修改

The exhaust gas and jacket water are utilized to produce power and cooling capacity in a designed combined cooling and power (CCP) system. Low boiling point fluid is chosen for its good thermodynamic performance in low temperature waste heat recovery. Considering the low decomposition temperature of the working fluid, a CO2 Brayton cycle is installed directly after the exhaust gas. To realize the cascading utilization of the thermal energy, a dual-pressure organic Rankine cycle (DORC) is added after the Brayton cycle. An ejector refrigeration cycle is added to the system to utilize the energy in the jacket water and produce cooling capacity. Six key parameters (BC turbine inlet temperature, compressor pressure ratio, high-pressure inlet pressure of the ORC turbine, high-pressure inlet temperature of the ORC turbine, low-pressure inlet temperature of the ORC turbine and the primary flow pressure) are selected to analyze the thermodynamic and exergoeconomic performance of the system. The net power output and the cooling capacity are the product of the system and the average cost per unit of exergy for the system product is obtained by calculating the total equipment cost and the consumption cost of the system. To harvest the minimum average cost per unit of exergy for the system product, single-objective optimization is carried out by means of genetic algorithm (GA). 14.7 $/MWh is gotten for the average cost per unit of exergy and 25.17% is gotten for the system exergy efficiency.

Nowadays, internal combustion engines (ICEs) are the major motive power source for the society. Internal combustion engines are used widely in transport, construction, agriculture, etc. However, the environment problems caused by the fuel consumption in internal combustion engines are also severe. Nearly half of the total transportation fuel is consumed by internal combustion engines. Whereas, the thermal efficiency of the ICEs is only 30-45% [1], leading to energy waste and the environment pollution. As a result, finding sustainable ways to fully utilized the fuel energy in the ICEs has attracted more and more attention of the researchers.

Previous researchers mainly focused on recycling waste heat from the exhaust gas which is in high temperature state. Many works have been carried out to utilize the energy in exhaust gas with the help of organic Rankine cycle (ORC). In 2010, Vaja et al. [2] matched an organic Rankine cycle to the internal combustion engine to recovery the waste heat. Later, further studies were carried out to improve the performance of the electricity generation system. Shu et al. [3] designed an organic Rankine cycle to harvest the exhaust waste heat of engines. Rita et al. [4] optimized a shell and louvered fin heat exchanger in the organic Rankine cycle driven by the internal combustion engine gas. Beside the exhaust gas, the coolant of the ICEs also has the potential to be utilized, considering the large amount of the mass flow rate and the relatively high temperature.

Research works about utilizing the exhaust gas and jacket water have been developed by many researchers. Zhang et al. [5] modeled a novel system combining a dual loop ORC and a vehicular light-dual diesel engine. The exhaust gas along with the coolant was utilized as the heat source for the system. They compared the power output of the high-temperature loop and the low-temperature loop and found that the low-temperature loop can produce more power. To avoid the complexity of the conventional multi source ORC system, a confluent cascade expansion ORC system was introduced by Chen et al. [6]. System parameters were calculated based on thermodynamic simulation. Comparing the results, they concluded that the architecture of the novel system is simper, the net power output of the system is larger (generating 8% more net power) and the thermal efficiency of the novel system is higher (improved to 49.5% from 45.3%). A dual-loop organic Rankine cycle was developed by Ge et al. [7] to recover the waste heat of the ICEs. In that study, isobutane and isopentane are mixed as the working fluid for the low-temperature loop (LTL) and cyclopentane and benzene mixtures are selected as the working fluid for the high-temperature loop (HTL). Comparing between mixed organic working fluid and pure organic working fluid was carried out and they drew the conclusion that less exergy destruction rate was achieved in the mixture using system. Seyedali et al. [8] studied a two-parallel-step organic Rankine cycle driven by the waste heat of the IEC. Comprehensive thermodynamic performance analysis and the optimization of the system were carried out by analyzing the key design parameters of the system. The got the result that 468 kW electricity power was produced by the system with an exergy efficiency of 21 %.

