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The Multi-Objective Optimization of the CCHP Driven By Gas-Steam Combined Cycle

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Abstract. The gas-steam combined cycle is gradually used in the cooling the heating combined system more and more. Given that the cogeneration efficiency and operation cost are the main parameter of the system, this paper have built a multi-objective optimization model of the system, and achieved the optimal operation strategies. The result shows that the cogeneration efficiency can improved about 20.5% and the operation cost can be reduced by up to 17.8%.

1. Introduction

The combined cooling and heating system is a complex energy system, and when the cooling and heating loads are determined, the system have many operating strategies, a reasonable operating strategy can greatly improve the running performance of the CCHP system [1].

Generally, there are two operation strategies for the CCHP system: following the electric load (FEL) and following the thermal load (FTL). In the case of FEL operation strategy, the system satisfies the electric load firstly, and the insufficient heat is provided by the gas boiler. In the case of FTL strategy, the prime mover generates enough waste heat to satisfy the heating and cooling load [2]. Many researchers have done a lot of analysis about the two operation strategy [3, 4, and 5]. Mago and Fumo [3] have investigated performance of CCHP and CHP systems operating following the electric load and operating following the thermal load on primary energy consumption, operation cost, and carbon dioxide emission for different climate condition.

Although the FEL and FTL are the most common in the CCHP system, they may not the best operation strategies, therefore some researchers have analyzed the operation optimization based on a single or multiple optimization objective [6, 7, 8, and 9]. Sakawa et al. [6] have proposed an approximate solution method based on genetic algorithms for mixed integer programming problems. Yokoyama et al. [7] have demonstrated that the efficiency of MILP to solve nonlinear problem.

In generally, the prime mover in CCHP or CHP system mentioned above is gas turbine, Stirling engine or internal combustion engine. But the steam turbine as the prime mover of CCHP is not discussed too much [10, 11]. Tan et al. [10] have analyzed a CCHP system driven by gas-steam cycle to optimize the operation cost and the primary energy rate. The cogeneration efficiency is a key index which reflect the quality of the system, a high cogeneration efficiency can make full use of the energy. In addition to the efficiency, the operation cost is also the important parameter to the CCHP system, therefore this paper chooses the cogeneration efficiency and the operation cost as the objective of optimization, and analyzes the optimal operation mode of the CCHP.



2. System construction

The combined cooling heating and power (CCHP) system is driven by gas-steam combined cycle, and the schematic diagrams of the cogeneration system is shown in Figure 1. The system mainly includes two sub-system, the gas-steam combined system and the auxiliary system.

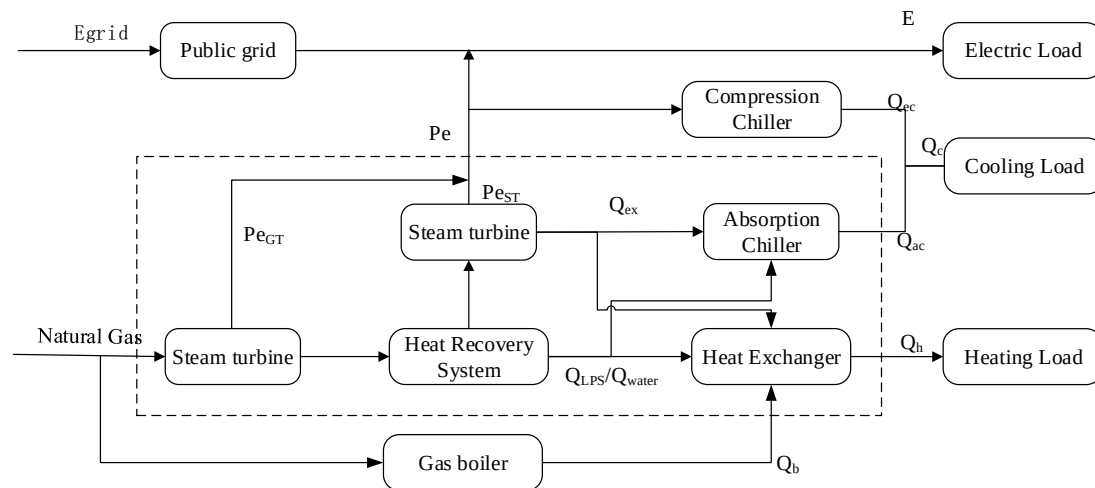


Figure 1. The schematic diagrams of the CCHP system

The gas-steam combined system consists of a gas turbine with total capacity of 30 MW (GT), a dual pressure heat recovery steam generator (HRSG), a condensing steam turbine (ST), an absorption chiller (AC) and heat exchanger (HE). The gas turbine, the heat recovery steam generator and the steam turbine are operated by a ‘two-to-one’ operation. When the CCHP system is running, the gas turbine consumes fuel and generates high temperature flue gas. The high-temperature flue gas is recovered by the heat recovery steam generator and generates high-pressure, low-pressure steam and hot water. The high-pressure steam is sent to the steam turbine for power generation, and the low-pressure steam is used for the cold and heat load. The steam extraction from steam turbines is also used to meet the demand.

The auxiliary system is mainly composed of compression electrical chiller (CC), gas boiler (GB) and power grid. When cooling load is inadequate, the insufficient section of cooling is supplemented by compression chillers. When the heat recovered by the system cannot meet the heating load, the gas boiler satisfies the shortage of heating. If the electric load is not enough, the insufficient power is supplied by the public power grid.

