**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, much research effort has been devoted to the study of ORC-based ICE waste heat recovery.

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. Rijpkema et al. [4] compared the thermodynamic performance of twelve 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 hinders 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 neatly 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 refrigeration 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 refrigeration 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 (CCP) 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 refrigeration. 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 refrigeration and fully utilize the jacket water waste heat.

**CCP system description**

The combined cooling and power system is shown in Fig. 1. The system integrates a dual-pressure organic Rankine cycle with a CO2­ Brayton cycle and an ejector refrigeration, which can produce power and refrigeration simultaneously. High-temperature gas heat from the ICE enters the gas heater to provide heat for the CBC. In the CBC, compressor compresses the CO2 to a supercritical state. The high-pressure CO2 flows into the gas heater to absorb heat. Then CO2 with high temperature and high pressure expands through the BC turbine to produce power.

Organic working fluid in the DORC is preheated by the jacket water. After that, the organic working fluid separates into two parts. One part is pumped to the vapor generator 1 to absorbs heat from the secondary engine exhaust gas in the low-pressure side cycle. Then this part of working fluid enters the low-pressure inlet of the ORC turbine to produce power. The other part of the organic working is pumped to the vapor generator 2 to absorb heat from the residual heat in exhaust CO2 after the BC turbine. Then this high-pressure part organic working fluid flows into the high-pressure inlet of the ORC turbine to produce power.

After the preheating, jacket water flows into the vapor generator 3 to provide heat for the ejector refrigeration cycle. There are two parts working fluid in the ERC. One part is pumped to the vapor generator 3 to absorb heat. After the vapor generator, the high-temperature and high-pressure vapor enters the primary inlet of the ejector, entrains a low-pressure part of working fluid into the secondary inlet of the ejector. The two parts of working fluid mixes with the low-pressure part in the ejector to obtain a relatively high average pressure. The mixed working fluid is condensed to liquid when flows out the ejector. After that, the liquid separates into two parts. One part of it flows through a throttle valve to provide refrigeration in the evaporator. The other part is pumped to the vapor generator to absorb heat again.

**System model**

Several assumptions are made to simplify the simulation of the system, which are: (1) the system keeps a steady state; (2) the heat and frication in the system are not considered; (3) the pressure losses in the vapor generators, preheater, evaporator, condensers and

This paper develops a combined cooling and power system, which consists of a CO2 Brayton cycle, a dual-pressure organic Rankine cycle and an ejector refrigeration cycle, to recover waste heat from exhaust gas and jacket water in internal combustion engines. Thermodynamic models of the system are performed and exergoeconomic methods are used to calculate the levelized exergy cost of the component products. Effects of seven parameters including inlet temperature and pressure of the Brayton cycle turbine, inlet temperature and pressure of the high-pressure and low-pressure side of the organic Rankine cycle turbine and the primary flow pressure of the ejector are evaluated. Single-objective optimization is carried out by means of genetic algorithm to obtain the minimum levelized exergy cost of system product. Results show that the increase of the temperature at Brayton cycle turbine inlet and high-pressure and low-pressure inlet of the organic Rankine cycle turbine contributes to the levelized exergy cost of the system product. Optimization shows that minimum levelized exergy cost for system product is 53.25 $ (MWh)-1. Under the levelized exergy cost optimal condition, the system net power output, refrigeration capacity and exergy efficiency are 374.37 kW, 188.63 kW and 37.31%, respectively.

[1] Heywood J. B. Internal combustion engine fundamentals. New York: McGraw-Hill; 1988.

[2] Chao H, Chao L, Hong G, Hui X, You L, Shuang W. The optimal evaporation temperature and working fluids for subcritical Organic Rankine Cycle. Energy 2012; 38: 136-143.

[3] Bombarda P, Invernizzi C, Pietra C. Heat recovery from Diesel engines: A thermodynamic comparison between Kalina and ORC cycles. Applied Thermal Engineering 2010; 30: 212-219.

[4] Kalyan K, Pedro J, Sundar R. Analysis of exhaust waste heat recovery from a dual fuel low temperature combustion engine using an Organic Rankine Cycle. Energy 2010; 35: 2387-2399.

[5] Wei M, Fang J, Ma C, Danish S. Waste heat recovery from heavy-duty diesel engine exhaust gases by medium temperature ORC system. Science China Technological Sciences 2011; 54: 2746-2753.

[6] Srinivasan K, Mago P, Zdaniuk G, Chamra L, Midkiff K. Improving the Efficiency of the Advanced Injection Low Pilot Ignited Natural Gas Engine Using Organic Rankine Cycles. 2008; 130: 022201.

[7] Tian H, Shu G, Wei H, Liang X, Liu L. Fluids and parameters optimization for the organic Rankine cycles (ORCs) used in exhaust heat recovery of Internal Combustion Engine (ICE). Energy 2012; 47: 125-136.

[8] Vaja I, Gambarotta A. Internal Combustion Engine (ICE) bottoming with Organic Rankine Cycles (ORCs). Energy 2010; 35(2): 1084-1093.

[9] Rosset K, Mounier V, Guenat E, Schiffmann J. Multi-objective optimization of turbo-ORC systems for waste heat recovery on passenger car engines. Energy 2018; 159: 751-765.

[10] Zhang H G, Wang E H, Fan B Y. A performance analysis of a novel system of a dual loop bottoming organic Rankine cycle (ORC) with a light-duty diesel engine. Applied Energy 2013;102: 1504-1513.