With the variation of the customers’ demand, more products other than electricity power were required. A number of studies began to pay attention to the combined systems. The design of combined cooling and power (CCP) system as a result was carried out by many researchers [9-11]. Chen et al. [12] investigated an ammonia-water combined cooling and power system using the waste heat from the ICEs. A gas engine with the power output of 300 kW was selected as the data source. By calculating the thermodynamic performance of the system, they concluded that the equivalent power output of the system is 92.86 kW and the exergy efficiency of the combined cooling and power system is 33.69%. In order to gain a large cooling capacity, ammonia-absorption cooling cycle was utilized by many researchers. Whereas, the capital investment of the system components and the operation cost was relatively high. Ejector refrigeration systems which were low in capital cost and simple in operation therefore were combined with the electricity generation cycles. And the economic analysis of a system has attracted the attention of studiers in recent years.

To better evaluate the thermodynamic and economic performance of a system, exergoeconomic (thermoeconomic) analysis methods were established. It provided a new aspect to design and operate the energy systems. YD Lee et al. [13] evaluated an SOFC-Engine hybrid power generation system. Exergoeconomic analysis methods were employed to analyzed the economic performance as well as the thermodynamic performance of the system. They found that the internal combustion engine accounted for the largest exergy destruction and followed the heat exchanger and the SOFC stack. An ejector refrigeration system driven by homogeneous charge compression ignition (HCCI) engine was designed by Mohsen et al. [14]. Exergoeconomic and thermodynamic performance of the system was calculated in MATLAB software. Multi-objective optimization was carried out with the objective function of exergy efficiency and the product unit cost of the system. Conclusion was obtained that in the highest exergy efficiency and the lowest product unit cost, the generator, condenser and the evaporator should work at temperature of 94.54 oC, 33.44, and 0.03, respectively. A combined cooling, heating and power (CCHP) system was analyzed by Wang et al. [15] using exergoeconomic methods. Energy costs of products in the system were calculated considering the natural gas price. They found that the cost of electricity increased from 0.537 to 1.077 Yuan/kWh with the change of the power output range (100-20%).

Because of the great thermodynamic performance for low grade waste heat recovery, low boiling point organic working fluid is wildly in Rankine cycle in place of the water steam. In most of the study, the exhaust gas was utilized directly by working fluid in organic Rankine cycle without considering the chemical stability. In general, the decomposition temperature is about 200 to 300 oC for many kinds of the organic working fluid. However, the exhaust gas temperature can get as high as 300 oC, causing the potential of the decomposition for the working fluid during the long working process [16] [17]. As a result, there is contradiction between the thermal stability of the system and the maximum utilization of the thermal energy when combining the organic Rankine cycle with the ICEs.

To solve the problems mentioned above, installing a preheater cycle is one solution.

Liu P et al. [] designed an organic Rankine cycle system with two-stage expansion to generate power. The temperature of the exhaust gas is about 520oC and the temperature of the EGR gas is about 650 oC, both of which are much higher than the decomposition temperature of the organic working fluid. They added a preheater between the organic Rankine cycle and the internal combustion engine gas to keep the stability of the system. However, the temperature difference between the exhaust gas and the organic working fluid is about 200oC, causing the exergy loss for the system. Also, installing and cycle with high decomposition temperature between the engine gas and the organic working fluid is another solution. Xia J et al. [] designed a combined cooling and power system with a Brayton cycle. The temperature of the exhaust gas is about 470oC in that system. They added the Brayton cycle between the engine gas and the organic Rankine cycle. The exhaust CO2 operated as the heat source for the organic cycle. However, because of the consumption of the compressor in the Brayton cycle, the net power of the system is relatively low.

To solve the problem of the exergy loss and the power consumption, in this study, a dual-pressure organic Rankine cycle combined with a CO2 Brayton cycle is installed.

A CO2 Brayton cycle is employed to utilized the high temperature of the exhaust gas and prevent the decomposition of the organic working fluid. The exhaust CO2 and the secondary exhaust gas operate as the high-temperature heat source and the low-temperature heat source, respectively. Jacket water preheats the low boiling point organic fluid before the separate of the high-pressure part and the low-pressure part. Besides, an ejector refrigeration cycle is added to the system for the cascade utilization of the jacket water. To consider the system comprehensively, thermodynamic and exergoeconomic analysis of the system is employed. Finally, optimization for the system based on the exergoeconomic analysis is obtained by means of genetic algorithm.

