Paper revise with a geothermal heating one, for the first time.

Several assumptions are made to simplify the simulation of the system

The system reaches a steady state;

The heat and friction losses in the system are not considered;

The pressure losses in the vapor generators, preheater, evaporator, condensers and pipes are neglected;

The gas temperature at the outlet of the vapor generator 1 is higher than 110 ℃, considering the low gas acid dew point temperature.

The working fluids at the out of the condensers and preheater are saturated liquids, and the evaporator outlet state is saturated vapor;

The process through the throttle valve is isenthalpic.

The detailed energy model equations of each component are list in Table 1. Note that there are two expanding processes in the ORC turbine. The high-pressure vapor expands in the turbine and then mixes with the vapor from vapor generator 1. After that, the mixed vapor expands in the turbine for the second time.

Thermodynamic 热力学的 and thermodynamics 热力学

The energy model of the system is based on the first law of thermodynamics. From the viewpoint of the first law, it is equivalent for work and heat. Nevertheless, according to the second law of the thermodynamics, the irreversibility of work and heat is different. The exergy is used to quantifies the difference between them. The exergy model of the system is based on a dead state (the ambient condition in this study). Definition of exergy is given as:

In this study, all the components in the system are associated directly or indirectly with fuel of other heat sources, such as exhaust as and jacket water. The heat sources provide exergy for the components to operate. For each component, there is an exergy balance equation, being expressed as:

where EF, EP, ED­, EL donate the rate of exergyfor the component fuel, the rate of exergyfor component product, the rate of component exergy destruction and the rate of component exergy loss, respectively.

A method of modeling the capital costs of main components is used in this study. According to Ref. [], the bare module cost of the components is calculated as the basic cost. The basic cost of the components includes the direct project cost (such as component cost, material cost of the installation, etc.) and the indirect project cost (like the taxes, insurance engineering expenses, etc.). The bare module cost of the components is calculated under basic conditions. For deviations from the based conditions, multiplying factors (the specific component type, the specific system pressure and the specific material of construction) are added in the calculation to correct the results.

The calculation of the bare module cost depends on past records or published correlations for price information. It is necessary to update the costs because of the inflation. This can be achieved by the following equation:

Exergoeconomic is a branch of engineering which combines the thermodynamic analysis and economic principles. Thermodynamic performance and economic cost of the system are all taken into consideration.

The thermodynamic parameters of the working fluid are calculated under the environment of MATLAB with the help of REFPROP. The basic conditions of simulation for the CCP system are listed in Table 3

Fig. 3 shows the effects of flash pressure on the steam turbine power, the ORC turbine power, the refrigeration capacity and the exergy efficiency of the system.

As the flash pressure rises, the temperature of the saturated steam separated from the flashing device rises, resulting in an increase in the enthalpy drops and a decrease in the mas flow rate of the fluid across the steam turbine. Since the effect of the decrease in the mass flow rate is greater than that of the increase in the specific enthalpy drops across the steam turbine, the power output of the steam turbine decreases.

Both the ORC turbine power output and the ejector refrigeration capacity increase with the rising flash pressure. These results can be explained by the ascending temperature and increasing mass flow rate of the brine stream separated from the flashing device, which could offer more energy for the bottom combined cooling and power subsystem. Thus, with the growing mass flow rate of the fluid across the ORC turbine, the power output of the ORC turbine increase, while the specific enthalpy drops of the fluid across the ORC turbine are kept unchanged. Note that the fluid exhausted from the ORC turbine also acts as the primary fluid for the ejector. Hence, with the increase of the mass flow rate of the primary fluid, more secondary fluids are entrained from the evaporator to the ejector, leading to an increase in the refrigeration capacity of the evaporator.

Although the amount of the refrigeration capacity is considerably large, considering the energy quality, it contains only a small amount of exergy output. As the amount of increased exergy output from the ORC turbine and the evaporator cannot make up for the amount of decreases exergy output from the steam turbine, the system exergy efficiency drops with the rising flash pressure.

