10–15% fuel efficiency improvement is reported for diesel engine truck applications. The application of RC to passenger vehicles is more challenging due to space limitations, which necessi-

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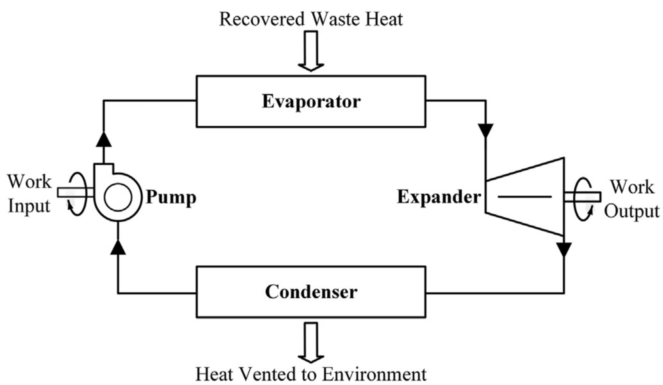

Fig. 1. Schematic of a general Rankine Cycle (RC) system layout including four main components: evaporator, expander, condenser and pump.

tates further investigation.

In this article, existing architectures of RC systems, prior research that has been done on RC passenger vehicle applications, expander selection, suitable working fluids, and RC system vehicle integration strategies are summarized. Thus, this review provides a comprehensive guideline for future RC system design for passenger vehicles. Additionally, as a point of differentiation from prior studies, a unique concept and case study on the future application of RC to passenger vehicle waste heat recovery logically follows the state-of-the-art summary.

2. RC architectures for passenger vehicle application

For automotive applications, the RC system is usually installed downstream of the catalyst to avoid negative influence on emission control by extending the time for the catalyst to reach light-off temperature at cold start and to utilize the extra energy produced by pollutant conversion within the catalyst [34]. Lecompte et al. [35] conducted a thorough review of organic RC architectures for general WHR. However, heat sources on vehicles are different from other typical industrial heat sources, which are stable and have fewer space limitations for system implementation. To be technically feasible for vehicle RC application, the system should be kept as simple as possible and utilize components that already exist to reduce cost, weight, and complexity. Another consideration requiring special treatment is related to the different temperature ranges of the two main heat sources found in vehicles. In this section, commonly used structures and associated flow loops of RC systems for passenger vehicle applications are summarized.

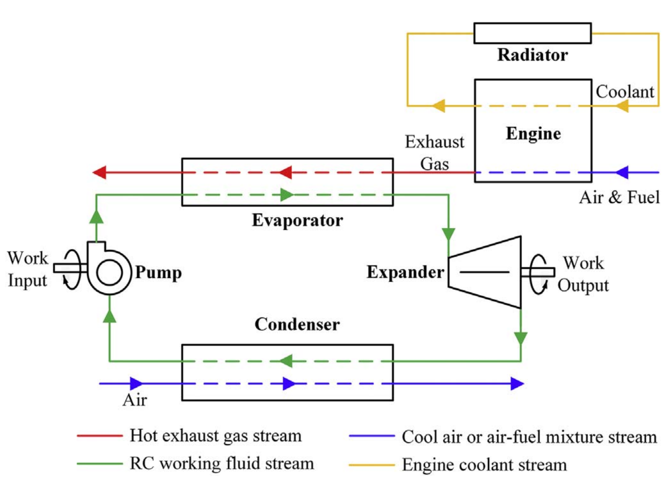

Fig. 2. Structure 1 of the RC system for application to passenger vehicles, which utilizes the exhaust gas as the only heat source to evaporate the working fluid.

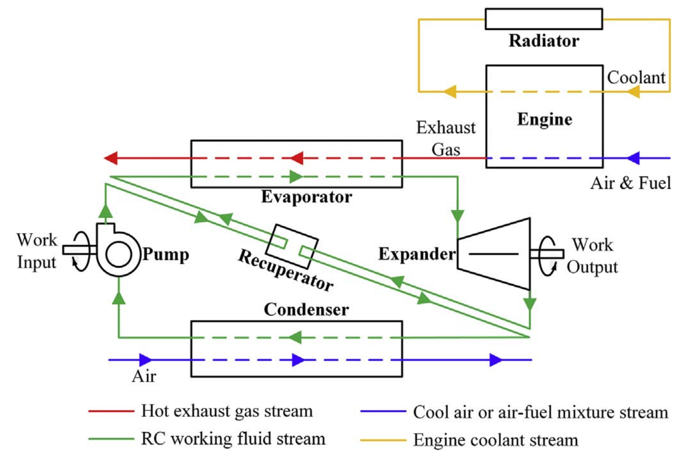

Fig. 3. Structure 2 of the RC system for application to passenger vehicles, in which a recuperator is added before the evaporator using the steam from the expander to preheat the working fluid.

The most common and simple Rankine Cycle system structure (structure 1) is shown in Fig. 2, which utilizes the exhaust gas as the only heat source to evaporate the working fluid. The heat from engine coolant is dissipated to the environment through the radiator and is not recovered by the RC system. The second structure design is shown in Fig. 3, in which another heat exchanger (i.e. recuperator) is added before the evaporator using the steam from the expander to preheat the working fluid. Similar to structure 1, the engine coolant waste heat is not utilized as well. A third structure is shown in Fig. 4; different from structure 2, waste heat from the 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 surface area, 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 a recuperator) is needed to cool down the vapor exiting from the expander, which is still superheated, to reduce the cooling load of the condenser.

There have been contradicting conclusions about the effect of preheating using engine coolant, e.g. structure 3, on the RC system efficiency. Based on Vaja and Gambarotta's work [36], the RC system with the engine coolant preheating allows a net increase in power output, compared to structure 1, of 10–35%, depending on which working fluid is chosen. Alberto Boretti [37,38] 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

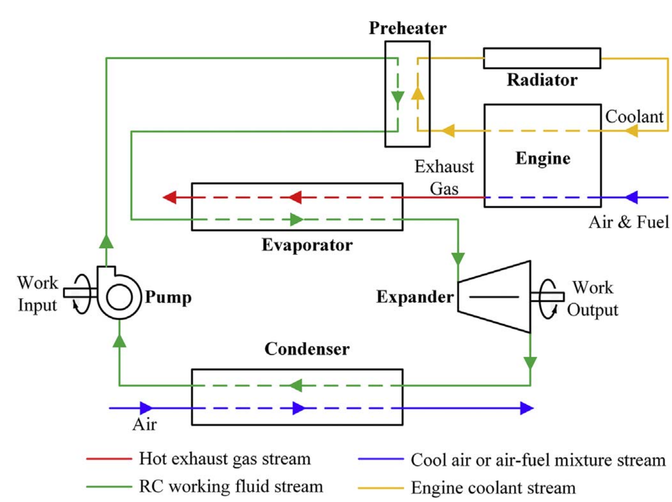

Fig. 4. Structure 3 of the RC system for application to passenger vehicles, in which waste heat from the engine coolant is used to preheat the working fluid.