**Introduction**

Nowadays, internal combustion engines (ICEs) are the major motive power source in energy field, which are widely used in transport, construction, agriculture, etc. Over 50% of the total transportation fuel is consumed by ICEs [1]. However, only 30-45% of the fuel energy is converted into effective power output, while the remaining energy is discharged to the environment via exhaust gas, jacket water and charge air [2]. A large amount of fuel energy is not harnessed. Thus, technology for waste heat recovery from ICEs has drawn much interest of researchers in the last decade. Compared to other waste heat recovery methods such as steam Rankine cycle and Kalina cycle, organic Rankine cycle (ORC) is a promising technology with advantages of high efficiency [3] and simple system structure [4]. So, studies about ICE waste heat recovery systems have been carried out by researchers around the world.

Traditionally, the organic working fluid in the ORC absorbs heat from the high-temperature exhaust gas in an evaporator. After that the vapor flows into the ORC turbine to expand and to produce power. More widespread use of ORC-based ICE waste heat recovery systems requires higher energy conversion efficiency and lower system capital cost. There are two important pathways that will lead to the improvement of the ORC-based ICE waste heat recovery system. One will be selecting organic working fluids which are suitable for the system under certain conditions. Another is to optimize the system configuration to make fully use of the waste heat.

Having significant impacts on the thermal efficiency, design of the components and the capital cost of the power system, the work of selecting suitable organic working fluids has been carried out by many researchers. Liu et al. [5] evaluated the performance of an ORC-based ICE waste heat recovery system using different working fluids. Dry, isentropic and wet types of working fluids were selected as candidates for comparison. Results showed that system with R125a provided the highest net power output when the ORC expander inlet temperature was 200 ℃. Su et al. [6] developed a theoretical thermal efficiency model about working fluids selecting for ORC-based ICE waste heat recovery system via strict mathematical derivation. They found that the thermal efficiency of the system was solely governed by the Jakob number when the evaporation and condensation temperatures were fixed. Ten working fluids with different Jakob number were compared and system with smaller Jakob number working fluids could achieve higher thermal efficiency.

System configuration optimization mainly focuses on the complete utilization of engine exhaust gas and jacket water. Typically, the jacket water cycles in the system with outlet temperature at about 90 ℃ and return temperature at about 80 ℃ [7], while the temperature of the exhaust gas is above 400℃ [8]. Because of the large temperature difference with the exhaust gas, jacket water is mainly used to preheat the organic working fluids or drive a low-temperature ORC. Kim et al. [9] proposed a novel single-loop ORC system to recovery engine waste heat. Jacket water was used to preheat the organic working fluid R245fa and exhaust gas was used to superheat the organic vapor. A high-temperature recuperator and a low-temperature recuperator were employed to increase the thermal efficiency. Comparison showed that net power output of the system was 35.6% more than traditional ORC system. Though the single-loop ORC system has simple structure, the maximum power output of it is lower than that of the dual-loop ORC system [10]. In single-loop ORC system, the relatively low temperature of the jacket water determines that working fluid preheated by the jacket water would have a large temperature difference with the high-temperature exhaust gas, which inevitably results in high irreversible rate in the waste heat recovery system. However, in the dual-loop ORC system, each loop could be optimized for each heat source with optimal temperature difference and mass flow rate. Thus, more attention has been focused on dual-loop ORC based ICE waste heat recovery system in recent years. Seyedkavoosi et al. [11] modeled a dual-pressure ORC system for ICE waste heat recovery. Working fluids in high-pressure and low-pressure side of the dual-pressure ORC system absorbed heat from the exhaust gas and jacket water respectively. Zhong et al. [12] proposed a dual-loop ORC system with zeotropic mixtures as working fluid in both high-temperature loop and low-temperature loop. They optimized the mole fraction of the mixtures in different loops to achieve a better performance of the system. Chen et al. [13] investigated a novel dual-loop ORC based ICE waste heat recovery system with only one kind of working fluid. High-temperature exhaust gas heated the organic working fluid in the high-temperature loop. Exhaust vapor from the high-temperature loop and jacket water operated as heat sources for the low-temperature loop.

