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# THERMODYNAMIC ANALYSIS OF A DUAL-LOOP ORGANIC RANKINE CYCLE (ORC) FOR WASTE HEAT RECOVERY OF A PETROL ENGINE

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## ABSTRACT

Huge amount of low-grade heat energy is discharged to the environment by vehicular engines. Considering the large number of vehicles in the world, such waste energy makes great impacts to our environment globally. Organic Rankine Cycle (ORC), which uses an organic fluid with a low boiling point working medium, is considered as the most promising technology to recover energy from low-grade waste heat. In this study, a dual-loop ORC is presented to simultaneously recover energy from both the exhaust gases and the coolant of a petrol engine. A high-temperature (HT) ORC loop is used to recover heat from the exhaust gases, while a low-temperature (LT) ORC loop is used to recover heat from the coolant and the condensation heat of the HT loop. Figure 1 shows the schematic of the dual-loop ORC. Differing from a previous research, two more environmentally friendly working fluids are used, and the corresponding optimisation is conducted. First, the system structure and operation principle are described. Then, a mathematical model of the designed dual-loop ORC is established. Next, the performance of the dual-loop is analysed over the entire engine operation region. Moreover, the states of each point along the cycle and the heat load of each component are compared with the results of a previous research. The results show that the dual-loop ORC can effectively recover the waste heat from the petrol engine, and that the effective thermal efficiency can be improved by about 20 ~ 24%, 14~20%, and 30% in the high-speed, medium-speed, and low-speed operation regions, respectively. The designed dual-loop ORC can achieve a higher system efficiency than the previous ORC of this structure. Therefore, it is a good choice for waste heat recovery from vehicle engines.

*Keywords:* Organic Rankine Cycle; Dual-loop; Waste heat recovery; Petrol engine; Thermodynamic analysis

## 1. INTRODUCTION

Nowadays, vehicles powered by internal combustion engines consume a large amount of petrol fuels. Furthermore, these vehicle emissions have led to serious environmental issues. Waste heat recovery from engines has been considered a good solution for energy saving by Saidur, 2012. Among various approaches for waste heat recovery, organic Rankine cycle (ORC) is the most feasible one. Boretti, 2012, used an ORC with R245fa as working fluid to recover engine waste heat, and found that an increase in fuel efficiency can be up to 9.2%. Zhang et al, 2014, designed a regenerative ORC to recover the exhaust heat of a diesel engine. Meinel et al, 2014, put forward a two-stage ORC system to recover the exhaust heat of an internal combustion engine where the exhaust temperature was 490 °C. Aiming at waste heat recovery of engine jacket cooling water, Peris et al, 2013, found that a single regenerative ORC using R236fa as working fluid and a reheat regenerative ORC using R134a were both feasible cycles.

Because the temperatures and thermodynamic properties of the exhaust and coolant from an internal combustion engine differ a lot, it is impossible to find a simple ORC architecture to complete heat recovery of these two kinds of waste heat simultaneously. Many different ORC systems were proposed for engine waste recovery. Currently, a dual-loop cycle designed by BMW has caused the greatest attention. Freymann et al, 2008, employed water and ethanol as the working fluids for BMW's schematic. Because both water and ethanol are wet fluids, large irreversibility will be produced during the heat transfer processes. As an improvement to BMW's waste heat recovery system, Wang et al, 2012, Zhang et al, 2013, and Yang et al,

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2014, proposed a dual-loop ORC system using R245fa and R134a as working fluids and estimated their energy saving potential for gasoline and diesel engines, respectively. Meanwhile, Shu et al, 2014, Song and Gu, 2015, studied the performances of dual-loop ORCs using different working fluids.