In order to benefit the analysis, a conventional separated system (CSS) shown in Figure 2 is introduced as a reference. In the separated system, the electrical load is provided by the power grid, the cooling load is provided by the electric refrigerator, and the heating load is provided by the Thermal power plant.

To find the optimal operation mode, the following assumptions are proposed under the premise of the reasonable error.

- (1) The CCHP system is connected to the public power grid, and the power can be obtained from the power grid but cannot be sold to the grid.
- (2) The AC COP, CC COP, HE efficiency, GB efficiency and electricity efficiency from the public supply network are simplified as fixed numbers.
- (3) The pressure and temperature of the high-pressure and low-pressure steam of the HRSG are fixed. The temperature of the back water is constant.
- (4) The two gas turbines share the gas fuel on average.

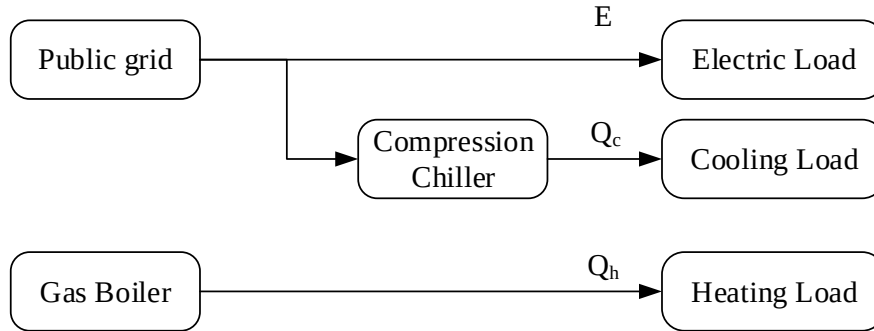


Figure 2. The conventional separated system

3. The model of optimization

3.1. Models of instruments

3.1.1. Gas turbine module. The gas turbine in the system is LM2500+G4 which is produced by GE, and the relationship between the power generated and the fuel is determined according to the manufacturer's design data. So the linear relationship is described as

$$Pe_{gt} = 21.74 \cdot G_{f_gt} - 8.90 \quad (1)$$

$$0.45 < G_{f_gt} < 1.9 \quad (2)$$

Where G_{f_gt} is the flow rate of the gas fuel, Pe_{gt} is the electricity generated by gas turbine.

3.1.2. Heat recovery steam generator module. The HRSG is used to recover the residual heat of the gas turbine and to generate high-pressure and low-pressure steam and hot water. According to the design data of the HRSG and GT, the high-pressure steam generated by HRSG is

$$Q_{HPS} = (4.92 \times G_{f_gt} + 2.17) \cdot \Delta h_{HPS} \quad (3)$$

The low-pressure steam generated by HRSG is

$$Q_{LPS} = (-0.62 \times G_{f_gt}^2 + 2.56 \times G_{f_gt} - 0.45) \cdot \Delta h_{LPS} \quad (4)$$

The hot water generated by HRSG is

$$Q_{water} = (7.10 \times G_{f_gt} + 3.43) \cdot \Delta h_{water} \quad (5)$$

Where Q_{HPS} , Q_{LPS} , Q_{water} are respectively the heat of high-pressure steam, low-pressure steam and hot water. Δh_{HPS} , Δh_{LPS} , Δh_{water} are respectively the difference of the enthalpy between the outlet of HRSG and the back water.

3.1.3. Condensing steam turbine module. The condensing steam turbine utilizes the high-pressure steam of HRSG to generate electricity and supply a certain heat, and the power generation is not only related to the flow of high-pressure steam, but also the flow of extraction steam. The power of steam turbine is

$$Pe_{st} = D_{HPS} \cdot (h_0 - h_c) - \alpha \cdot D_{HPS} \cdot (h_{ex} - h_c) \quad (6)$$

The heat of steam turbine is

$$Q_{ex} = \alpha \cdot D_{HPS} \cdot (h_{ex} - h_{bw}) \quad (7)$$

Where the Pe_{st} is the power generated by the steam turbine, Q_{ex} is the heat provided by the extraction steam. D_{HPS} is the flow of the high-pressure steam, α is the extraction ratio of the flow of extraction to the flow of main steam in the ST, and h_0 , h_c , h_{ex} , h_{bw} is respectively the enthalpy of the main-steam of ST, exhausted steam, extraction steam and back water.

3.1.4. Other module. Other modules of the CCHP system comprise the absorption chiller, the compression electric chiller, heat exchanger, gas boiler.

Absorption chiller:

$$Q_{ac} = (Q_{ex_Qc} + Q_{LPS_Qc} + Q_{water_Qc}) \cdot COP_{ac} \quad (8)$$

Compression electric chiller:

$$Q_{ec} = Pe_{ec} \cdot COP_{ec} \quad (9)$$

Heat exchanger:

$$Q_h = (Q_{ex_Qh} + Q_{LPS_Qh} + Q_{water_Qh}) \cdot \eta_h \quad (10)$$

Gas boiler:

$$Q_b = G_{f_b} \cdot LHV \cdot \eta_b \quad (11)$$

The Q_{ac} , Q_{ec} , Q_h , Q_b is respectively the cooling or heating generated by the absorption chiller, the compression electric chiller, heat exchanger and gas boiler. The COP_{ac} , COP_{ec} , η_b , η_h is respectively the coefficient of performance or efficiency of absorption chiller, compression chiller and gas boiler, heat exchanger. Q_{i_j} ($i=ex, LPS, water$; $j=Q_c, Q_h$) is the cooling (Q_c) or the heating (Q_h) provide by extraction steam, low-pressure steam or hot water.