Wh. The net power of the CCP system is gotten as 3247.3 kW. The cooling capacity of the CCP system is harvested as 1520.5 kW.

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**Reference**

[1] Tartakovsky L, Sheintuch M. Fuel reforming in internal combustion engines. Progress in Energy and Combustion Science 2018; 67: 88-114.

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

[3] Shu G, Liu P, Tian H, Wang X, Jing D. Operational profile based thermal-economic analysis on an Organic Rankine cycle using for harvesting marine engine’s exhaust waste heat. Energy Conversion and Management 2017; 146: 107-123.

[4] Mastrullo R, Mauro A W, Revellin R, Viscito L. Modeling and optimization of a shell and louvered fin mini-tubes heat exchanger in an ORC powered by an internal combustion engine. Energy Conversion and Management 2015; 101: 697-712.

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] Zare V. A comparative thermodynamic analysis of two tri-generation systems utilizing low-grade geothermal energy. Energy Conversion and Management 2016; 118: 264–274.

[10] Wang J, Xie X, Lu Y, Liu B, Li X. Thermodynamic performance analysis and comparison of a combined cooling heating and power system integrated with two types of thermal energy storage. Applied Energy 2018; 219: 114–122.

[11] Hamdy M, Askalany A A, Harby K, Kora N. An overview on adsorption cooling systems powered by waste heat from internal combustion engine. Renewable and Sustainable Energy Reviews 2015; 51: 1223–1234.

[12] 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.

[13] Lee Y D, Ahn K Y, Morosuk T, Tsatsaronis G. Exergetic and exergoeconomic evaluation of an SOFC-Engine hybrid power generation system. Energy 2018; 145: 810–822.

[14] Sadeghi M, Mahmoudi S M S, Khoshbakhti Saray R. Exergoeconomic analysis and multi-objective optimization of an ejector refrigeration cycle powered by an internal combustion (HCCI) engine. Energy Conversion and Management 2015; 96: 403–417.

[15] Wang Z, Han W, Zhang N, Su B, Liu M, Jin H. Assessment of off-design performance of a combined cooling, heating and power system using exergoeconomic analysis. Energy Conversion and Management 2018; 171: 188–195.

[16] Dai X, Shi L, An Q, Qian W. Influence of alkane working fluid decomposition on supercritical organic Rankine cycle systems. Energy 2018; 153:422–430

[17] 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

[18] 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 for truck diesel engine. Energy 2018; 147: 337-350.

[19] Xia J, Wang J, Lou J, Zhao P, Dai Y. Thermo-economic analysis and optimization of a combined cooling and power (CCP) system for engine waste heat recovery. Energy Conversion and Management 2016; 128: 303-316.

[20] 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: 576–82.

[21] 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.

[22] Zhang J, Zhang HG, Yang K, Yang FB, Wang Z, Zhao GY, 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: 282–94.

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

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

[25] Kandylas IP, Stamatelos AM. Engine exhaust system design based on heat transfer computation. Energy Conversion Management 1999; 40:1057–72.

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

[27] Wang J, Wang J, Dai Y, Zhao P. Thermodynamic analysis and optimization of a transcritical CO2 geothermal power generation system based on the cold energy utilization of LNG. Applied Thermal Engineering 2014;70(1):531–40.

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

[29] Gungor KE, Winterton RHS. Simplified general correlation for saturated flow boiling and comparisons of correlations with data. Chemical Engineering Research and Design, 1987; 65:148–56.

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

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

[32] Mignard, D. (2014). Correlating the chemical engineering plant cost index with macro-economic indicators. Chemical Engineering Research and Design, 2013, 92(2), 285-294.

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

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

[35] Shengjun Z, Huaixin 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):2740–54.

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

[37] 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; 16:4175–89.

[38] Lazzaretto A, Tsatsaronis G. SPECO: a systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy 2006; 31:1257–89

[39] Kim YM, Kim CG, Favrat D. Transcritical or supercritical CO2 cycles using both low- and high-temperature heat sources. Energy 2012; 43:402–15

[40] Zvonimir G, Predrag R, Zoran B. The comparison of a basic and a dual-pressure ORC (Organic Rankine Cycle): Geothermal Power Plant Velika Ciglena case study. Energy 2014; 76: 175-186.