The influence of the BC turbine inlet temperature (TBt,in) on the output and the exergy efficiency of the system are shown in Fig. 2. The net power output of the CBC increases with the rise of TBt,in. That can be explained by the large decrease of the compressor power consumption. With the increase of the CO2 temperature at the BC turbine inlet, the mass flow rate of CO2 decreases, leading to the decrease of the compressor power consumption. Although the drop of CO2 mass flow rate would cut down the BC turbine power output, the decrease quantity of compressor power consumption is larger than the decrease of the BC turbine power output. Thus, the large decrease of the compressor power consumption determines the increase trend of the CBC net power output.

It is presented that the net power output of the DORC increase with the rise of the BC turbine inlet temperature. Since the residual heat in exhaust CO2 acts as the heat source for the high-pressure side DORC, the temperature rise of the exhaust CO2, caused by the rise of TBt,in, would offer more heat for the bottom cycle, which causes the increase of the mass flow rate of the organic working fluid in the high-pressure side of DORC . Hence the power output of the ORC turbine increases, leading to the increase of the net power output of the DORC.

With the increase of TBt,in, the refrigeration capacity of the ERC decreases, as shown in Fig. 2. The increase of the organic working fluid mass flow rate in DORC would absorb more heat from jacket water, resulting in the decrease of energy available for the ERC. As a result, less secondary flow working fluid from the evaporator is entrained to the ejector, resulting the decrease of the refrigeration capacity of the CCP system.

The increase of the CBC net power output and the DORC net power output account for the increase of the net power output of the whole CCP system. Though the refrigeration capacity of the ERC is large, it produces only a small amount of exergy. The decrease of the exergy output caused by the refrigeration capacity decrease can be made up by the increase of the power exergy output. Thus, the exergy efficiency of the system increases.

Fig. 4 shows the effects of flash pressure in the levelized costs per unit of exergy for major stream as well as the average levelized costs per unit of exergy products for the overall system.

For the three productive components in the given system, namely the steam turbine, the ORC turbine and the evaporator, the levelized costs per unit of products for each of them can be divided into two parts: one is the exergy-fuel-related part, which is brought from the exergy fuel stream across the component; the other is the equipment-cost-related part, which is generated by the equipment cost of the component.

For the variation of the levelized costs per unit of steam turbine exergy output, both the exergy-fuel-related part and the equipment-cost-related part of it are analyzed. Concerning the exergy-fuel-related part, when flash pressure increases, the separator volume decreases as a result of the increase in density of the vapor generated from it, which further reduces the separator cost. Lower separator cost contributes to a lower value of the levelized costs per unit of exergy fuels for the steam turbine, which further cuts down the exergy-fuel-related part of c. As for the equipment-cost-related part, when the flash pressure increases, the impact of the decrease in steam turbine power output is greater than that of the steam turbine cost and hence result in an increase in the equipment-cost related part of c. Integrating the variations of the two parts, c increase with the rising flash pressure, as shown in Fig.4.

The levelized costs per unit of exergy products for the ORC turbine decrease with the increasing flash pressure; this can be explained by the variation in the exergy-fuel-related part and the equipment-cost-related part of it. Regarding the exergy-fuel-related part, it can be observed from Fig. that the levelized costs per unit of exergy fuels for the ORC turbine drop with the increasing flash pressure; hence the exergy-fuel-related part if c decreases. For the equipment-cost-related part, when the flash pressure increases, the impact of the increase in ORC turbine power output is greater than that of the increase in ORC turbine cost; therefore, the equipment-cost-related part of c also decreases. Consequently, c shows a descending variation.

In addition, the levelized cost per unit of cold exergy products decrease dramatically with the increasing flash pressure, which is prominently influenced by the sharp decrease in the equipment-cost-related part of c. when the flash pressure rises, the impact of the increase in cold exergy output is much greater than that in the increase evaporator cost, which leads to the sharp decline of the c

The influences of the BC turbine inlet temperature on the levelized exergy cost and the system capital cost of the system are shown in Fig. 3. The levelized exergy cost for the BC turbine power output (cBt) drops with the rise of the BC turbine inlet temperature (TBt,in). That can be explained by the decrease of the capital-cost-related part of cBt. The capital-cost-related part of cBt decreases with the decrease of cost of compressor, which is cut down by the drop of the compressor power consumption. The levelized exergy cost for the ORC turbine (cOt) decreases with the rise of TBt,in. The increase of the ORC turbine power output causes the decrease of both the capital-cost related part and the fuel-cost-related part of cOt, resulting in the decrease of cOt.

