**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 methods such as steam Rankine cycle and Kalina cycle, organic Rankine cycle (ORC) is a promising technology with advantages of high efficiency [] and simple structure []. Consequently, ICE waste heat recovery system based on ORC have drawn the interest of 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 capital cost. There are two important pathways that will lead to the improvement of the ORC 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. [] tested the thermodynamic performance of dry, isentropic and wet types of working fluids in an ORC-based ICE waste heat recovery system to find the suitable candidate. Su et al. [] developed a theoretical efficiency model about working fluids selecting for ORC-based ICE waste heat recovery system via strict mathematical derivation.

System configuration optimization mainly focuses on reducing the system irreversible rate to fully utilize the engine waste heat. Kim et al. [] proposed a novel single-loop ORC system to recovery engine waste heat. They employed two recuperators to gradually heat the working fluid. Thus, temperature difference between exhaust gas and organic working fluid was kept in a suitable range. Comparison showed that the net power output of the system was 35.6% more than traditional ORC system. On general, the maximum power output of single-loop ORC is lower than that of the dual-loop ORC system []. Thus, more attention has been focused on dual-loop ORC based ICE waste heat recovery system in recent years. Huang et al. [] modeled a dual-loop ORC system for engine waste heat recovery. Organic working fluid in the high-temperature loop absorbed heat from exhaust gas with a small temperature difference. After that, high-temperature exhaust vapor from the turbine provided heat for the low-temperature loop to further utilize the waste heat. Zhong et al. [] proposed a dual-loop ORC system with zeotropic mixtures as working fluid in both loops. The temperatures of zeotropic mixtures are variable during the evaporation and condensation processes. Thus, in the dual-loop ORC system, temperature profiles between exhaust gas and working fluid match mutually, resulting the increase of system thermal efficiency and power output. Wang et al. [] investigated a complex dual-loop ORC system for ICE waste heat recovery. Exhaust gas provided heat for the high-temperature loop for the first time. Then the exhaust gas provided heat for the low-temperature loop for the second time to realize the cascading utilization of the waste heat.

When referring to 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. The decomposition temperatures of refrigerants were relatively low (200-300 ℃) [], while the temperature of exhaust gas is above 400 ℃ []. Direct heat transfer between high-temperature exhaust gas and refrigerant caused the risk 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. Traditionally, an intermediate loop with heat transfer oil would be placed between the exhaust gas and the ORC system []. 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. [] introduced thermoelectric generator (TEG) technology. High-temperature exhaust gas was first exploited by the TEG, then the cooled exhaust gas could drive the ORC safely. But the energy conversion capacity of TEG is low because of the material limitation. Shu et al. [] placed a steam Rankine cycle between the ORC and the exhaust gas. However, the system structure is complex because of the phase changing during the evaporation and condensation processes. 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 fluid has the advantage of low environmental impact and good thermodynamic performance.

Few studies about ORC system coupled with CO2 Brayton cycle (CBC) have been published. Even Zhang et al. [] carried out some relevant studies, their attention was focused on the performance comparison with dual-loop ORC system. The energy in jacket water was not harnessed at all in their system.

Typically, the jacket water cycles in the engine system with outlet temperature at about 90 ℃ and return temperature at about 80 ℃ []. There is a large amount energy exist in jacket water. For most ICEs (rated power between 500 kW and 200kW), thermal energy in jacket water is approximate the same as the energy in exhaust gas []. But the utilization rate of jacket water is low. Yu et al. [] calculated the energy recovery efficiency from an ORC-based ICE waste heat recovery system. 75% waste heat could be recovered from the exhaust gas, while only 9.5% waste heat was recovery from jacket water. In most ORC-based ICE waste heat recovery system, jacket water is mainly used to preheat the organic working fluids. However, the mismatch mass flow rate of working fluid in the preheater and evaporator causes a great amount of energy in jacket water unharnessed []. Thus, the utilization of energy in jacket water could be further explored.

To fulfill the variable demand of consumers, combined cooling and power systems which can generate power and cooling capacity simultaneously with high efficiency are investigated by many researchers. Yin et al. [] modeled a novel combined cooling and power system driven by low-grade waste heat. Fatih [] developed a multigeneration system driven by solar energy. Yang et al. [] designed a combined cooling and power system with biomass gasification.

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 its 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 utilize the 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).

The innovative features of this paper are as follow:

* A CO2 Brayton cycle is investigated to prevent the risk of decomposition of organic working fluid.
* A dual-pressure ORC system is developed to cascading utilize the waste heat in exhaust gas and jacket water and provide large amounts of power output.
* An ejector refrigeration cycle driven by jacket water is designed to provide cooling capacity and fully utilize the jacket water waste heat.