[11] Yang F, Cho H, Zhang H, Zhang J. Thermoeconomic multi-objective optimization of a dual loop organic Rankine cycle (ORC) for CNG engine waste heat recovery. Applied Energy 2017; 205: 1100-1118.

[12] Ge Z, Li J, Liu Q, Duan Y, Yang Z. Thermodynamic analysis of dual-loop organic Rankine cycle using zeotropic mixtures for internal combustion engine waste heat recovery. Energy Conversion and Management 2018; 166: 201-214.

[13] Chen T, Zhuge W, Zhang Y, Zhang L. A novel cascade organic Rankine cycle (ORC) system for waste heat recovery of truck diesel engines. Energy Conversion and Management 2017;138: 210-223.

[14] Mansoury M, Jafarmadar S, Khalilarya S. Energetic and exergetic assessment of a two-stage Organic Rankine Cycle with reactivity-controlled compression ignition engine as a low temperature heat source. Energy Conversion and Management 2018; 166: 201-214.

[15] Seyedkavoosi S, Javan S, Kota K. Exergy-based optimization of an organic Rankine cycle (ORC) for waste heat recovery from an internal combustion engine (ICE). Applied Thermal Engineering 2017; 126: 447-457.

[16] Rajabloo T, Davide B, Paolo lora. Effect of a partial thermal decomposition of the working fluid on the performances of ORC power plants. Energy 2017; 133:1013-1026.

[17] Shu G, Zhao M, Tian H, Wei H, Liang X, Huo Y, et al. Experimental investigation on thermal OS/ORC (Oil Storage/Organic Rankine Cycle) system for waste heat recovery from diesel engine. Energy 2016; 107: 693-706.

[18] Wang X, Tian H, Shu G. Part-load performance prediction and operation strategy

design of organic Rankine cycles with a medium cycle used for recovering waste heat from gaseous fuel engines. Energies 2016; 9: 527.

[19] Miller E, Hendricks T, Peterson R. Modeling Energy Recovery Using Thermo-electric Conversion Integrated with an Organic Rankine Bottoming Cycle. Journal of Electron Mater 2009; 38: 1206-1213.

[20] Miller E, Hendricks T, Wang H, Peterson R. Integrated dual-cycle energy recovery using thermoelectric conversion and an organic Rankine bottoming cycle. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 2011; 225: 33-43.

[21] Shu G, Wang X, Tian H. Theoretical analysis and comparison of Rankine cycle and different organic Rankine cycles as waste heat recovery system for a large gaseous fuel internal combustion engine. Applied Thermal Engineering 2016; 108: 525-537.

[22] Galindo J, Guardiola C, Dolz V, Kleut P. Further analysis of a compression-expansion machine for a Brayton Waste Heat Recovery cycle on an IC engine. Applied Thermal Engineering 2018; 128: 345-356.

[23] Yu G, Shu G, Tian Hua, Wei H, Liu L. Simulation and thermodynamic analysis of a bottoming Organic Rankine Cycle (ORC) of diesel engine (DE). Energy 2013; 51: 281-290.

[24] Ma J, Liu L, Zhu T, Zhang T. Cascade utilization of exhaust gas and jacket water waste heat from an Internal Combustion Engine by a single loop Organic Rankine Cycle system. Applied Thermal Engineering 2016; 107: 218-226.

[25] Chen Y, Han W, Jin H. Investigation of an ammonia-water combined power and

cooling system driven by the jacket water and exhaust gas heat of an internal combustion engine. International Journal of Refrigeration 2017; 82: 174-188.

[26] Salek F, Moghaddam A, Naserian M. Thermodynamic analysis of diesel engine coupled with ORC and absorption refrigeration cycle. Energy Conversion and Management 2017; 140: 240-246.

[27] Wang J, Dai Y, Sun Z, A theoretical study on a novel combined power and ejector refrigeration cycle. International Journal of Refrigeration 2009; 32: 1186-1194.

[28] Ahmadi P, Dincer I, Rosen M. Performance assessment and optimization of a novel integrated multigeneration system for residential buildings. Energy and Buildings 2013; 67: 568-578.

[29] Dai Y, Wang J, Gao L. Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery. Energy Conversion Management 2009; 50: 576-582.

[30] Shu G, Zhao M, Tian H, Huo Y, Zhu W. Experimental comparison of R123 and R245fa as working fluids for waste heat recovery from heavy-duty diesel engine. Energy 2016; 115: 756-769.

[31] Zhang J, Zhang H, Yang K, Yang F, Wang Z, Zhao G, et al. Performance analysis of regenerative organic Rankine cycle (RORC) using the pure working fluid and the zeotropic mixture over the whole operating range of a diesel engine. Energy Conversion Management 2014; 84: 282-294.

[32] Adrian Bejan GT, Moran Michael. Thermal design and optimization. New York: Jogn Wiley & Sons; 1996.

[33] Turton R. Analysis, synthesis, and design of chemical processes. 3rd ed. Upper Saddle River, N.J: Prentice Hall; 2009.

[34] Li J, Ge Z, Liu Q, Duan Y, Yang Z. Thermo-economic performance analyses and comparison of two turbine layouts for organic Rankine cycles with dual-pressure evaporation. Energy Conversion and Management, 2018; 164: 603-614.