The system capital cost (zcapital) rises with the rise of TBt,in. The large increase of the ORC turbine power output increases the cost of the ORC turbine. Moreover, the increase of the mass flow rate of the organic working fluid in the DORC causes the increase of cost for the vapor generator 2 and the preheater. Though the cost of compressor decreases, it can’t change the ascending trend of the total system capital.

It can be obtained in Fig. 3 that the levelized exergy cost for the system product (cproduct) decreases with the rise of TBt,in. The decline in levelized exergy cost for the BC turbine and ORC turbine power output, according to Eq. (31), would cause the decrease of the fuel-cost related part of cproduct. Though the increase of zcapital would cut down the capital-cost-related part of cproduct, the impact of levelized exergy cost for the BC turbine and ORC turbine is greater, which leads to the descending trend of cproduct.

On the one hand, as the mass flow rate and the specific enthalpy difference of the fluid through the steam turbine are kept unchanged, the power output of the steam turbine remains constant. On the other hand, the increases pinch point temperature difference results in the reduction of the energy input into the bottom combined cooling and power subsystem. Consequently, the mass flow rate of the ejector, dwindles down; hence fewer secondary fluids are entrained from the evaporator to the ejector. Consequently, both the ORC turbine and the refrigeration capacity decrease with the declined mass flow rate.

The levelized costs per unit of exergy products for the steam turbine remains as constant since the parameters of the steam turbine are irrelevant to the pinch point temperature difference in the vapor generator.

With the rising pinch point temperature difference in the vapor generator, the levelized costs per unit of exergy for the ORC turbine increase, which is determined by the variations in the two parts of it. For the exergy-fuel-related part, since c rises slightly as shown in Fig. 6, the exergy increases.

The influence of the BC turbine inlet pressure (PBt, in) on the output and the exergy efficiency of the system are shown in Fig. 4. The net power output of the CBC increases with the increase of PBt, in, which can be explained by the rise of enthalpy drop of the CO2 in the BC turbine. Though the rise of PBt, in requires more compressor power consumption, the increase of the BC turbine power output is larger in quantity than the consumption, which leads to the increase of the CBC net power output.

The net power output of the DORC decreases with the rise of PBt, in. On the one hand, the temperature of the exhaust CO2 at the BC turbine outlet decreases with the increase of PBt, in. Thus, less heat is offered to the high-pressure cycle of DORC, resulting in the decrease of the high-pressure cycle power output. On the other hand, the increase of PBt, in causes the increase of the compressor power consumption, which results in the rise of the CO2 temperature at the compressor outlet. Thus, less heat is released in the gas heater and more heat is provided to the low-pressure cycle of DORC, which leads to the increase of the low-pressure cycle power output. However, the increase of the power output in low-pressure side is smaller than the decrease of the power output in the high-pressure side. Thus, the net power of the whole DORC decreases slightly.

The refrigeration capacity of the system increases with the increase of PBt, in. Just like the variation of the power output, the decrease of the mass flow rate in the high-pressure side of DORC is larger than that in the low-pressure side. Therefore, the total mass flow rate in the DORC decreases, resulting in the reduction of heat provided for the ejector refrigeration cycle. Thus, the refrigeration capacity of the ERC decreases.

Though the net power output of the DORC decreases, the increase of CBC net power output is much larger. Thus, the net power output of the CCP system increases with the increase of PBt, in. The exergy efficiency of the system likewise has the same rising trend.

The influences of the BC turbine inlet pressure (PBt, in) on the levelized exergy cost and the system capital cost of the system are depicted in Fig. 5. The levelized exergy cost for the BC turbine output cBt increases with the rise of the PBt, in, which can be explained by the variations of the capital-cost-related part and the fuel-cost-related part. The increase of PBt, in causes the increase of cost for both the BC turbine and the compressor, which lead to the rise of the two related parts.