3.2. Objective of optimization

3.2.1. Cogeneration efficiency improvement. For the CCHP system, the cogeneration efficiency is described as

$$\eta_{co} = \frac{Q_{ac} + Q_h + Pe}{G_{f_gt} \cdot LHV / 1000} \quad (12)$$

Where the Q_{ac} , Q_h , Pe are respectively the cooling, heating and power provided by absorption, heat exchanger and cogeneration system. The G_{f_gt} is the flow of fuel in the inlet of gas turbine, η_{co} is the cogeneration efficiency of the cogeneration system.

For the convenience of analysis, this paper have calculated a minimum efficiency as the reference value, and proposed the cogeneration efficiency improvement (CEI)

$$CEI = \frac{\eta_{co} - \eta_{ref}}{\eta_{ref}} \quad (13)$$

Where η_{ref} is the reference value of the efficiency. The η_{ref} is the minimum value of different single objective optimization results.

3.2.2. Operation Cost Saving. Operation cost (OC) mainly includes the electricity purchase cost from the public grid, the cost of natural gas consumed in the gas turbine and gas boiler, the cost of equipment's maintenance. For the CCHP system, the operation cost is

$$OC_{des} = C_{grid} \cdot E_{grid} + C_{fuel} \cdot F_{fuel} + \sum_{i=1}^n C_{ope_i} \cdot N_i \quad (14)$$

Where the C_{grid} , C_{fuel} , C_{ope_i} are respectively the cost of power from the public grid, the natural gas and the maintenance of each equipment. i represents different equipment, n is the number of the equipment, N_i is the output of different equipment.

Operation cost saving (OCS) is the operation cost reduction of the CCHP system relative to the separated system, and the operation cost saving is

$$OCS = \frac{OC_{sp} - OC_{des}}{OC_{sp}} \quad (15)$$

Where the OC_{sp} , OC_{des} respectively indicate the operation cost of the separated system and the CCHP system.

3.2.3. Integrated Performance. For the CCHP system driven by gas-steam cycle, the cogeneration efficiency and the operation cost are both important. So the paper chooses the cogeneration efficiency improvement and the operation cost as the objective of optimization

$$IP = \omega_1 \cdot CEI + \omega_2 \cdot COS \quad (16)$$

Where the IP is the integral performance, ω_1 , ω_2 are respectively the weight of cogeneration efficiency and operation cost saving in the objective function, and $\omega_1, \omega_2 = 0.5$.

3.3. Constraints.

The constraints mainly include the equipment and energy balance constraints which are shown below.

$$G_{f_gt\ min} < G_{f_gt} < G_{f_gt\ max} \quad \alpha_{min} < \alpha < \alpha_{max} \quad (17)$$

$$\begin{cases} G_{f_b} \geq 0 \\ E_{grid} \geq 0 \\ Q_{ec} \geq 0 \end{cases} \quad (18)$$

$$\begin{cases} 0 \leq Q_{ac} \leq Q_{ac\max} \\ 0 \leq Q_h \leq Q_{h\max} \end{cases} \quad (19)$$

$$\begin{cases} Q_h \geq Q_{h_load} \\ Q_{ac} + Q_{ec} \geq Q_{c_load} \\ Pe_{st} + Pe_{gt} - Pe_{ec} + E_{grid} \geq E_{load} \end{cases} \quad (20)$$

Where the Eq.17 ensure that the input is within reasonable range, and Eq.18 make the input or output of GB, power grid or CC can be positive. The Eq.19 ensure that the output of AC and HE don't excess the maximum. The last Eq.20 is to make the output of heating, cooling and power which the CCHP provide can meet the load demand.

3.4. The settings of the efficiency or parameter mentioned above.

The range or value of some parameters are listed in Table 1.

Tab 1. The range or value of parameters

Parameters	Value
$G_{f_gt} / kg/s$	0.45-1.9
α	0.1-0.7
η_b	0.8
η_h	0.8
COP_{ac}	0.7
COP_{cc}	3.2
$LHV / kJ/kg$	29307

The price of natural gas and power are listed in Table 2.

Table 2. Emission parameters of natural gas and electricity

Energy	Price	
Natural gas/ (Yuan/m ³)	2.5	
Power/ (Yuan/kWh)	Valley (0 - 7)	0.305 0
	Flat (13-17, 22-24)	0.615 1
	Peak (8-12, 18- 21)	1.025 2

The operation cost of various equipment are listed in Table 3.

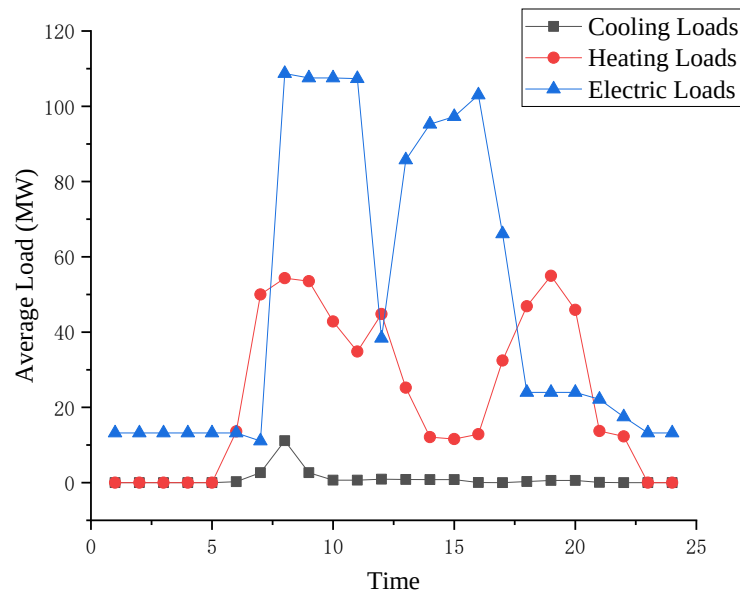
Table 3. The operation cost of various equipment