[35] <http://www.chemengonline.com/pci-home>

[36] Sheng Z, Huai W, Tao G. Performance comparison and parametric optimization of subcritical organic Rankine cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. Applied Energy 2011;88(8):2740-2754.

[37] Tempesti D, Fiaschi D. Thermo-economic assessment of a micro CHP system fueled by geothermal and solar energy. Energy 2013; 58: 45-51.

[38] Velez F, Segovia JJ, Martin MC, Antonlin G, Chejne F, Quijano A. A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. Renewable and Sustainable Energy Reviews, 2012; 16:4175-4189.

[39] Akbari D, Mahmoudi M. Thermoeconomic analysis & optimization of the combined supercritical CO2 (carbon dioxide) recompression Brayton/ organic Rankine cycle. Energy 2014; 78:501-512.

[40] Zare V, Mahmoudi M, Yari M. An exergoeconomic investigation of waste heat recovery from the Gas Turbine-Modular Helium Reactor (GT-MHR) employing an ammonia–water power/cooling cycle. Energy 2013;61. 397-409.

[41] Lemmon EW, Huber ML, McLinden MO. NIST standard reference database 23, reference fluid thermodynamic and transport properties (REFPROP). Version 9.1. National Institute of Standards and Technology; 2010

[42] Wang J, Dai Y, Gao L. Parametric analysis and optimization for a combined power and refrigeration cycle. Applied Energy 2008;85(11):1071-1085

[43] Kern DQ. Process heat transfer. New York: McGraw-Hill; 1950

[44] Kandylas IP, Stamatelos AM. Engine exhaust system design based on heat transfer computation. Energy Conversion Management 1999; 40:1057-1072.

[45] Incropera FP, DeWitt DP. Fundamentals of heat and mass transfer. New York: Wiley; 2002

[46] Gungor KE, Winterton RHS. Simplified general correlation for saturated flow boiling and comparisons of correlations with data. Chemical Engineering Research and Design, 1987; 65:148-156.

[47] Shah MM. A general correlation for heat transfer during film condensation inside pipes. International Journal of Heat and Mass Transfer 1979; 22:547-556.

[1] Liu P, Shu G, Tian H, Wang X, Yu Z. Alkanes based two-stage expansion with interheating Organic Rankine cycle for multi-waste heat recovery of truck diesel engine. Energy 2018; 147:337-50.

[2] Heywood J. B. Internal combustion engine fundamentals. New York: McGraw-Hill; 1988.

[3] Wang J, Yan Z, Wang M, Ma S, Dai Y. Thermodynamic analysis and optimization of an (organic Rankine cycle) ORC using low grade heat source. Energy 2013; 49:356-65.

[4] Rijpkema J, Munch K, Andersson S. Thermodynamic potential of twelve working fluids in Rankine and flash cycles for waste heat recovery in heavy duty diesel engines. Energy 2018; 160:996-1007.

[5] Su X, Shedd T A. Towards working fluid properties and selection of Rankine cycle based waste heat recovery (WHR) systems for internal combustion engines – A fundamental analysis. Appl Therm Eng 2018; 142:502-10.

[6] Kim M, Shin G, Kim G, Cho B. Single-loop organic Rankine cycle for engine waste heat recovery using both low-and high-temperature heat sources. Energy 2016; 96:482-94.

[7] Ringer J, Seifert M, Guyotot V, Hübner W. Rankine cycle for waste heat recovery of IC engines. SAE. 2009. 2009-01-0174.

[8] Huang H, Zhu J, Deng W, Ouyang T, Yan B, Yang X. Influence of exhaust heat distribution on the performance of dual-loop organic Rankine Cycle (DORC) for waste heat recovery. Energy 2018; 151:54-65.

[9] Ge Z, Li J, Liu Q, Duan Y, Yang Z. Thermodynamic analysis of dual-loop organic Rankine cycle using zeotropic mixtures for internal combustion engine waste heat recovery. Energy Convers Manage 2018; 166:201-14.

[10] Wang E, Yu Z, Zhang H, Yang F. A regenerative supercritical dual-loop organic Rankine cycle system for energy recovery from the waste heat of internal combustion engines. Appl Energy 2017; 190:574-90.

[11] Rajabloo T, Bonalumi D, Lora P. Effect of a partial thermal decomposition of the working fluid on the performances of ORC power plants. Energy 2017; 133:1013-26.

[12] Shi L, Shu G, Tian H, Deng S. A review of modified Organic Rankine cycles (ORCs) for internal combustion engine waste heat recovery (ICE-WHR). Renew Sustain Energy Rev 2018; 92:95-110.

[13] Xia J, Wang J, Zhang G, Lou J, Zhao P, Dai Y. Thermo-economic analysis and comparative study of transcritical power cycles using CO2-based mixtures as working fluids. Appl Therm Eng 2018; 144:31-44.

[14] Shu G, Gao Y, Tian H, Wei H, Liang X. Study of mixtures based on hydrocarbons used in ORC (organic Rankine cycle) for engine waste heat recovery. Energy 2014; 74:428-38.

[15] Miller E, Hendricks T, Wang H, Peterson R. Integrated dual-cycle energy recovery using thermoelectric conversion and an organic Rankine bottoming cycle. Proceedings of the Institution of Mechanical Engineers, Part A: J Power Energy 2011; 225:33-43.

[16] Shu G, Wang X, Tian H. Theoretical analysis and comparison of Rankine cycle and different organic Rankine cycles as waste heat recovery system for a large gaseous fuel internal combustion engine. Appl Therm Eng 2016; 108:525-37.