The levelized exergy cost for the ORC turbine product (cOt) increases with the rise of PBt. The decrease of the mass flow rate in the DORC causes that less exergy is produced in vapor generator 2, causing the increase of the fuel-related part of cOt. Therefore, the levelized exergy cost for the ORC turbine (cOt) increases.

The system capital cost (zcapital) increases with the rise of (PBt, in). The increase of the mass flow rate in the ERC causes the rise of capital cost for the evaporator and vapor generator 3, which combined with the rise of the BC turbine cost and compressor cost accounts for the system capital cost rise.

The levelized exergy cost for the system product decreases with the rise of PBt, in as presented in Fig. 5. According to Eq. (31), the rise of the cOt, cBt would cause the rise of the fuel-cost-related part of cproduct. However, because of the large increase of the system net power output, the capital-cost-related part and the fuel-cost-related part decrease actually, which determines the decrease of cproduct.

The influence of inlet temperature at the high-pressure side of ORC turbine (TOt, in, h) on the output and the exergy efficiency of the system are shown in Fig. 6. The net power output of the CBC remains unchanged since thermal parameters in dual-pressure ORC are irrelevant to the thermodynamic performance of the CBC.

The net power output of the DORC decreases with the increase of TOt, in, h. Though the increase of the vapor temperature could lead to the rise of the enthalpy drop in the ORC turbine, it would also cause the decrease of the mass flow rate in the high-pressure side, whose impact is greater than that of the enthalpy drop. Therefore, the power output of the DORC decreases.

The refrigeration capacity of the ejector refrigeration cycle increases with the rise of TOt, in, h. More heat is provided for the ERC because of the decrease of the mass flow rate in the DORC, leading to the increase of the mass flow rate in vapor generator 3. Thus, more secondary flow from the evaporator is entrained into the ejector, resulting in the increase of the refrigeration capacity.

The net power output of the CCP system decreases with the rise of TOt, in, h. The unchanged CBC power output and the drop of the DORC power output determine the decrease of the net power output of the CCP system. The exergy efficiency of the system as well drops with the increase of the increase of TOt, in, h.

The influences of inlet temperature at the high-pressure side of ORC turbine on the levelized exergy cost and the system capital cost of the system are presented in Fig. 7. The levelized exergy cost for the ORC turbine output (cOt) increases with the increase of TOt, in, h. The reason is that the two related parts of cOt increase with the drop of the ORC turbine power output.

The levelized exergy cost for the BC turbine power output (cBt) increases with the rise the TOt, in, h. Since the decrease of the mass flow rate in the high-pressure side of DORC, the exergy generated in the vapor generator 2 decreases, causing the increase of the levelized exergy cost of the vapor. Thus, the increase levelized exergy cost of the vapor, which is heated by the BC turbine residual heat, causes the increase of the levelized exergy cost for the exhaust CO2. According to Eq. (32), the fuel-cost-related part of cBt increases, leading to the increase of cBt.

The system capital cost (zcapital) decreases with the increase of TOt, in, h. The decrease of the DORC power output causes the drop of the ORC turbine cost, which leads to the descending trend of zcapital.

The levelized exergy cost for the system product (cproduct) increases with the rise of TOt, in, h, as shown in Fig. 7. The increase of the levelized exergy cost for the BC turbine and ORC turbine power output cause the rise of fuel-cost-related part of cproduct. Meanwhile, the large decrease of the net power of the CCP system causes the increase of the capital-cost-related part. The two increase parts determine the rise of cproduct.

The influences of the inlet pressure at the high-pressure side of ORC turbine (POt, in, h) on the output and exergy efficiency of the system are presented in Fig. 8. The net power of the CBC keeps unchanged because of the unchanged thermal parameters in the cycle.

The net power output of the DORC increase with the rise of POt, in, h. The increase of the evaporation pressure cuts down the latent heat of the organic working fluid, which causes the increase of the mass flow rate in the high-pressure side of DORC. As a result, the net power output of the ORC turbine increases, leading to the increase of the net power output of the DORC.

Considering the increase of the DORC net power output and the unchanged CBC net power output, the net power output of the whole system increases. Also, the exergy efficiency of the system increases.