Equipment	Value / (Yuan/ kWh)
Heat Exchanger	0.001
Absorption Chiller	0.0008
Compression Chiller	0.0097
Heat Recovery System	0.00216
Gas Boiler	0.00216
Gas Turbine	0.0683

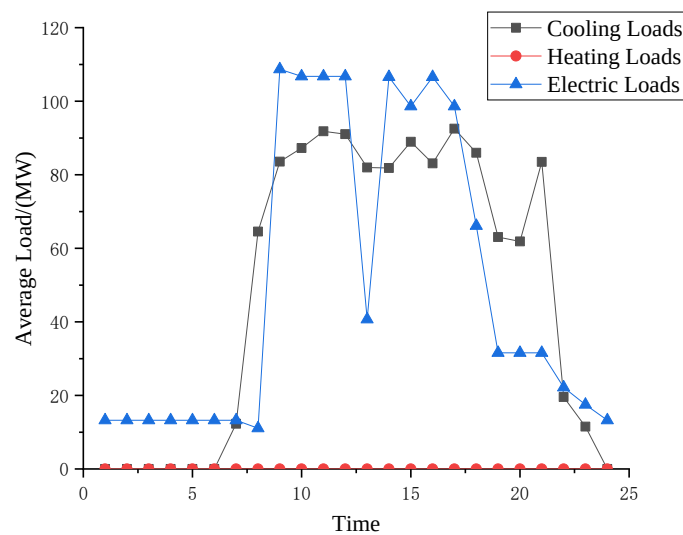
4. Result and discussion

4.1. The characteristic of load.

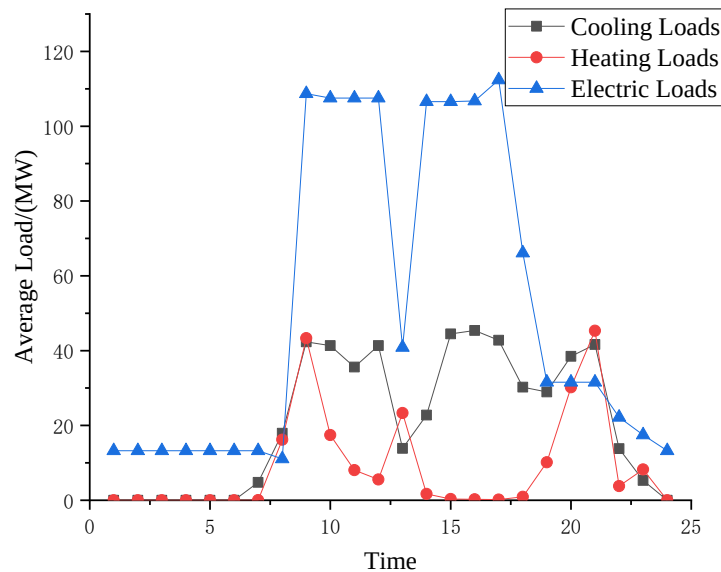
This paper chooses the load of office building groups in an area of Beijing as the analysis object the hourly cooling, heating and power load are obtained through the software Dest, and the different load in winter, summer, transient season is shown in the Figure 3a, b, c.