The selection of working fluid for an ORC has a great effect on system performance. Apart from evaluating the thermodynamic performance, the safety and environmental properties of the working fluid also need to be considered. Previous studies indicate R245fa is a promising solution by Wang et al, 2011. Cummins used R245fa to recover the exhaust heat of a diesel engine. However, as more and more rigid legislation is placed for environmental protection, working fluids with high Global Warming Potential (GWP) must be forbidden. Therefore, it is necessary to find substitute working fluids with better environmental properties. In this paper, the working fluids R1233zd and R1234yf are used to recover waste heat of a gasoline engine. A high-temperature (HT) ORC loop using R1233zd as working fluid recovers the exhaust heat and a low-temperature (LT) ORC loop using R1234yf recovers the coolant heat as well as the condensation heat of the HT loop. The thermodynamic performance of this dual-loop ORC system is evaluated and compared with a dual-loop ORC system using R245fa and R134a.

## 2. DUAL-LOOP ORC SYSTEM

The designed dual-loop ORC system is shown in Figure 1. An HT loop recovers exhaust waste heat whereas an LT loop is employed to recover coolant waste heat. Meanwhile, the LT loop is coupled with the HT loop and recovers the condensation heat from the HT loop. The HT loop consists of reservoir 1, pump 1, evaporator 1, expander 1, and the preheater. The LT loop is composed of reservoir 2, pump 2, the preheater, evaporator 2, expander 2, and the condenser.

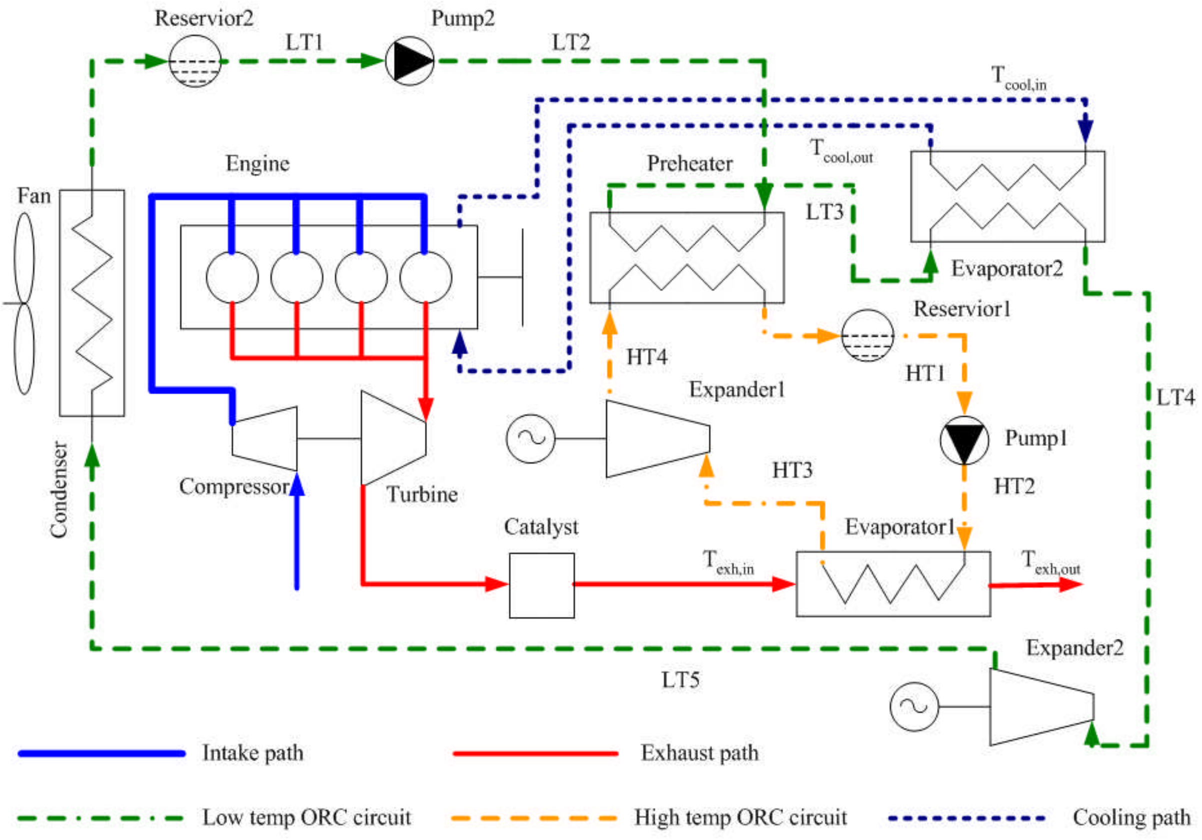

**Figure 1: Schematic of a dual loop ORC system used for a gasoline engine**

In the reference by Wang et al, 2012, R245fa and R134a were applied for the HT and LT loops, respectively.