[17] Nader W, Mansour C, Dumand C, Nemer M. Brayton cycles as waste heat recovery systems on series hybrid electric vehicles. Energy Convers Manage 2018; 168:200-14.

[18] Zhang C, Shu G, Tian H, Wei H, Liang X. Comparative study of a alternative ORC-based combined power systems to exploit high temperature waste heat. Energy Convers Manage 2015; 541-54.

[19] Peris B, Navarro-Esbrí J, Molés F. Bottoming organic Rankine cycle configurations to increase Internal Combustion Engines power output from cooing waster waste heat recovery. Appl Therm Eng 2013; 61:364-71.

[20] Ma J, Liu L, Zhu T, Zhang T. Cascade utilization of exhaust gas and jacket water waste heat from an Internal Combustion Engine by a single loop Organic Rankine Cycle system. Appl Therm Eng 2016; 107:218-26.

[21] Yu G, Shu G, Tian H, Wei H, Liu L. Simulation and thermodynamic analysis of a bottoming Organic Rankine Cycle (ORC) of diesel engine (DE). Energy 2013; 51:281-90.

[22] Xia J, Wang J, Lou J, Pan Z, Dai Y. Thermo-economic analysis and optimization of a combined cooling and power (CCP) system for engine waste heat recovery. Energy Convers Manage 2016; 128:303-16.

[23] Yin J, Yu Z, Zhang C, Tian M, Han J. Thermodynamic analysis of a novel combined cooling and power system driven by low-grade heat sources. Energy 2018; 156:319-27.

[24] Fatih Y. Thermodynamic performance evaluation of a novel solar energy based multigeneration system. Appl Therm Eng 2018; 143:429-37.

[25] Yang K, Zhu N, Ding Y, Chang C, Yuan T. Thermoeconomic analysis of an intergrated combined cooling heating and power system with biomass gasification. Energy Convers Manage 2018; 171:671-82.

[26] Wang J, Dai Y, Sun Z. A theoretical study on a novel combined power and ejector refrigeration cycle. Int J Refrig 2009; 32(6):1186-94.

[27] Dai Y, Wang J, Gao L. Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery. Energy Convers Manage 2009; 50:576-82.

[28] Shu G, Zhao M, Tian H, Huo Y, Zhu W. Experimental comparison of R123 and R245fa as working fluids for waste heat recovery from heavy-duty diesel engine. Energy 2016; 115:756-69.

[29] Zhang J, Zhang H, Yang K, Yang F, Wang Z, Zhao G, Liu H, Wang E, Yao B. Performance analysis of regenerative organic Rankine cycle (RORC) using the pure working fluid and the zeotropic mixture over the whole operating range of a diesel engine. Energy Convers Manage 2014; 84:282-94.

[30] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: John Wiley & Sons; 1996.

[31] Turton R, Bailie RC, Whiting WB, Shaeiwitz JA. Analysis, synthesis, and design of chemical processes. 3rd ed. Upper Saddle River, N.J: Prentice Hall; 2009.

[32] Li J, Ge Z, Liu Q, Duan Y, Yang Z. Thermo-economic performance analyses and comparison of two turbine layouts for organic Rankine cycles with dual-pressure evaporation. Energy Convers Manage, 2018; 164:603-14.

[33] http://www.chemengonline.com/pci-home

[34] Sheng Z, Huai W, Tao G. Performance comparison and parametric optimization of subcritical organic Rankine cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. Appl Energy 2011;88(8):2740-54.

[35] Tempesti D, Fiaschi D. Thermo-economic assessment of a micro CHP system fueled by geothermal and solar energy. Energy 2013; 58: 45-51.

[36] Velez F, Segovia JJ, Martin MC, Antonlin G, Chejne F, Quijano A. A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. Renew Sustain Energy Rev 2012; 16:4175-89.

[37] Akbari D, Mahmoudi M. Thermoeconomic analysis & optimization of the combined supercritical CO2 (carbon dioxide) recompression Brayton/ organic Rankine cycle. Energy 2014; 78:501-12.

[38] Zare V, Mahmoudi M, Yari M. An exergoeconomic investigation of waste heat recovery from the Gas Turbine-Modular Helium Reactor (GT-MHR) employing an ammonia–water power/cooling cycle. Energy 2013;61. 397-409.

[39] Vaja I, Gambarotta A. Internal Combustion Engine (ICE) bottoming with Organic Rankine Cycles (ORCs). Energy 2010; 35(2):1084-93.

[40] Lemmon EW, Huber ML, McLinden MO. NIST standard reference database 23, reference fluid thermodynamic and transport properties (REFPROP). Version 9.1. National Institute of Standards and Technology; 2010

[41] Wang J, Dai Y, Gao L. Parametric analysis and optimization for a combined power and refrigeration cycle. Appl Energy 2008;85(11):1071-85.

[42] Kern DQ. Process heat transfer. New York: McGraw-Hill; 1950

[43] Kandylas IP, Stamatelos AM. Engine exhaust system design based on heat transfer computation. Energy Convers Manage 1999; 40:1057-72.

[44] Incropera FP, DeWitt DP. Fundamentals of heat and mass transfer. New York: Wiley; 2002

[45] Gungor KE, Winterton RHS. Simplified general correlation for saturated flow boiling and comparisons of correlations with data. Chem Eng Res and Des, 1987; 65:148-56.