a) The load in the winter



b) The load in the summer



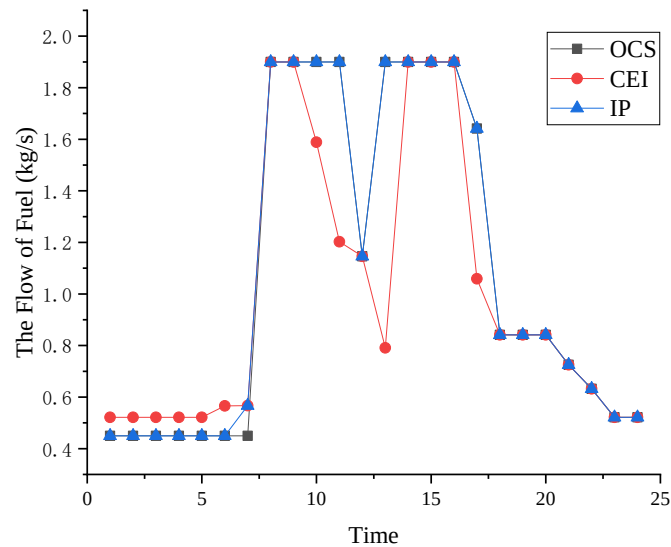
c) The load in the transient season

Figure 3. The load of the different season

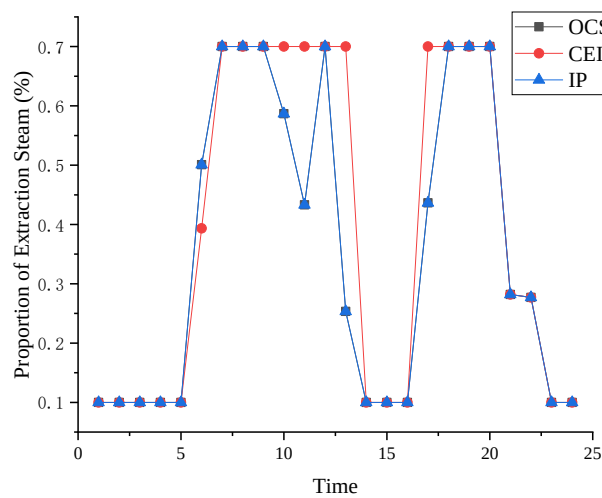
From the three graph above, the electric load in the office building is very low and the cooling and heating load is none from 11 pm to 7 am as the result of no people in the buildings. From 8 am to 10 am and from 1 am to 5 pm, the electric loads of the reference building are the highest, and the electricity consumption is mainly used for lights, equipment operation, refrigeration and lights. At noon, people will have a break from 10 am to 2 pm, so the electric load have a significant drop of 66%. From the perspective of the season, when in the summer, there is little heating load and the cooling load and the electric load is much higher than the heating load as a result of the massive use of air conditioners and the high outdoor temperatures. When in the winter, the cooling load is almost none, and the electric load and the heating load is very high. When in the autumn, all the power, heating and cooling load exist, and the cooling and heating load is not much different and both loads are about 30MW. From the Figure 3, we can see that the electrical load is the highest in any season and the maximum load can up to 115MW because in the office building, the main method of energy consumption is the use of electrical equipment such as the computer, the lights and etc.

4.2. The changes of decision variables in different optimization.

This paper first optimizes and analyzes the fuel of GT and proportion of extraction steam under different operating modes in different seasons which is shown in the Figure 4.



a) The changes of fuel in the winter

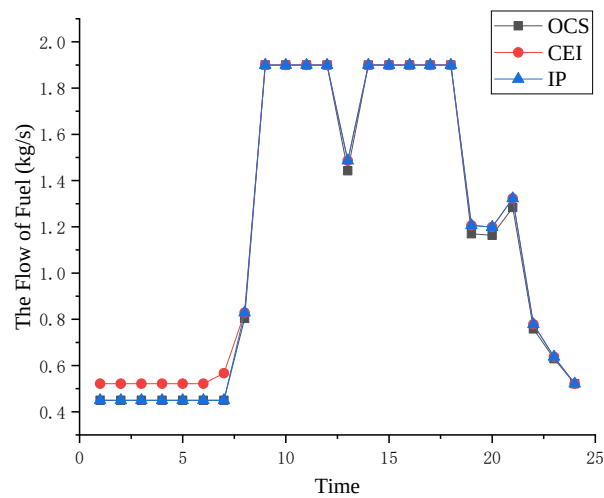


b) The changes of extraction steam in the winter

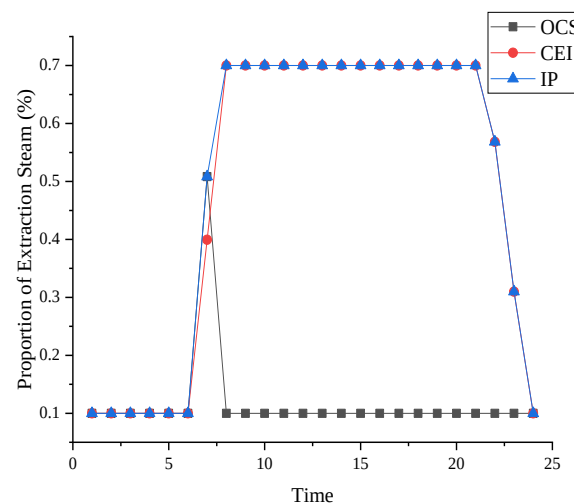
Figure 4. The changes of variables under different optimization in the winter

From Figure 4a-b, it can be seen that in the winter, the result of IP optimization is consistent with the results of OCS optimization, so when using the IP as the objective function, the operating costs have a greater impact on the optimization results. When in the period time of valley electricity, the fuel of the OCS optimization keeps a very small value of 0.45, while in the cogeneration efficiency optimization, the fuel is a little higher than the result of OCS optimization, it is reason that when the fuel is very low, the cogeneration efficiency is very low. During periods of high load in the daytime, the fuel of OCS optimization always keeps highest, while in the cogeneration efficiency optimization, the fuel of GT is lower than the OCS optimization for a relative higher cogeneration efficiency.

For the extraction steam, the proportion of total extraction steam always keeps the maximum condition from 7 am to 1 pm and 5 pm to 8 pm under CEI operation, and as a result that the heating load drops from 1 pm to 5 pm, the proportion all decrease in all optimization.