However, the GWP indexes for both these two working fluids are greater than 1000 and cannot fulfill the forthcoming European environmental regulations. In this paper, two new refrigerants—R1233zd and R1234yf—are used to replace R245fa and R134a. The properties of these working fluids are listed and compared in Table 1. The physical properties of R1233zd are close to R245fa but the toxicity and GWP of R1233zd are much better than those of R245fa. On the other hand, the physical properties of R1234yf are similar to R134a while the GWP value of R1234yf is much lower than that of R134a. Hence, taking into account the strict requirements of vehicle application, R1233zd and R1234yf are more appropriate.

**Table 1: The properties of the selected pure work fluids**

| Substance | Molecular mass [kg/kmol] | Normal boiling point [K] | Critical pressure [Mpa] | Critical temperature [K] | ASHRAE 34 safety group | ODP | GWP |
|---|---|---|---|---|---|---|---|
| R1233zd | 130.5 | 291.47 | 3.5709 | 438.75 | A1 | 0 | 5 |
| R245fa | 134.05 | 288.05 | 3.639 | 427.2 | B1 | 0 | 1030 |
| R1234yf | 114.04 | 243.7 | 3.3822 | 367.85 | A2L | 0 | 4 |
| R134a | 102.03 | 247.08 | 4.059 | 374.21 | A1 | 0 | 1430 |

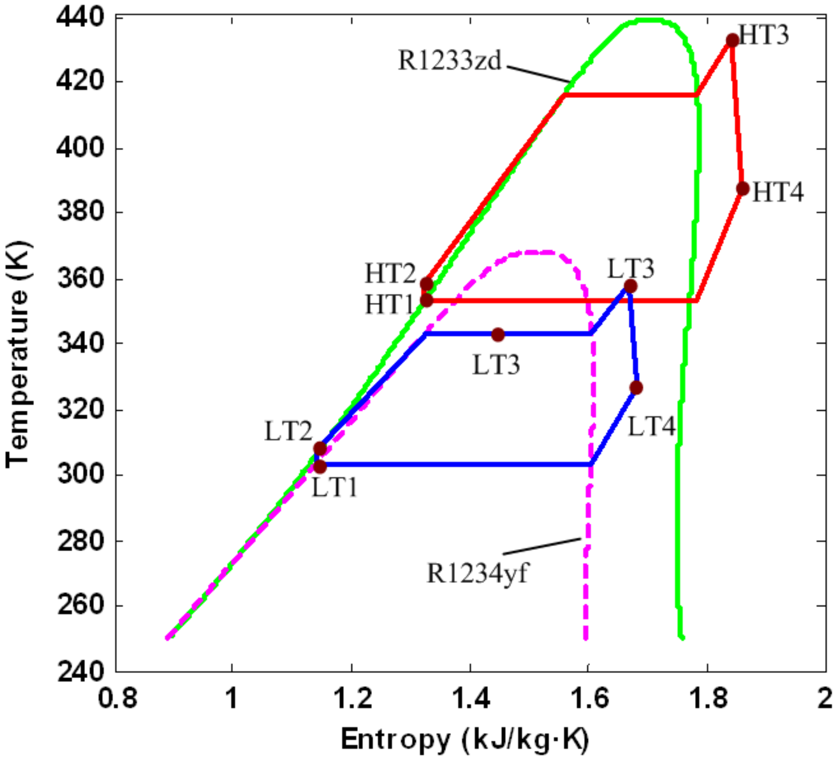

Figure 2: T-s diagram of the dual-loop ORC

The operation principles of the dual-loop ORC system are described as Figure 2. The red lines indicate the