[41] Zheng B, Weng YW. A combined power and ejector refrigeration cycle for low temperature heat sources. Solar Energy 2010; 84:784–91

[42] 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

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

[44] <http://www.wartsila.com/products/marine-oil-gas/engines-generating-sets/>

[38] Akbari D, Mahmoudi M. Thermoeconomic analysis & optimization

of the combined supercritical CO2 (carbon dioxide) recompression Brayton/

organic Rankine cycle. Energy 2014; 78:501–12.

[39] 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. 397-09.

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%----------%7月14日白天改论文，改了abstract, introduction, 和一些细节

A combined cooling and power (CCP) system is built to recover waste heat from exhaust gas and jacket water in internal combustion engines (ICEs) using low boiling point fluid as working fluid. A CO2 Brayton cycle (BC) is used to recover the waste heat directly from engine exhaust gas. A dual-pressure organic Rankine cycle (ORC) is coupled with the CO2 Brayton cycle. An ejector refrigeration cycle is introduced to recover waste heat from engine jacket water and produce cooling capacity. R245fa is selected as the working fluid both in dual-pressure ORC and ejector refrigeration cycle. Six key parameters (BC turbine inlet temperature, compressor pressure ratio, high-pressure inlet pressure of the ORC turbine, high-pressure inlet temperature of the ORC turbine, low-pressure inlet temperature of the ORC turbine and the primary flow pressure) are selected to analyze the thermodynamic and exergoeconomic performance of the system. The net power output and the cooling capacity are the product of the system and the average cost per unit of exergy for the system product is obtained by calculating the total equipment cost and the consumption cost of the system. To harvest the minimum average cost per unit of exergy for the system product, single-objective optimization is carried out by means of genetic algorithm (GA). 14.7 $/MWh is obtained for the average cost per unit of exergy and 25.17% is obtained for the system exergy efficiency.

1. **Introduction**

Nowadays, internal combustion engines are the major motive power source for energy field. Internal combustion engines are used widely in transport, construction, agriculture, etc. Nearly half of the total transportation fuel is consumed by internal combustion engines. Whereas, the thermal efficiency of the ICEs is only 30-45% [1], leading to large amount waste heat. The widespread using and the low thermal efficiency of the IEC aggravate the environment problem. As a result, finding sustainable ways to effectively recover the waste heat from the ICEs has attracted more and more attention of the researchers.

The exhaust gas in the IECs is often in high temperature. The discharge of the high temperature gas not only causes the thermal pollution of the environment but also leads to the heat waste. Organic Rankine cycles can exploit low grade heat source using organic working fluid. To couple the ORCs with the internal combustion engines has attracted the interest of researchers. Thus, previous researchers mainly focused on recycling waste heat from the exhaust gas. Many works have been carried out to recover waste heat from engine exhaust gas with the help of organic Rankine cycle (ORC) [2-3]. Kalyan et al. [4] coupled the organic Rankine cycle with the internal combustion engine to examine the potential of waste heat recovery. They optimized the pinch point temperature difference of the ORC heat exchanger to reduce the exergy destruction of the system and obtain a high system exergy efficiency.

Later, further studies were carried out to improve the performance of the electricity generation system. Jacket water is the coolant in the engine to cool the cylinder. The temperature of the jacket water is about 90℃ which is much higher than the ambient temperature. Moreover, the mass flow rate of the jacket water in the engine is large. Hence, exploiting the jacket water as heat source can recover a large amount of waste heat. The attempts to examine the potential of recovering heat from jacket water have been carried out by many researchers. Many generation systems driven by exhaust gas and jacket water are introduced to recover waste heat [5-10]. Vaja et al. [11] matched an organic Rankine cycle to the internal combustion engine to recovery the waste heat. Different working fluids were analyzed to fit different working conditions. They designed three different cycles to analyze the different cycle configurations. Calculating based on second law of thermodynamic, they obtained the suitable working fluid and fitting cycle configuration to reach a high system thermal efficiency. Yu et al. [12] built an ORC system to recover waste heat from engine exhaust gas and jacket water. Evaporating pressure was chosen to analyze the thermodynamic performance of the system. 75% waste heat from exhaust gas and 9.5% waste heat from jacket water could be recovered, according to the simulation results. Shu et al. [13] modeled a steam Rankine cycle and an organic Rankine cycle for waste heat recovery from the gas engines. They compared the thermal efficiency, system feasibility of the cycles to obtain the reference for waste heat recovery engineering application.