a) The changes of fuel in the summer

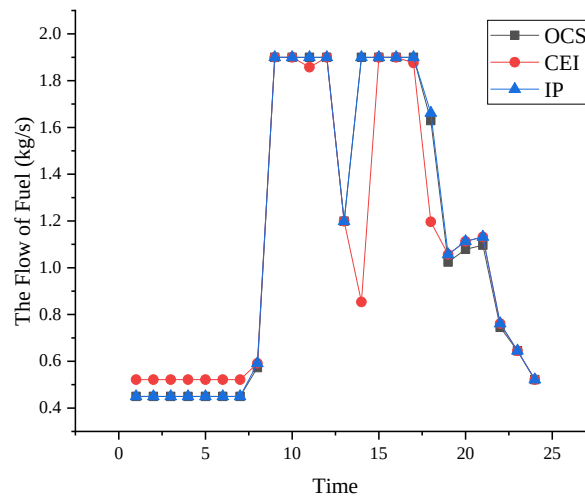


b) The changes of extraction steam in the summer

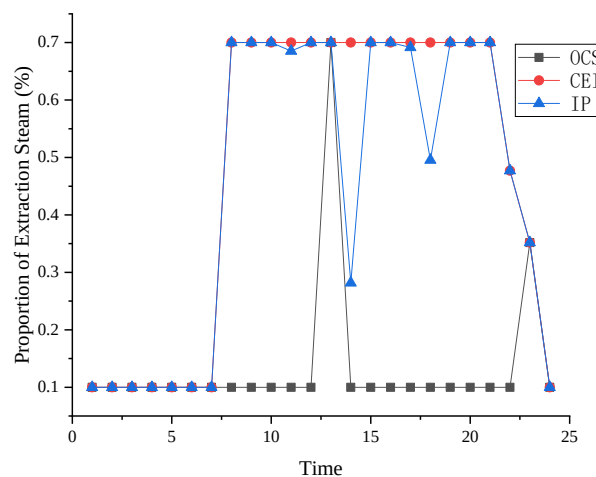
Figure 5. The changes of variables under different optimization in the summer

From Figure 5a-b, we can see that in the summer, the results of the fuel is almost same under the three optimization except that the time is at valley period. When in the valley period, the cogeneration the fuel of OCS optimization keep the minimum while the fuel of IP and CEI optimization is higher of about 0.52.

For the extraction steam, the result of the OCS optimization is all kept at a minimum of 0.1, because the low operation cost of compression chiller lead to the massive use of CC, and the CCHP will generate power as far as possible. The result of the IP and CEI optimization is always at a maximum of 0.7, only when the load decreases, the value starts decreases gradually for no excessive heating generated.



a) The changes of fuel in the transient season



b) The changes of extraction steam in the transient season

Figure 6. The changes of variables under different optimization in the transient season

From Figure 6a-b, we can see that in the transition season, the result of OCS optimization and the IP optimization keep consistent, and when the time is between the 0 am and 7 am, the fuel consumption is still the minimum, and when the objective is cogeneration efficiency improvement, the fuel is higher than the other two optimization result. For the steam extraction, when the system takes the OCS as the objective, the value always keeps the minimum, and when taking the cogeneration efficiency as the objective, the value of optimization is the maximum of 0.7, the result of IP optimization is between the other two optimization.

4.3. The distribution of loads in different optimization

From the Figure 7a, the distribution of heating load during the valley period is same under different optimization and the most of heating load is satisfied by the gas boiler. During the flat period, when optimized in cogeneration efficiency, the heating provided by extraction is the most as the result of the maximum extraction steam. During the peak period, the heating supply is almost same, and in each optimization, the heating provided by the extraction steam and gas boiler are at a close level.

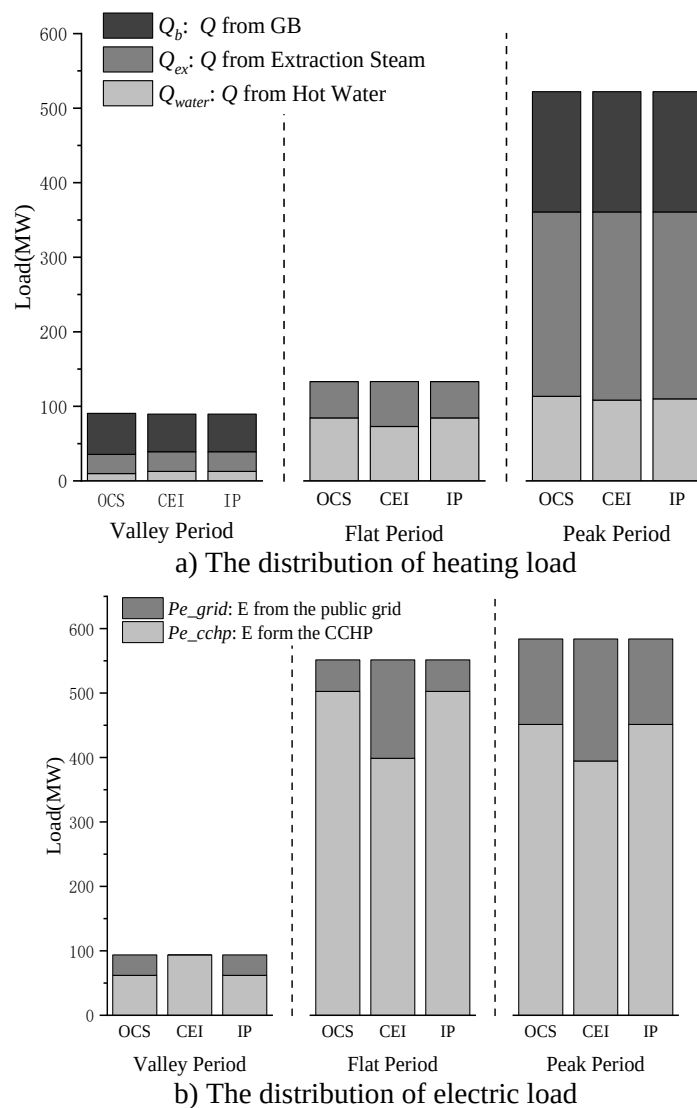
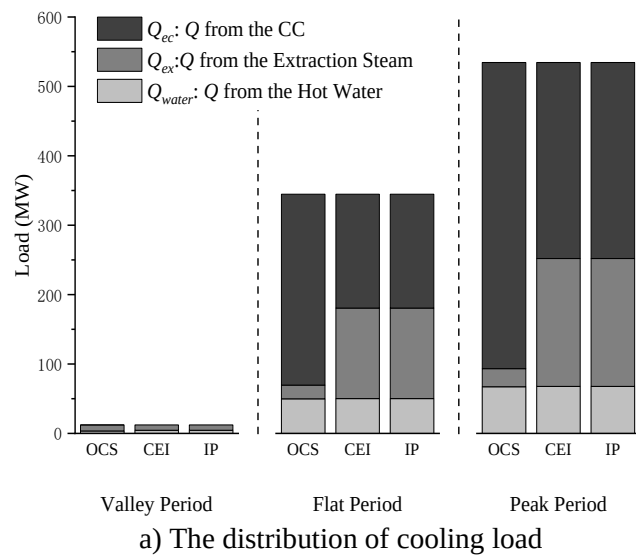
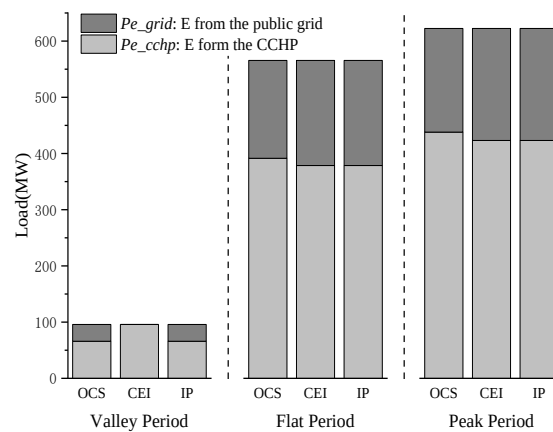