HT loop and the blue lines represent the LT loop. Once the dual-loop ORC system starts, the R1233zd is pumped to evaporator 1. The corresponding process is shown as HT1—HT2 in Figure 2. The exhaust heat from the gasoline engine is delivered to the working fluid inside evaporator 1 and the R1233zd is turned to the superheated state HT3. Subsequently, the R1233zd is expanded in expander 1 and useful work is generated. In Figure 1, the preheater is also used as the condenser of the HT loop. In the preheater, R1233zd is changed into the saturated state HT1. In the LT loop, pump 2 pressurizes the R1234yf to the preheater. The corresponding process is shown as LT1—LT2. The R1234yf is then heated to a two-phase state LT3 in the preheater. Next, the coolant of the engine heats the R1234yf to the superheated state LT4 inside evaporator 2. Afterwards, the R134a is expanded in expander 2 and changed into the low-pressure state LT5. Finally, the R1234yf is condensed and turned into a saturated state LT1.

## 3. SYSTEM PERFORMANCE ANALYSIS

To compare the dual-loop ORC system using R1233zd and R1234yf with that using R245fa and R134a, the same model of gasoline engine as found in Wang et al, 2012, was selected. First, the waste heat amount of the exhaust and coolant at the working point of the rated engine power were measured. Then, using a mathematical model based on the first law method, the thermodynamic performance is analyzed. The ambient temperature is set to 25°C and other working parameters remain the same as those in Wang et al, 2012.

The results of the thermodynamic properties for the HT loop when the engine operates at the rated power are shown in Table 2, and the corresponding results for the LT loop are given in Table 3. The energy load and exergy destruction rate of each component are given in Table 4. In this study, to improve the thermal efficiency of the HT loop with R1233zd, the maximum temperature of the R1233zd is set to 160 °C. The condensation pressure of the HT loop equals 0.658 MPa, which is less than the HT loop with R245fa by 0.131 MPa. Moreover, the evaporation pressure of the LT loop with R1234yf equals 2.045 MPa, which approximates to that with R134a which equals 2.117 MPa. In this study, the maximum temperature of the R1234yf is 10 °C greater than that of the R134a. However, the difference in the condensation pressure between the R1234yf and the R134a is very small. In Table 4, the energy load for each component is similar with the results of the dual-loop ORC system with R245fa and R134a.

**Table 2: Thermodynamic properties of the HT loop at the rated engine power**

| State no. | Pressure (MPa) | Temperature (K) | Enthalpy (kJ/kg) | Entropy (kJ/kg·K) |
|---|---|---|---|---|
| 1 | 0.658 | 353.15 | 310.46 | 1.324 |
| 2 | 2.4 | 354.59 | 303.40 | 1.325 |
| 3 | 2.4 | 433.15 | 513.09 | 1.845 |
| 4 | 0.658 | 387.39 | 493.13 | 1.862 |

**Table 3: Thermodynamic properties of the LT loop at the rated engine power**

| State no. | Pressure (MPa) | Temperature (K) | Enthalpy (kJ/kg) | Entropy (kJ/kg·K) |
|---|---|---|---|---|
| 1 | 0.784 | 303.15 | 240.51 | 1.139 |
| 2 | 2.045 | 304.27 | 241.98 | 1.140 |
| a | 2.045 | 343.15 | 302.22 | 1.326 |
| 3 | 2.045 | 343.15 | 360.77 | 1.497 |
| b | 2.045 | 343.15 | 398.57 | 1.607 |
| 4 | 2.045 | 358.15 | 420.90 | 1.671 |
| 5 | 0.784 | 326.69 | 406.88 | 1.685 |

From the results shown in Table 4, the energy loads of evaporator 1, the preheater, evaporator 2, and the condenser are greater than those of the other components. The exergy destruction rate of evaporator 2, evaporator 1, and the preheater are the largest among the other components while the exergy destruction rate of the condenser is small. The reason is that high-temperature phase change processes exist in evaporator 2, the preheater, and evaporator 1, which results in the irreversibility of these three components are greater.