[46] Shah MM. A general correlation for heat transfer during film condensation inside pipes. Int J Heat Mass Transf 1979; 22:547-56.

**Nomenclature**

|  |  |  |  |
| --- | --- | --- | --- |
| Latin symbol | | ρ | density, kg m-3 |
| A | area, m2 | μ | dynamic viscosity, m2 s-1 |
| Bo | boiling number | η | efficiency, % |
| c | levelized average cost, $ (MWh)-1 | δ | thickness, m |
| cp | specific heat, kJ kg-1 K-1 | Subscribe | |
| C | cost rate, $ year-1 | 1-31 | state points |
| D | diameter, m | g1-g3 | state points |
| e | exergy, kJ kg-1 | w1-w3 | state points |
| E | exergy flow rate, kJ s-1 | Bt | Brayton cycle turbine |
| Ey | exergy flow rate per year, kJ year-1 | BM | bare module |
| F | multiplying factor | cond | condenser |
| f | friction factor | comp | compressor |
| G | mass flow rate, kg s-1 | D | destruction |
| h | enthalpy, kJ kg-1 | elec | electricity |
| H | depth, m | es | equivalent diameter |
| ieff | interest rate | ev | evaporation/evaporator |
| l | length, m | ex | exergy |
| M | mass flow rate, kg s-1 | F | fuel |
| n | lifetime, year | g | exhaust gas |
| Nu | Nusselt number | gh | gas heater |
| P | pressure, MPa | he | heat exchanger |
| Pr | Prandtl number | L | loss |
| Pt | center distance between tubes, m | l | liquid |
| Pr | reduced pressure | M | material |
| Q | heat transfer rate, kW | Ot | ORC turbine |
| Qcool | cooling capacity, kW | P | product |
| qm | average imposed wall heat flux, W m-2 | p1 | pump 1 |
| rf | enthalpy of vaporization, kJ kg-1 | p2 | pump 2 |
| T | temperature, K | p3 | pump 3 |
| U | overall heat transfer coefficient, W m-2 K-1 | p4 | pump 4 |
| W | power, kW | pf | primary flow |
| Wy | annually power, MWh year-1 | prec | precooler |
| x | vapor quality | preh | preheater |
| Z | annually levelized cost value, $ year-1 | s | shell |
| z | capital cost, k$ | t | tube |
| Acronym | | th | thermal |
| BC | Brayton cycle | turb | turbine |
| CBC | CO2 Brayton cycle | vg | vapor generator |
| CCP | combined cooling and power | w | tube wall |
| CRF | capital recovery factor |  |  |
| CEPCI | chemical engineering plant cost index |  |  |
| DORC | dual-pressure organic Rankine cycle |  |  |
| ERC | ejector refrigeration cycle |  |  |
| GA | genetic algorithm |  |  |
| TEG | thermoelectric generator |  |  |
| Greek symbol | |  |  |
| α | convection heat transfer coefficient, W m-2 K-1 |  |  |
| λ | heat conductivity, W m-1 K-1 |  |  |



The parameters analysis reveals that the potential pf optimization for the CCP system. With the increase of the BC turbine inlet temperature, the net power output of the system increases while the refrigeration capacity decreases. With the increase of the inlet temperature at the high-pressure side of the ORC turbine, the net power output of the system decreases while the cooling capacity increases. In this study, seven key parameters (TBt,in, PBt, in, TOt, in, h, POt, in, h, TOt, in, l, POt, in, l and Pej, in) are chosen as the variables.

The work of selecting suitable organic working fluids for ORC was carried out by many researchers to improve the efficiency of the ICE waste heat recovery. Lu et al. [] evaluated the performance of six different working fluids in a small-scale ORC system for ICE waste heat recovery. Rijpkema et al. [4] compared the performance of twelve working fluids in an ORC-based ICE waste heat recovery system to find the suitable candidate. Su et al. [5] developed a theoretical efficiency model about working fluids selecting for ORC-based ICE waste heat recovery system via strict mathematical derivation.

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Configuration optimization in ORC-based ICE waste heat recovery system mainly focuses on reducing the system irreversible rate to fully utilize the engine waste heat. Vaja and Gambarotta [8] added a preheater and a recuperator separately to a simple ORC system to improve the performance for the ICE waste heat recovery. Kim et al. [6] proposed a novel single-loop ORC system to recovery engine waste heat. They employed two recuperators in series to heat the working fluid. Comparison showed that the net power output of the system was 35.6% more than simple ORC system. Because that the maximum power output of single-loop ORC is lower than that of the dual-loop ORC system [7], thus, more attention has been focused on dual-loop ORC based ICE waste heat recovery system in recent years. Wang et al. [8] modeled a dual-loop ORC system for engine waste heat recovery. The high-temperature loop absorbed heat from exhaust gas and its residual heat acted as heat source for the low-temperature loop. Wang et al. [10] investigated a dual-loop ORC system for ICE waste heat recovery. The high-temperature loop absorbed heat from exhaust gas for the first time. Then the low-temperature loop absorbed heat from the residual heat of the exhaust gas to realize the cascading utilization of the waste heat. Huang et al. [] proposed a complex dual-loop ORC system for engine waste heat recovery. The high-temperature loop absorbed heat from the exhaust gas and residual heat from both the exhaust gas and the high-temperature loop provided heat for the low-temperature loop.

