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Performance analysis of a novel system combining a dual loop organic Rankine cycle (ORC) with a gasoline engine

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ABSTRACT

An organic Rankine cycle (ORC) can be used to harness the wasted heat from an internal combustion engine. In this paper, the characteristics of a novel system combining a gasoline engine with a dual loop ORC which recovers the waste heat from both the exhaust and coolant systems is analyzed. A high temperature loop recovers the exhaust heat while a low temperature loop recovers both the residual high temperature loop heat and the coolant heat. The performance map of a gasoline engine is measured on an engine test bench and the heat quantities wasted by the exhaust and coolant systems are calculated and compared within the engine's entire operating region. Based on this data, the working parameters of a dual loop ORC are defined, and the performance of a combined engine-ORC system is evaluated across this entire region. The results show that the net power of the low temperature loop is higher than that of the high temperature loop, and the relative output power improves by from 14 to 16% in the peak effective thermal efficiency region to 50% in the small load region, and the absolute effective thermal efficiency increases by 3–6% throughout the engine's operating region.

1. Introduction

Energy conservation and environmental protection have become ever more important with the rapid development of global industrialization and urbanization. Huge amounts of energy are consumed by the internal combustion engines used on all kinds of vehicles, with much of this energy wasted by the exhaust and cooling systems. From the viewpoint of thermal equilibrium, the useful output power of a gasoline engine accounts for only a small part of the total energy generated by fuel combustion. Exacerbating this problem is that these combustion products from internal combustion engines also cause serious environmental issues. Thus, engine waste-heat recovery could improve fuel thermal efficiency, reserve fuel consumption, and reduce engine emissions. An organic Rankine cycle (ORC) can be adopted to harness the low-grade wasted heat from these systems. Moreover, the thermal efficiency of an ORC is the highest among all the technical solutions used to recover low-grade waste heat, and is the technology closest to being usable in mass production at the present.

When designing an ORC, special attention must be paid to the choice of appropriate working fluid based on the heat source temperature, an important factor that affects the ORC's thermal and exergetic efficiencies. Desai and Bandyopadhyay selected 16 different organic fluids and adopted a new methodology represented by a grand composite curve to integrate and optimize an ORC [1]. Sauret and Rowlands selected five high-density working fluids for ORCs using moderate-temperature geothermal heat sources. After optimizing the design using radial-inflow turbines for each cycle, the net power output was largest for the ORC system using R134a as the working fluid [2]. Hung et al. investigated Rankine cycles which used organic fluids as the working fluid for converting low-grade energy (such as from a solar pond). Results indicated that wet fluids with very steep saturated vapor curves in a *T*–*s* diagram had better overall energy conversion efficiencies than that of dry fluids [3]. Saleh et al. conducted a thermodynamic screening of 31 pure component working fluids for organic Rankine cycles [4]. Lai et al. considered alkanes, aromates, and linear siloxanes as working fluids for high-temperature organic Rankine cycles [5].

Many researchers have also investigated ORC system design and parametric optimization. Roy et al. conducted a parametric optimization and performance analysis of a waste-heat recovery system based on an organic Rankine cycle using R12, R123, and R134a as the working fluids for power generation [6]. Schuster presented a simulation study of an ORC when using supercritical

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parameters and various working fluids [7]. Teng et al. studied a supercritical organic Rankine cycle system for recovery of waste heat from heavy-duty diesel engines [8]. The performance of a novel, thermally activated system combining an ORC with a vapor compression cycle for vehicular engine waste-heat recovery was studied by Little and Garimella [9], Wang et al. [10], and Wang et al. [11]. Guo et al. investigated the performance of a novel cogeneration system that consisted of a low temperature, geothermally-powered ORC subsystem, an intermediate heat exchanger subsystem, and a heat pump subsystem [12,13]. Yamada et al. carried out a basic experiment using a new pumpless organic Rankine cycle for power generation from a low-temperature heat source [14]. Vaja and Gambarotta described a specific thermodynamic analysis in order to efficiently match an ORC to that of a stationary internal combustion engine. The analysis demonstrated that a 12% increase in the overall efficiency could be achieved with respect to the engine with no bottoming occurring [15]. Srinivasan et al. examined the exhaust waste-heat recovery potential of a high-efficiency, low-emissions, dual-fuel, low-temperature combustion engine using an ORC. Results showed that fuel conversion efficiency improved by an average of 7 percent for all injection timings and loads with hot exhaust gas recirculation (EGR) and ORC turbocompounding [16]. Arias et al. presented a theoretical study of different waste-heat recovery strategies for an internal combustion engine operating in a hybrid vehicle [17]. While few of these investigations have concentrated on spark ignition engine applications, the auto company BMW has accomplished some pioneering research in this area, performing an analysis of the Rankine cycle as an additional power generation process using the waste heat of a car engine [18,19].