**Table 4: Results of energy load and exergy destruction rate at the rated engine power**

| Subsystems | $\dot{E}$ (kW) | $\dot{I}$ (kW) |
|---|---|---|
| Pump1 | 1.240 | 0.209 |
| Evaporator1 | 133.58 | 98.705 |
| Expander1 | 12.718 | 3.292 |
| Preheater | 122.10 | 113.81 |
| Pump2 | 2.973 | 0.583 |
| Evaporator2 | 241.24 | 303.69 |
| Expander2 | 28.467 | 8.719 |
| Condenser | 337.85 | 7.418 |

To evaluate the feasibility of the dual-loop ORC using R1233zd and R1234yf as working fluids, the thermal efficiencies of the dual-loop ORC using R1233zd and R1234yf under different ambient temperatures when the engine is working at the rated power are compared with those of the R245fa and R134a and are shown in Figure 3, where 1 represents the HT loop, and 2, 3, 4 denote the LT loop at the ambient temperature of 25°C, 5°C, and -15°C, respectively. The thermal efficiency of the HT loop with R1233zd is slightly higher than that of the R245fa. On the other hand, the thermal efficiencies of the LT loop using R1234yf are slighter lower than those of the R134a under all the ambient temperatures. As a result, the thermodynamic performance of the dual-loop ORC with R1233zd and R1234yf is slightly higher than that with R245fa and R134a.

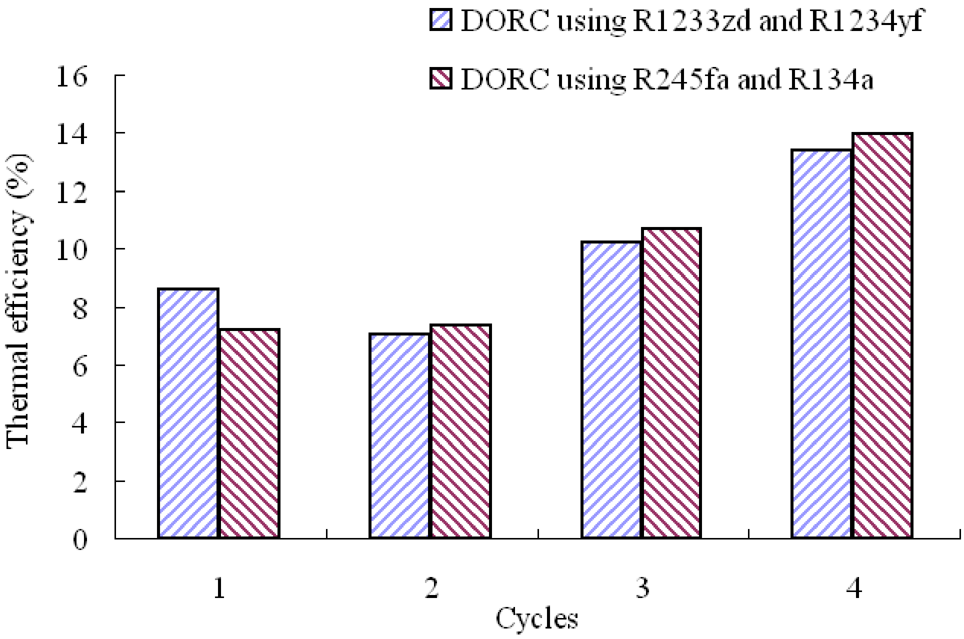

**Figure 3: Comparison of the thermal efficiencies for the two dual-loop ORCs**

## 4. CONCLUSION

To improve the efficiency of internal combustion engine, it is critical to use new technology to recover waste heat generated by the combustion process. It is very difficult to find a suitable working fluid for engine waste heat recovery with high efficiency because of the rigid safety requirements working with vehicles, which hindered the application of organic Rankine cycle technology for vehicles. In this study, the thermodynamic performance of a dual-loop ORC with R1233zd and R1234yf as working fluids is evaluated. The results indicate that the performance of the dual-loop ORC with R1233zd and R1234yf can be very close to that with R245fa and R134a. However, the dual-loop ORC with R1233zd and R1234yf has better environmental performance and thus more suitable for engine waste heat recovery.

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