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Nowadays, internal combustion engines (ICEs) are the major motive power source in energy field, which are widely used in transport, construction, agriculture, etc. Over 49 % 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, causing a large amount of fuel energy unharnessed. Thus, technology for waste heat recovery from ICEs has drawn much interest of researchers in the last decade. Much effort has been devoted to the study of ORC-based ICE waste heat recovery system for its advantages of high efficiency and simple structure [3].

There are two important pathways that will lead to the improvement of the ORC system for ICE waste heat recovery. 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.

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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 fluids. The decomposition temperatures of refrigerants were relatively low (200-300 ℃) [11], while the temperature of exhaust gas is above 450 ℃ [12]. 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 were adopted by some researchers, their flammability hindered their further applications [13]. Though placing a heat transfer oil intermediate loop between the exhaust gas and the ORC system could address this issue [14], that would cause a large amount of the high-temperature waste heat unharnessed. Therefore, some other high-temperature loops for waste heat recovery were employed by researchers to couple with the ORC. Miller et al. [15] 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. Steam Rankine for its high efficiency and stable operation attracted much attention of researchers. Shu et al. [16] placed a steam Rankine cycle between the ORC and the exhaust gas. Yu et al. [] coupled a steam Rankine cycle with an ORC for the ICE waste heat recovery. However, the large bulk of the components in steam Rankine cycle limits further applications (such as application in vehicles). 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 [17]. Few studies about ORC system coupled with CO2 Brayton cycle (CBC) for ICE waste heat recovery have been published. Though Zhang et al. [18] carried out some relevant studies, their attention was focused on comparing the performance of CBC, TEG and steam Rankine cycle when coupled with the same bottom ORC. Detailed analysis of the CBC was not given and the energy in jacket water was not harnessed.

Jacket water, though containing large amounts of energy [20], obtained little attention in the previous studies. For its relatively low temperature, jacket water was mainly used to preheat the organic working fluid in the ORC system. In the ORC-based ICE waste heat recovery system designed by Zhang et al. [] jacket water was used to preheat the organic working fluid. Then the organic working fluid was heat by the high-temperature exhaust gas to vapor state and expanded in the ORC turbine. In Yang’s [] ICE waste heat recovery system, jacket water and secondary exhaust gas were used to preheat the organic working fluids in ORC. In the dual-loop ORC based ICE waste heat recovery system investigated by Chen et al. [], jacket water was used to preheat the low-temperature-loop. Yu et al. [21] 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 the ORC system with jacket water preheating, the utilization efficiency of energy from jacket water is relatively low. The mismatch of mass flow rate of organic working fluid in the preheater and evaporator causes a great amount of energy in the jacket water unharnessed. Thus, the utilization of energy in jacket water could be further explored.

Multigeneration system driven by waste heat has drawn increasing interest of researchers in light of the trend towards reducing emissions, increasing the efficiency of energy use and providing variable energy. Li et al. [] modeled a combined cooling, heating and power system to highly utilize the waste heat. Yari et al. [] proposed a waste heat recovery system to provide power, distilled water and heat. Bai et al. [] investigated a cooling, heating and power system driven by exhaust gas to recovery the waste heat. Combined cooling and power systems driven by ICE waste heat were also investigated by some researchers. Chen et al. [25] designed an ammonia-water combined cooling and power system using the waste heat from the ICEs. Ammonia-water was heated by exhaust gas and jacket water. One part of the ammonia-water vapor flew into the turbine to provide power and the other part flew into the evaporator to provide refrigeration. Salek et al. [26] coupled an ammonia absorption refrigeration cycle and a bottoming Rankine cycle with internal combustion engine to produce power and cooling capacity.

Ammonia absorption refrigeration cycle (AARC) were widely used in the combined cooing and power system for its larger refrigeration output. However, the complex cycle structure and high driven temperature requirement of AARC might sometimes limit its applications. On the contrary, ejector refrigeration cycle (ERC) exhibits the advantages of easy maintenance and high reliability [25] and it can be driven by low-temperature heat source such as the jacket water. Thus, ICE waste heat recovery system with ERC driven by jacket water not only simultaneously generate power and refrigeration 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 (CCP) 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 to prevent the decomposition risk. 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 which increases the mass flow rate of the organic working fluid preheated by jacket water. What’s more, the ejector refrigeration cycle is adopted to produce refrigeration and fully utilize waste heat in jacket water. 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).

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[] Li Fan, Sun Bo, Zhang C, Zhang L. Operation optimization for combined cooling, heating, and power system with condensation heat recovery. Appl Energy 2018; 230:305-16.

[] Yari Mortaza, Ariyanfar Leyli, Aghdam EA. Analysis and performance assessment of a novel ORC based multigeneration system for power, distilled water and heat. Renew Energy 2018; 119:262-81.

[] Bai Z, Liu T, Liu Q, Lei J, Gong L, Jin H. Performance investigation of a new cooling, heating and power system with methanol decomposition based chemical recuperation process. Appl Energy 2018; 229: 1152-63.

[1] Liu P, Shu G, Tian H, Wang X, Yu Z. Alkanes based two-stage expansion with interheating Organic Rankine cycle for multi-waste heat recovery of truck diesel engine. Energy 2018; 147:337-50.

[2] Heywood J. B. Internal combustion engine fundamentals. New York: McGraw-Hill; 1988.

[3] Wang J, Yan Z, Wang M, Ma S, Dai Y. Thermodynamic analysis and optimization of an (organic Rankine cycle) ORC using low grade heat source. Energy 2013; 49:356-65.