Figure 7. The distribution of different loads in the winter

From the Figure 7b, we can see that during the valley period, when the system is in the CEI optimization, the electric load is totally satisfied by the CCHP to avoid low cogeneration efficiency. During the flat period, the electric power provided by the CCHP is less than that other two optimizations offer, it is the reason that when the system operation in cogeneration efficiency optimization, the proportion of the extraction steam is larger than other operation mode, so the electricity generated by the CCHP is less than the other two operation strategies.



a) The distribution of cooling load

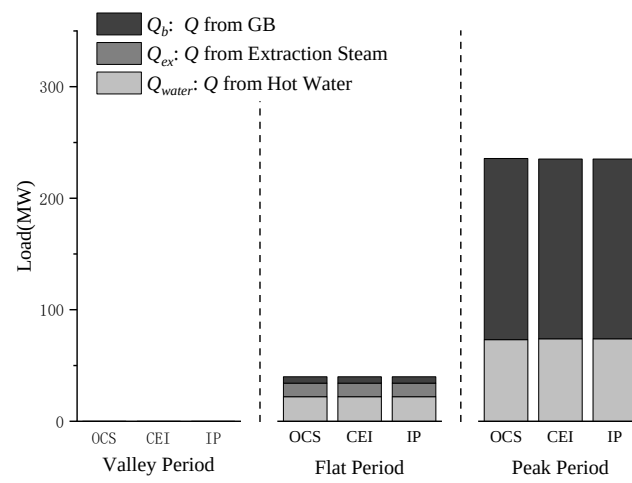


b) The distribution of electric load

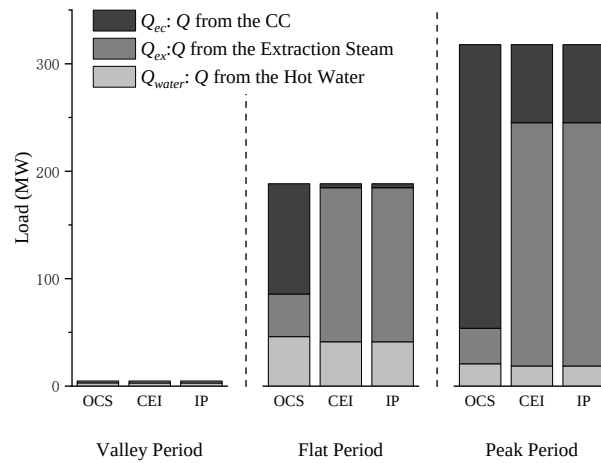
Figure 8. The distribution of different loads in the summer

From the Figure 8a, when the system operates at the OCS optimization, the cooling load is mainly offered by the compression chiller, because the COP of CC is several times to the COP of AC, the cost of using power is cheaper than the cost of using heating, and the ratio of the cooling load offered by the CC is 79.8% and 82.5% during the flat and peak period. When the objective is the cogeneration or IP, the cooling load provided by heating will gain an increase obviously, and the ratio of the cooling load offered by the AC is 65.6% and 47.1% during the flat period and peak period.