When referring to the heat transfer in the high-temperature loop, thermal stability of organic working fluid is necessary to be considered. In previous studies, refrigerants were most selected as working fluid, while their decomposition temperatures were relatively low (200-300 ℃). Direct heat transfer between high-temperature exhaust gas and refrigerant caused the potential of working fluid decomposition. Though high decomposition temperature working fluids such as siloxanes and alkanes are adopted by some researchers, their flammability limits the further applications. Thus, many researchers tried to change the configuration in the high-temperature loop. Traditional, an intermediate loop with heat transfer oil would be placed between the exhaust and the ORC system [14]. But that would cause a large amount of the high-temperature waste heat unharnessed. Therefore, some other waste heat recovery systems were employed by researchers to couple with the ORC. Miller et al. [15] introduced thermoelectric generator (TEG). High-temperature exhaust gas was first exploited by the TEG, then the cooled exhaust gas could drive the ORC safely. But limited by the material, the energy conversion capacity of the TEG is low [16]. Shu et al. [17] placed a steam Rankine cycle between the ORC and the exhaust gas. But because of the phase change of water during the evaporation and condensation, the structure of the steam Rankine cycle system is complex. Considering the requirement of high thermal efficiency and compact configuration, Brayton cycle could be a compromise solution. Brayton cycle with CO2 (carbon dioxide) as working medium has the advantage of low environmental impact and good thermodynamic performance.

ORC system coupled with CO2 Brayton cycle (CBC) was introduced by some researchers. Xia et al. [18] integrated a CBC with an ORC system for ICE waste heat recovery. Zhang et al. [19] compared the thermodynamic performance of a dual-loop ORC system and a CBC-ORC system. However, in the previous CBC-ORC system studies attention was mainly focused on preventing the decomposition potential of the organic working fluids and less attention was paid to fully utilize the waste heat in exhaust gas and jacket water. In the study of Zhang et al. [19], energy in jacket water was not harnessed at all.

A large amount energy exists in jacket water because of the large mass flow rate. Quite a few studies have been published to improve the waste heat recovery from the exhaust gas. Jacket water, though explored by some researchers, is mainly used as the low-temperature heat source to preheat the working fluids in ORC. However, the mass flow rate of working fluid is determined by the exhaust gas in the evaporation process. The mismatch mass flow rate of working fluid in the preheater and evaporator causes a great amount of energy in jacket water unharnessed. Yu et al. [20] calculated the energy recovery efficiency from and ORC-based ICE waste heat recovery system. 75 waste heat could be recovered from the exhaust gas, while only 9.5% waste heat was recovered from jacket water. But for most ICEs (rated power between 500 kW and 200 kW), thermal energy in jacket water is approximate the same as the energy in exhaust gas [21]. Thus, energy in jacket water could be further utilized.

Simple power generation systems only generate power and can’t fulfill the consumers’ demand for variable energy supply. One the contrary, combined cooling and power system not only presents high thermal efficiency but also generate power and cooling capacity simultaneously. Combined cooling and power systems were investigated by many researchers. Xia et al. [22] designed a transcritical CO2 Rankine cycle system coupled with an ejector cycle to generate both power and cooling capacity. Yin et al. [23] modeled a novel combined cooling and power system driven by low-grade waste heat. Fatih [24] developed a multigeneration system driven by solar energy.

Combine cooling and power systems driven by ICE waste heat were also investigated by some researchers. But in most of them, cooling capacity was provided by ammonia absorption refrigeration cycle (AARC) driven by high-temperature waste heat from exhaust gas. The complex cycle structure and high driven temperature requirement of AARC limit further applications. On the contrary, ejector refrigeration cycle (ERC) exhibits the advantages of easy maintenance and high reliability. Moreover, ERC can be driven by low-temperature heat source such as the jacket water. As mentioned ahead, a large amount in the jacket water can be further utilized. Thus, ICE waste heat recovery system with ERC driven by jacket water not only simultaneously generate power and cooling capacity but also fully utilized the jacket water waste heat. Whereas, no combined cooling and power system with ERC driven by jacket water has been investigated before.

In this study, a combined cooling and power system is developed, which comprises a CO2 Brayton cycle, a dual-pressure organic Rankine cycle and an ejector refrigeration cycle. The CO2 Brayton cycle absorbs heat from the high-temperature exhaust gas directly. The turbine exhaust in the CO2 Brayton cycle and the engine exhaust gas after heat transfer are respectively regarded as the heat sources for the high-pressure side and low-pressure side of the dual-pressure ORC, realizing the cascading utilization of exhaust gas. Meanwhile, organic working fluids in high-pressure side and low-pressure side are both preheated by jacket water to make full use of waste heat. What’s more, the ejector refrigeration cycle is adopted to utilize rest waste heat in jacket water and produce cooling capacity. Thermodynamic and exergoeconomic analysis is carried out to examine the effects of key parameters on system performance. Then a system optimization is conducted to obtain the minimum levelized exergy cost for the system product by means of genetic algorithm (GA).