The increase of the mass flow rate in the DORC absorbs more heat from the jacket water in the preheater. Thus, less heat is released in the vapor generator 3, causing the decrease of the mass flow rate of the working fluid in the ERC. As a result, the refrigeration capacity of the system decreases.

The influence of the inlet pressure at the high-pressure side of the ORC turbine (POt, in, h) on the levelized exergy cost and system capital cost of the system are presented in Fig. 9. The large increase of the ORC turbine power output accounts for the decrease of the levelized exergy cost for the ORC turbine power output (cOt). The increase of the mass flow rate in the high-pressure side of DORC means that more exergy in the vapor is generated by the vapor generator 2, which leads to the decrease of its levelized exergy cost. Thus, the levelized exergy cost for the BC turbine exhaust CO2, which provides heat for the vapor, decreases with the vapor levelized exergy cost. Moreover, the drop of the CO2 levelized exergy cost causes the decrease of the fuel-cost-related part of cBt, which further results in the decrease of cBt.

The increase of the ORC turbine power output and the increase of mass flow rate in the DORC cause the increase of cost for the turbine and the vapor generator 2, leading to the rise of the system capital cost.

The levelized exergy cost for the system product (cproduct) decreases with the increase of POt, in, h. The decrease of cOt and cBt account for the decrease of the fuel-cost-related part of the levelized exergy for the system product. The impact of cOt and cBt is greater than that of the system capital cost whose rise would result in the increase of the capital-cost-related part of cproduct. Thus, the levelized exergy cost of the system product (cproduct) shows a descending trend.

The influences of the inlet temperature at the low-pressure side of ORC turbine (TOt, in, l) on the output and the exergy efficiency of the system are presented in Fig. 10. Parameters changes in the DORC are irrelevant to the thermodynamic performance of the CBC. Thus, the net power of the CBC remains unchanged.

The net power output of the DORC decreases with the increase of TOt, in, l. The increase of the inlet temperature causes the decrease of the mass flow rate in the low-pressure side of the DORC, leading to the decrease of the DORC net power output.

Considering the decrease of the DORC net power output and the unchanged CBC net power output, the net power output of the whole system deceases. Likewise, the exergy efficiency of the system decreases.

The refrigeration capacity of the ejector refrigeration cycle increases with the increase of TOt, in, l. The decrease of the mass flow rate in the low-pressure side means that more heat is offered to the ERC. Thus, the mass flow rate of the working fluid in the vapor generator 3 increases and more working fluid is entrained to the ejector from the evaporator, which leads to the increase of the refrigeration cycle.

The influence of inlet temperature at the low-pressure side of the ORC turbine (TOt, in, l) on the levelized exergy cost and system capital cost of the system are presented in Fig. 11. The levelized cost for the BC turbine power output increase with the increase of TOt, in, l. The decrease of the mass flow rate in the vapor generator 1 leads to the drop of the vapor exergy output, which results in the increase of the levelized exergy cost for the vapor. The levelized exergy cost for vapor in vapor generator 2, which is the equal to that of the vapor in vapor generator 1, decreases as a result, causing the increase of the levelized exergy cost of the exhaust CO2 after the BC turbine. Thus, the fuel-cost-related part of cBt decreases, resulting in the drop of cBt.

The levelized exergy cost for the ORC turbine (cOt) increases with the increase of TOt, in, l. That can be explained by the increase of the levelized exergy cost of the ORC low-pressure inlet vapor and the decrease of the power output of the ORC turbine power output. Both the fuel-cost-related part and the capital-cost-related part of cOt increases.

The decrease of the mass flow rate and the ORC turbine power output cause the decrease of the vapor generator 1 cost and the turbine cost. Thus, the capital cost of the system decreases.

The levelized exergy cost for the system product increases with the increase of TOt, in, l. The increase of cBt and cOt cause the increase of the fuel-cost-related part of the levelized exergy cost for the system product. Though, the decease of the system capital cost causes the decrease of the capital-cost-related part, its effect is less important. Thus, the increase of the fuel-cost-related part determines the increase of the levelized exergy cost for the system product.