[4] Lu Y, Roskilly A, Jiang L, Yu X. Working fluid selection for a small-scale organic Rankine cycle recovering engine waste heat. Energy Procedia 2017; 123:346-52.

[5] Rijpkema J, Munch K, Andersson S. Thermodynamic potential of twelve working fluids in Rankine and flash cycles for waste heat recovery in heavy duty diesel engines. Energy 2018; 160:996-1007.

[6] Su X, Shedd T A. Towards working fluid properties and selection of Rankine cycle based waste heat recovery (WHR) systems for internal combustion engines – A fundamental analysis. Appl Therm Eng 2018; 142:502-10.

[7] Vaja I, Gambarotta A. Internal Combustion Engine (ICE) bottoming with Organic Rankine Cycles (ORCs). Energy 2010; 35(2):1084-93.

[8] Kim M, Shin G, Kim G, Cho B. Single-loop organic Rankine cycle for engine waste heat recovery using both low-and high-temperature heat sources. Energy 2016; 96:482-94.

[9] Ringer J, Seifert M, Guyotot V, Hübner W. Rankine cycle for waste heat recovery of IC engines. SAE. 2009. 2009-01-0174.

[10] Wang X, Shu G, Tian H, Liu P, Jing D, Li X. Dynamic analysis of the dual-loop Organic Rankine Cycle for waste heat recovery of a natural gas engine. Energy Convers Manage 2017; 148:724-736.

[11] Wang E, Yu Z, Zhang H, Yang F. A regenerative supercritical dual-loop organic Rankine cycle system for energy recovery from the waste heat of internal combustion engines. Appl Energy 2017; 190:574-90.

[12] Huang H, Zhu J, Deng W, Ouyang T, Yan B, Yang X. Influence of exhaust heat distribution on the performance of dual-loop organic Rankine Cycle (DORC) for waste heat recovery. Energy 2018; 151:54-65.

[13] Rajabloo T, Bonalumi D, Lora P. Effect of a partial thermal decomposition of the working fluid on the performances of ORC power plants. Energy 2017; 133:1013-26.

[14] Shi L, Shu G, Tian H, Deng S. A review of modified Organic Rankine cycles (ORCs) for internal combustion engine waste heat recovery (ICE-WHR). Renew Sustain Energy Rev 2018; 92:95-110.

[15] Xia J, Wang J, Zhang G, Lou J, Zhao P, Dai Y. Thermo-economic analysis and comparative study of transcritical power cycles using CO2-based mixtures as working fluids. Appl Therm Eng 2018; 144:31-44.

[16] Shu G, Gao Y, Tian H, Wei H, Liang X. Study of mixtures based on hydrocarbons used in ORC (organic Rankine cycle) for engine waste heat recovery. Energy 2014; 74:428-38.

[17] Miller E, Hendricks T, Wang H, Peterson R. Integrated dual-cycle energy recovery using thermoelectric conversion and an organic Rankine bottoming cycle. Proceedings of the Institution of Mechanical Engineers, Part A: J Power Energy 2011; 225:33-43.

[18] Shu G, Wang X, Tian H. Theoretical analysis and comparison of Rankine cycle and different organic Rankine cycles as waste heat recovery system for a large gaseous fuel internal combustion engine. Appl Therm Eng 2016; 108:525-37.

[19] Yu G, Shu G, Tian H, Huo Y, Zhu W. Experimental investigations on a cascaded steam-/organic-Rankine-cycle (RC/ORC) system for waste heat recovery (WHR) from diesel engine. Energy Convers Manage 2016; 129:43-51.

[20] Zhang C, Shu G, Tian H, Wei H, Liang X. Comparative study of alternative ORC-based combined power systems to exploit high temperature waste heat. Energy Convers Manage 2015; 89:541-54.

[21] Cao Y, Rattner AS, Dai Y. Thermoeconomic analysis of a gas turbine and cascaded CO2 combined cycle using thermal oil as an intermediate heat-transfer fluid. Energy 2018; 162:1253-68.

[22] Ma J, Liu L, Zhu T, Zhang T. Cascade utilization of exhaust gas and jacket water waste heat from an Internal Combustion Engine by a single loop Organic Rankine Cycle system. Appl Therm Eng 2016; 107:218-26.

[23] Zhang H G, Wang E H, Fan B Y. A performance analysis of a novel system of a dual loop bottoming organic Rankine cycle (ORC) with a light-duty diesel engine. Applied Energy 2013;102: 1504-1513.

[24] Yang F, Cho H, Zhang H, Zhang J. Thermoeconomic multi-objective optimization of a dual loop organic Rankine cycle (ORC) for CNG engine waste heat recovery. Applied Energy 2017; 205: 1100-1118.

[25] Song J, Gu C. Parametric analysis of a dual loop Organic Rankine cycle (ORC) system for engine waste heat recovery. 2015; 105:995-1005.

[26] Yu G, Shu G, Tian H, Wei H, Liu L. Simulation and thermodynamic analysis of a bottoming Organic Rankine Cycle (ORC) of diesel engine (DE). Energy 2013; 51:281-90.

[27] Li Fan, Sun Bo, Zhang C, Zhang L. Operation optimization for combined cooling, heating, and power system with condensation heat recovery. Appl Energy 2018; 230:305-16.

[28] Yari Mortaza, Ariyanfar Leyli, Aghdam EA. Analysis and performance assessment of a novel ORC based multigeneration system for power, distilled water and heat. Renew Energy 2018; 119:262-81.