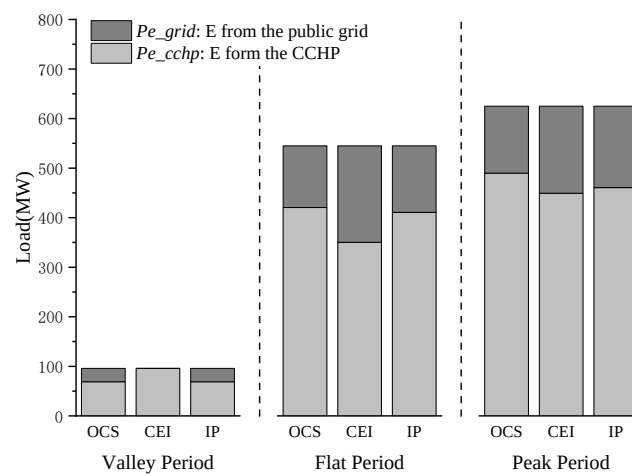
From the Figure 8b, during the valley, the electric load is totally provided by the CCHP system when the system is operated at a CEI optimization. When the time is during the period of flat period and peak period, the result of output in different equipment is similar.



a) The distribution of the heating load



b) The distribution of the cooling load



c) The distribution of the electric load

Figure 9. The distribution of different loads in the transient season

Form the Figure 9a, when in the transient season, the heating supply is same in different optimization all day. From the Figure 9b, the cooling load is satisfied firstly by the hot water or the extraction steam when the system is operated in the cogeneration efficiency optimization, and thermal refrigeration can totally satisfy the cooling load because of the low cooling load. When operated in the OCS optimization, the most of the cooling load are provided by the compression chiller. From the figure 9c, because of the high electric price, the electric load is mostly satisfied by the CCHP system, and when operating in the CEI, the electric load bought from the public grid is more than the other two optimization method, and when operating in the IP optimization, the electric load from the public grid is between the other two result.

4.4. Annual indicator analysis.

The Figure 10a and Figure 10b show the trend of the two objective respectively in three operation mode. From the Figure 10a, it is obviously that when operating in the OCS optimization, the OCS is the highest in any month, and the CEI is the least in all year. When in the winter which needs much heating load, the result of the OCS and IP optimization are nearly the same, and the two optimizations both reach the largest OCS of 0.178 in the Jan. When in the summer season and the transient season, the changes of OCS is little and keep floating around 0.155. From the Figure 10a, when the system is operating in the cogeneration efficiency optimization. The OCS keeps a relative low level of 0.12-0.14, and the value do not have too much changes during the all year.

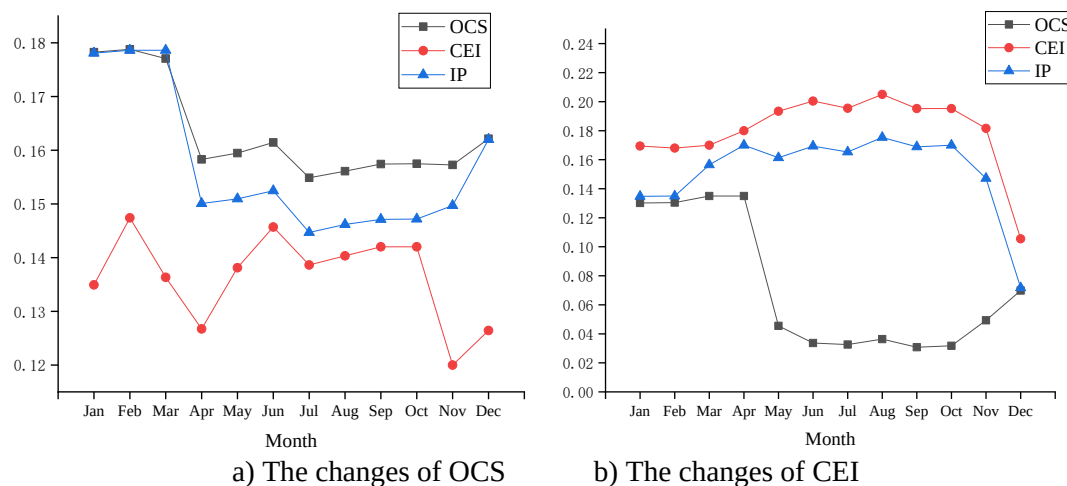


Figure 10. The changes of different indicators

From the Figure 10b, when the system operate in the CEI optimization, the cogeneration efficiency can always keep at a high level of 0.52. When in the winter, the difference of efficiency between the OCS optimization and CEI optimization is not too much, but when in the summer, the efficiency in the cogeneration efficiency increases gradually, while the efficiency in the OCS optimization decrease greatly, and when entering the heating season of Nov and Dec, the difference among the three optimization starts to decrease again. When the system operates in the IP optimization, the value of indicator almost between the other two optimization methods.

5. Conclusion

The paper have established a model of CCHP which is driven by the gas-steam cycle, and chosen the CEI, COS and IP as the objective to analyze the optimal operation strategies under different loads. Some conclusion can be summarized as follows.

In the OCS optimization, the cooling load is firstly satisfied by the compression chiller in the summer, and the heating load is offered by the hot water and extraction steam, while for the electric load, the CCHP provides the power first in the peak period. In the CEI optimization, the cooling load is firstly satisfied by the AC for improving the cogeneration efficiency, and the heating load is offered by the extraction steam more, while the electric load are provided by the public grid, because overload operation will decrease the efficiency when the load is high. In the IP optimization, the result is the same as the result under OCS optimization in the winter, and the same as the result under CEI optimization in the summer. When in the transient season, the result of the IP optimization is between the other two optimization.

The operation strategies of the CCHP under the three optimization can all improve the cogeneration efficiency by the average of 5.1%, 18.5%, 16.1% and reduce the operation cost by the average of 16.2%, 15.1%, 14%. According the analysis, when the system operates under the IP optimization all the year, the system can maintain a CEI of about 16% and an OCS of about 15%, therefore the proposed operation strategy can achieve a comprehensive benefit relative to the other two optimization method.

Acknowledgements

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