The influences of the inlet temperature of the low-pressure side of the ORC turbine (POt, in, l) on the output of the exergy efficiency of the system are shown in Fig. 12. The net power of the CBC keeps unchanged with the increase of the increase of the low evaporation pressure. The reason is that the thermodynamic of the CBC is irrelevant to the thermal parameters in DORC.

The net power output of the DORC increases with the rise of POt, in, l. The increase of enthalpy drop of the organic working fluid in the low-pressure side, which is caused by the rise of POt, in, l, results in the increase of the power output of the low-pressure side. Though mass flow rate in the low-pressure side would decrease, its impact is less important than that of the enthalpy drop. Thus, the net power output of DORC increases.

The unchanged CBC power output and the increase of the DORC power accounts for the increase of the system net power output and exergy efficiency of the system.

The refrigeration capacity increases with the increase of POt, in, l. Because of the decrease of the mass flow rate in DORC, less heat is released in the preheater and more heat is provided in vapor generator 3. Thus, the mass flow rate of the working fluid in the ERC increases, resulting in the increase of the refrigeration capacity.

The influences of inlet pressure at the low-pressure side of the ORC turbine (POt, in, l) on the levelized exergy cost and system capital cost of the system are shown in Fig. 13. The levelized exergy cost for the ORC turbine power output decreases with the increase of POt, in, l. That can be explained by the decrease of the vapor generator 1 cost, caused by the decrease of the mass flow rate in DORC, and the increase of the DORC power output. Both the capital-cost-related part and the fuel-cost-related part of cOt decrease.

The levelized exergy cost for the BC turbine power output decreases with of POt, in, l. The decrease of the cOt causes the drop of levelized exergy cost for the vapor in vapor generator 2, which is heated by the residual heat in the BC turbine exhaust CO2. Thus, the levelized exergy cost of the exhaust CO2 decreases, which further leads to the drop of the fuel-cost-related part of cBt. Therefore, the levelized exergy cost for the BC turbine power output (cBt) decreases, as shown in Fig. 13.

The increase of the ORC turbine power output causes the increase of the ORC turbine cost. Meanwhile, the increase of the refrigeration capacity causes the increase of the heat transfer area in the evaporator which requires the rise of the evaporator cost. Thus, the capacity cost of the system increases.

The levelized exergy cost for the system product decreases with the increase of POt, in, l. The decrease of the levelized exergy cost for the BC turbine power output and ORC turbine power cause the decrease of the fuel-cost-related part of the system levelized exergy cost, which determined the decrease of the levelized exergy cost for the system product.

The influence of ejector primary inlet pressure (Pej, in) on the output and the exergy efficiency of the system are shown in Fig. 14. Thermal parameter changes in the ERC can’t affect the thermodynamic performance of the CBC and DORC. Thus, the net power output of the two cycles remain unchanged. With the increase of the ejector primary inlet pressure, the power consumption of pump 4 increases, leading to the slight decrease of the power output of the whole system.

The increase of the ejector primary inlet pressure causes the increase of the entrainment ratio of the ejector. Thus, more secondary flow is entrained to the ejector from the evaporation, leading to the increase of the refrigeration capacity.

With the increase of the ejector primary inlet pressure, the power consumption of pump 4 increases gradually. At first, the exergy loss in pump 4 is smaller than the exergy produced by the refrigeration capacity. Then, with the increase of the pump power consumption, the exergy loss in pump 4 becomes larger than the refrigeration exergy increase. Thus, the exergy efficiency for the system increases at first and then decreases with the increase of the ejector primary inlet pressure.

The influence of the ejector primary inlet pressure on the levelized exergy cost and the system capital cost of the system are presented in Fig. 15. The increase of the ejector primary inlet pressure can’t affect the power output of the BC turbine and the ORC turbine. Thus, the levelized exergy cost for the BC turbine and the ORC power output remain unchanged.

The increase of the pump power consumption results in the increase of the pump 4 cost. The increase of the mass flow rate in the evaporator causes the increase of the evaporator cost. Thus, the system capital cost increases, which leads to the increase of the capital-cost-related part of cproduct. As a result, the levelized exergy cost for the system increases.