To achieve a better performance for the waste heat recovery system, many studies try to modify the organic Rankine cycles. Traditional organic Rankine cycles need to overcome the problem of large temperature difference between the exhaust gas and the working fluid. As a result, a part of the heat is sacrificed to fulfill the thermal match requirement and the prevent the thermal decomposition of the working fluid. Systems integrated with complicated organic Rankine cycles have been developed by researchers [14-18]. Some researchers designed the dual-loop organic Rankine cycle to harness the waste heat in internal combustion engines. Zhang et al. [19] developed a novel system driven by waste heat in an IEC with a dual-loop ORC. The high-temperature cycle absorbed heat from the exhaust gas while the low-temperature cycle recovered heat from the high-temperature cycle and the jacket water. Ge et al. [20] designed a dual-loop ORC system to recover waste heat using different working fluids. Zeotropic mixtures are chosen for the high-temperature loop while R600a/R601a mixtures are adopted for the low-temperature loop to achieve a good thermodynamic performance of the system. Also, some researchers designed the dual-pressure organic Rankine cycle to utilize the waste heat in internal combustion engines. Seyedkavoosi et al. [21] designed a dual-pressure organic Rankine cycle for waste heat recovery. Different working fluid were compared to obtain the most suitable one under the considered conditions. The high pressure and the low pressure were chosen as variables to optimize the net power output and the exergy efficiency of the system.

Usually, traditional power plants can only generate electricity and can not fulfill the requirements of the consumers for energy supply. Cooling capacity, for example, is needed in many places such as hospital, hotel, restaurant, etc. To satisfy the various demands of the consumers and to recover the waste heat more efficiently, cogeneration systems have aroused the interest of researchers. The design of combined cooling and power (CCP) system, as a result, was carried out by many researchers [22-25]. Many cogeneration systems driven by low grade heat in internal combustion engine were developed [26-27]. Chen et al. [28] investigated an ammonia-water combined cooling and power system using the waste heat from the ICEs. By calculating the thermodynamic performance of the system, they concluded that the total equivalent power output of the system is 92.86 kW and the exergy efficiency of the combined cooling and power system is 33.69%. Salek et al. [29] coupled an ammonia absorption refrigeration cycle and a bottoming Rankine cycle with internal combustion engine to produce power and cooling capacity. Ammonia absorption refrigeration cycles were introduced by many researchers to produce cooling capacity for it large output. However, traditional ammonia absorption refrigeration cycle is relatively complicated. Moreover, the cost of building an ammonia absorption refrigeration cycle is relative high. Hence, ejector refrigeration cycle is employed by many researchers [30-31]. Xia et al. [32] designed a combined cooling and power system to recover waste heat from internal combustion engine. Ejector refrigeration cycle was employed in the system to produce cooling capacity.

In this study, A CO2 Brayton cycle coupled with a dual pressure organic Rankine cycle is developed. An ejector refrigeration cycle driven by the jacket water is introduced to produce cooling capacity. Because of the great thermodynamic performance for low grade waste heat recovery, low boiling point organic working fluid is wildly used in place of the water steam for waste heat recovery. CO2 is selected as the working fluid in the Brayton cycle and R245fa is selected as the working fluid for the ORC and ejector refrigeration cycle. The CO2 Brayton cycle is employed to recover waste heat directly from the exhaust gas for its high thermal efficiency and good thermal stability. The exhaust CO2 in the CO2 Brayton cycle operates as the heat source for the high-pressure part of the organic Rankine cycle. The low-pressure part of the organic Rankine absorbs from the secondary exhaust gas, realizing the cascading utilization of the waste heat and preventing the thermal decomposition of the organic working fluid [33-34]. To make fully use of the waste heat in the jacket water, it is used to preheat the organic working fluid in the ORC and provide heat for the ejector refrigeration cycle. Net power output and cooling capacity are the product of the system. To comprehensively evaluate the system, thermal-economic method is adopted to calculate the average cost per unit of exergy for the system product. Finally, optimization to obtain the minimum average cost per unit of exergy for the system product is achieved with the help of genetic algorithm.