For this paper, a dual loop ORC system was designed which combines a high temperature (HT) loop and a low temperature (LT) loop to simultaneously recover the waste heat from the exhaust and the coolant of a gasoline engine. The HT loop only recovers the exhaust heat while the LT loop recovers both the residual HT loop heat and the coolant heat. The two separate loops are coupled with a preheater. The system structure is similar to that of BMW's design, but organic working fluids are substituted for water and ethanol as the working fluids. In order to evaluate the dual loop system performance when combined with a gasoline engine, the waste heat quantities were first calculated using engine test data. Based on these calculations, the working parameters for the HT and LT loops were configured and R245fa and R134a were selected as the working fluids for the HT loop and the LT loop. Finally, the performance map of the combined system was calculated and compared to a system with a non-bottoming ORC.

2. System description

When a gasoline engine is running, the energy and exergy quantities of the exhaust and the coolant are significantly different. Because of this, it is very difficult to design a system that can comprehensively recover waste heat from both the exhaust and the coolant of that system. Some previous designs have used the coolant heat to preheat the working fluid and the exhaust heat to evaporate and superheat the working fluid [15,17,20]. However, the heat addition quantity during the evaporating process is greater than that of the preheating process, whereas, the waste heat quantity of the coolant almost equals that of the exhaust. Therefore, the waste heat of the coolant is not comprehensively utilized.

The dual loop ORC designed for this study is shown in Fig. 1. A HT loop recovers the exhaust waste heat while a LT loop is coupled to recover the residual heat of the HT loop and the coolant waste heat. The HT loop consists of pump 1, evaporator 1, expander 1, the preheater, reservoir 1, and the connecting pipes. The LT loop consists of pump 2, the preheater, evaporator 2, expander 2, the condenser, reservoir 2, and the connecting pipes. The LT loop is coupled with the HT loop via the preheater. In this design, a single screw expander is employed as the expander, which has better performance for small-scale applications [21]. The working fluid of the HT loop was chosen to be R245fa because of its good safety and environmental properties [22,23]. For the low-temperature ORC, on the other hand, using a zeotropic mixture as the working fluid can improve system performance [24,25]. However, R134a was selected

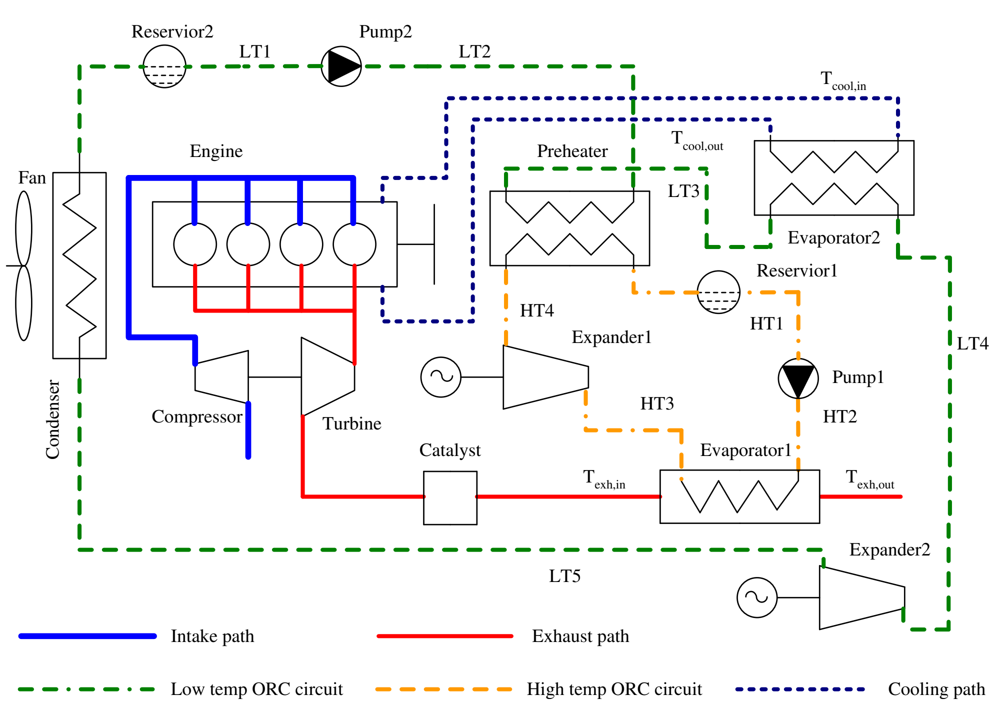

Fig. 1. Schematic of a dual loop ORC system combined with a gasoline engine.