[29] Bai Z, Liu T, Liu Q, Lei J, Gong L, Jin H. Performance investigation of a new cooling, heating and power system with methanol decomposition based chemical recuperation process. Appl Energy 2018; 229: 1152-63.

[30] Chen Y, Han W, Jin H. Investigation of an ammonia-water combined power and

cooling system driven by the jacket water and exhaust gas heat of an internal combustion engine. International Journal of Refrigeration 2017; 82: 174-188.

[31] Salek F, Moghaddam A, Naserian M. Thermodynamic analysis of diesel engine coupled with ORC and absorption refrigeration cycle. Energy Conversion and Management 2017; 140: 240-246.

[32] Wang J, Dai Y, Sun Z. A theoretical study on a novel combined power and ejector refrigeration cycle. Int J Refrig 2009; 32(6):1186-94.

[33] Dai Y, Wang J, Gao L. Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery. Energy Convers Manage 2009; 50:576-82.

[34] Shu G, Zhao M, Tian H, Huo Y, Zhu W. Experimental comparison of R123 and R245fa as working fluids for waste heat recovery from heavy-duty diesel engine. Energy 2016; 115:756-69.

[35] Zhang J, Zhang H, Yang K, Yang F, Wang Z, Zhao G, Liu H, Wang E, Yao B. Performance analysis of regenerative organic Rankine cycle (RORC) using the pure working fluid and the zeotropic mixture over the whole operating range of a diesel engine. Energy Convers Manage 2014; 84:282-94.

[36] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: John Wiley & Sons; 1996.

[37] Turton R, Bailie RC, Whiting WB, Shaeiwitz JA. Analysis, synthesis, and design of chemical processes. 3rd ed. Upper Saddle River, N.J: Prentice Hall; 2009.

[38] Xia J, Wang J, Zhou K, Zhao P, Dai Y. Thermodynamic and economic analysis and multi-objective optimization of a novel transcritical CO2 Rankine cycle with an ejector driven by low grade heat source. Energy 2018; 161:337-51.

[39] Sheng Z, Huai W, Tao G. Performance comparison and parametric optimization of subcritical organic Rankine cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. Appl Energy 2011;88(8):2740-54.

[40] Tempesti D, Fiaschi D. Thermo-economic assessment of a micro CHP system fueled by geothermal and solar energy. Energy 2013; 58: 45-51.

[41] Velez F, Segovia JJ, Martin MC, Antonlin G, Chejne F, Quijano A. A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. Renew Sustain Energy Rev 2012; 16:4175-89.

[42] Akbari D, Mahmoudi M. Thermoeconomic analysis & optimization of the combined supercritical CO2 (carbon dioxide) recompression Brayton/ organic Rankine cycle. Energy 2014; 78:501-12.

[43] Zare V, Mahmoudi M, Yari M. An exergoeconomic investigation of waste heat recovery from the Gas Turbine-Modular Helium Reactor (GT-MHR) employing an ammonia–water power/cooling cycle. Energy 2013;61. 397-409.

[44] Lemmon EW, Huber ML, McLinden MO. NIST standard reference database 23, reference fluid thermodynamic and transport properties (REFPROP). Version 9.1. National Institute of Standards and Technology; 2010

[45] Wang J, Dai Y, Gao L. Parametric analysis and optimization for a combined power and refrigeration cycle. Appl Energy 2008;85(11):1071-85.

[46] Kern DQ. Process heat transfer. New York: McGraw-Hill; 1950

[47] Kandylas IP, Stamatelos AM. Engine exhaust system design based on heat transfer computation. Energy Convers Manage 1999; 40:1057-72.

[48] Incropera FP, DeWitt DP. Fundamentals of heat and mass transfer. New York: Wiley; 2002

[49] Gungor KE, Winterton RHS. Simplified general correlation for saturated flow boiling and comparisons of correlations with data. Chem Eng Res and Des, 1987; 65:148-56.

[50] Shah MM. A general correlation for heat transfer during film condensation inside pipes. Int J Heat Mass Transf 1979; 22:547-56.

This study investigates a combined cooling and power system for internal combustion engine waste heat recovery. We integrate a dual-pressure organic Rankine cycle with a corban dioxide Brayton cycle and an ejector refrigeration cycle in the system. Thermodynamic and exergoeconomic models of the system are built and we select seven key parameters to analyze the performance of the system. To obtain a better system performance, we use genetic algorithm to conduct the optimization of the system. Parametric analysis shows that the increase of the Brayton cycle turbine inlet temperature and inlet pressure are beneficial for the system thermodynamic and exergoeconomic performance. The increase of the inlet temperature at both the high-pressure side and low-pressure side of the organic Rankine cycle turbine causes the increase of the levelized exergy cost for the system product while the increase of the inlet pressure does the opposite. Single-objective optimization is carried out to obtain the minimum of levelized exergy cost for the system product. Results show that the minimum system product levelized exergy cost is 53.25 $ (MWh)-1. When system product levelized exergy cost is minimum, system net power output, cooling capacity and exergy efficiency are 374.37 kW, 188.63 kW and 37.31%, respectively.

Effects of seven parameters, including Brayton cycle turbine inlet temperature and inlet pressure, organic Rankine cycle turbine high-pressure side and low-pressure side inlet temperature and ejector primary inlet pressure, are evaluated.