%---------------------% July 15th writing abstract and introduction

**Nomenclature**

**Nomenclature**

|  |  |  |  |
| --- | --- | --- | --- |
| A | area, m2 |  | thickness, m |
| BC | Brayton cycle |  | entrainment ratio |
| Bo | boiling number | subscribe |  |
| c | average cost per unit of exergy, $ (MWh)-1 | 1-16 | state points |
| cp | specific heat, kJ kg-1℃-1 | g1-g4 | state points |
|  | cost rate, $ year-1 | bt | Brayton cycle |
| CCP | combined cooling and power | BM | bare module |
| CRF | capital recovery factor | cond | condenser |
| CEPCI | chemical engineering plant cost index | comp | compressor |
| D | diameter, m | d | diffuser section |
| e | exergy, kJ kg-1 | D | destruction |
|  | exergy flow rate, kJ s-1 | e | exit |
| y | exergy flow rate per year, kJ year-1 | elec | electricity |
| f | friction factor | ej | ejector refrigeration cycle |
| G | mass flow rate, kg s-1 | es | equivalent diameter |
|  | convection heat transfer coefficient, W m-2℃ -1 | ev | evaporation |
| h | enthalpy, kJ kg-1 | ex | exergy |
| H | depth, m | F | fuel |
| ieff | interest rate | he | heat exchanger |
| l | length, m | hf | hot flow |
|  | mass flow rate, kg s-1 | in | inside |
| n | lifetime, year | L | loss |
| Nu | Nusselt number | l | liquid |
| P | space between pipe, m | M | material |
| Pr | Prandtl number | m | mixing section |
| Pt | center distance between tubes, m | mas | maximum |
| Pr | reduced pressure | mf | mixed working fluid |
|  | heat transfer rate, kW | ORC | organic Rankine cycle |
|  | heat transfer rate per year, MWh year-1 | ot | organic Rankine turbine |
| T | temperature, ℃ | out | outside |
| U | overall heat transfer coefficient, W m-2℃-1 | pf | primary flow |
| v | velocity, m s-1 | s | single phase |
|  | power, kW | sf | secondary flow |
| y | power per year, MWh year-1 | t | tube |
| x | vapor quality | turb | turbine |
|  | annually levelized cost value, $ year-1 | vg | vapor generator |
| Greek symbol |  | w | tube wall |
|  | convection heat transfer coefficient, W m-2℃ -1 | wbt | BC turbine power |
|  | heat conductivity, W m-1℃-1 | wot | ORC turbine power |
|  | density, kg m3 |  |  |
|  | dynamic viscosity, m2 |  |  |
|  | efficiency, % |  |  |

System description

The combined cooling and power (CCP) is shown in Fig 1. The system integrates a CO2 Brayton cycle, a dual-pressure organic Rankine cycle and an ejector refrigeration which can produce power and cooling simultaneously. The system begins with a CO2 Brayton cycle as shown in Fig. 1. The exhaust gas from the internal consumption engine enters the gas heater to drive the CO2 Brayton cycle. CO2 cooled by the precooler flows through the compressor to be compressed to a supercritical state. The high-pressure CO2 absorbs heat in the gas heater to become high-pressure and high-temperature vapor. Then, the supercritical CO2 enters the BC turbine to produce power.

The exhaust CO2 and secondary exhaust gas are used to drive the dual-pressure ORC. After expanding in the BC turbine, the exhaust CO2 is still in a high temperature state. One part of the organic working fluid is heated by the CO2 fluid and then flows into the high-pressure inlet of the ORC turbine. The secondary exhaust gas from the gas heater is also in a relatively high temperature state. The other part of the organic working fluid is heated by the secondary exhaust gas and then flows into the low-pressure inlet of the ORC turbine. The organic working fluid steam expands in the ORC turbine to generate electricity.

Considering the large mass flow rate, jacket water is used to preheat the organic working fluid and provide heat for the ejector refrigeration cycle. Converged in the ORC turbine, the exhaust organic working steam is then cooled by condenser 1 to liquid state. Pump 1 is used to rise the pressure of the liquid organic working fluid for the first time. The organic working fluid is preheated by the jacket water to saturate state and then separates. One part of the fluid flows into the vapor generate 1 to run in the low-pressure ORC. The other part pumped by pump 2 to enter the vapor generator 2 to run in the high-pressure ORC.

The jacket water then flows into vapor generator 3 to release heat for the ejector refrigeration cycle. After the condensation process in condenser 2, liquid working fluid is divided into two separated parts. One part of the fluid is pumped to the vapor generator 3 to absorb heat and then becomes superheated steam. The other part of the working fluid flows through the throttle valve where the working fluid is vaporized to vapor state. The vapor enters the evaporator to produce cooling capacity when absorbing heat from the environment. After that, the two parts working fluid converge in the ejector. The superheated vapor mixes with the cooling fluid in the ejector to rise the total pressure. The mixed working fluid enters the condenser 2 to be condensed to liquid to continue the cycle.

Low boiling point fluidR245fa is selected as the working fluid for the organic Rankine cycle and the ejector refrigeration cycle because of the great thermodynamic performance and the low environment effect [35] [36].



**Fig. 7.** Effects of the high-pressure inlet pressure of ORC turbine on the output and the exergy efficiency of the system.

The change thermodynamic performance of the with the increase of the high-pressure inlet pressure of the ORC turbine is shown in Fig. 7. The pressure increase in the organic Rankine cycle can’t affect the thermodynamic performance of the Brayton cycle. The power output of the BC turbine and the consumption of the compressor in the Brayton cycle remain unchanged. Thus, the net power output of the Brayton cycle keeps unchanged.

The increase of the pressure at the ORC turbine high-pressure inlet causes the decrease of the working fluid steam and the increase of the enthalpy drop during the expanding process. The increase of the enthalpy drop in the ORC turbine offsets the decrease of the mass flow rate of the working fluid, leading to the slightly rise of the power output of the organic Rankine cycle.

The unchanged Brayton cycle power output along with the rise of the increase of the organic Rankine cycle accounts for the increase of the net power of the CCP system.

The decrease of the mass flow rate in the organic Rankine cycle means the drop of the heat transferred in the preheater. More thermal energy of the jacket water is utilized in the vapor generator 3, leading to the increase of the cooling capacity of the ejector refrigeration cycle.

The rise of the net power output and the cooling capacity accounts for the increase of the exergy efficiency of the system.



**Fig. 8.** Effects of the high-pressure inlet pressure of the ORC turbine on the average cost per unit of exergy and heat transfer area of the system.

The exergoeconomic effects of the pressure at the high-pressure inlet of the ORC turbine are obtained in Fig. 8. The increase of the pressure at the high-pressure inlet of the ORC turbine causes the increase of the exergy for the steam produced by the vapor generator 2. The increase power output of the ORC turbine means the increase of the value for the steam product. The exhaust CO2 operates as the heat source of the steam. The thermal parameters of the exhaust CO2 remain unchanged while the value of the product increases. Thus, the average cost per unit of exergy for the exhaust CO2­ increases, which at the same time causes the increase of the average cost per unit of exergy for the BC turbine power output. Hence, the average cost per unit of exergy for the BC turbine power output (cbt) increases.

The increase of the power output of the ORC turbine causes the decrease of the average cost per unit of exergy (cot) as shown in the figure.

The heat transfer area in the gas heater and the vapor generator 1 keeps the same because of the unchanged thermal parameters in the Brayton cycle and the low-pressure organic Rankine cycle. The heat transfer area in the vapor generator 2 and the preheater decreases as the decrease of the mass flow rate of the working fluid in the organic Rankine cycle. The increase of the mass flow rate in the ejector refrigeration cycle leads to the increase of the heat transfer area in the vapor generator 3 and the evaporator. Combining all the changes of the heat transfer area mention above, the total heat transfer area of the heat exchangers in the system increases, which means the increase of the total equipment cost of the system.

Because of the larger magnitude of the compressor consumption comparing with the pump consumption, the increase of the average cost per unit of exergy for the BC turbine power output causes the increase of the consumption cost of the system.

The increase equipment cost and the consumption cost offsets the effect of the increase of the net power output of the system, resulting in the slightly increase of the average cost per unit of exergy for the system product.