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Configuration Optimization and Novel Operation Strategies for Combined Cooling Heating and Power System Based on Micro Gas Turbine

CHENG Kanru[1], ZHANG Qing[1], LI Jiao[1], HU Daoming[1], WANG Yuzhang[1, 2, *]

1 School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Rd. Shanghai 200240, China

2 Gas Turbine Research Institute, Shanghai Jiao Tong University, 800 Dong Chuan Rd. Shanghai 200240, China

ABSTRACT

Integrated energy system can effectively improve the efficiency and economy of energy utilization, and is an effective means of realizing carbon neutralization. The configuration optimization of CCHP system based on micro gas turbine is proposed to improve the overall performance of CCHP system in economy, energy saving and environmental protection. Three operation strategies are also proposed. The results show that the optimized CCHP system performs better than the traditional SP system, and is more suitable for users with low power load and big fluctuation.

Keywords: Integrated energy system; Combined cooling heating and power system; Multi-objective optimization; Optimization design

NONMENCLATURE

Abbreviations	
ATCSR	Annual total cost saving ratio
CCHP	Combined cooling heating and power system
CO2ERR	CO_2 emission reduction ratio
IES	Integrated energy system
PESR	Primary energy saving ratio
PGU	Power generation unit
PSO	Particle Swarm Optimization
Symbols	
ATC^{CCHP}	The annual total cost of CCHP system
ATC^{SP}	The annual total cost of SP system
CO_2E^{CCHP}	The CO2 emission of CCHP system
CO_2E^{SP}	The CO2 emission of SP system
F^{CCHP}	The total primary energy consumption of the CCHP system
F^{TES}	The total primary energy consumption of the SP system
U_{obj}	Objective function

1. INTRODUCTION

With the growth of global population and social industrialization, human demand for energy has reached an unprecedented level. The large consumption of fossil energy has caused energy shortage and environmental pollution. Under these circumstances, systems with various forms of energy carriers have higher reliability, enhanced economic operation, decreased power loss and more flexibility compared to the systems with only one energy carrier. In order to ensure energy security and protect the environment, Integrated Energy Systems (IES) are currently developing fast in China with the new power industry reform policy. In recent years, the Chinese government has vigorously promoted the development of low-carbon parks and a number of IES demonstration projects have been developed, such as Sino-German Eco-Park, the Langfang Eco-city, etc. [1-3], which are in need of an effective method to schedule and coordinate the interrelated energy systems of IES in an optimal way.

Combined Cooling Heating and Power (CCHP) system is an important and typical type of IES, and is considered to be an effective technology to promote energy savings and mitigate the global warming due to its highly efficient, low pollution and high flexibility [4, 5]. CCHP system can be described as a tri-generation system,

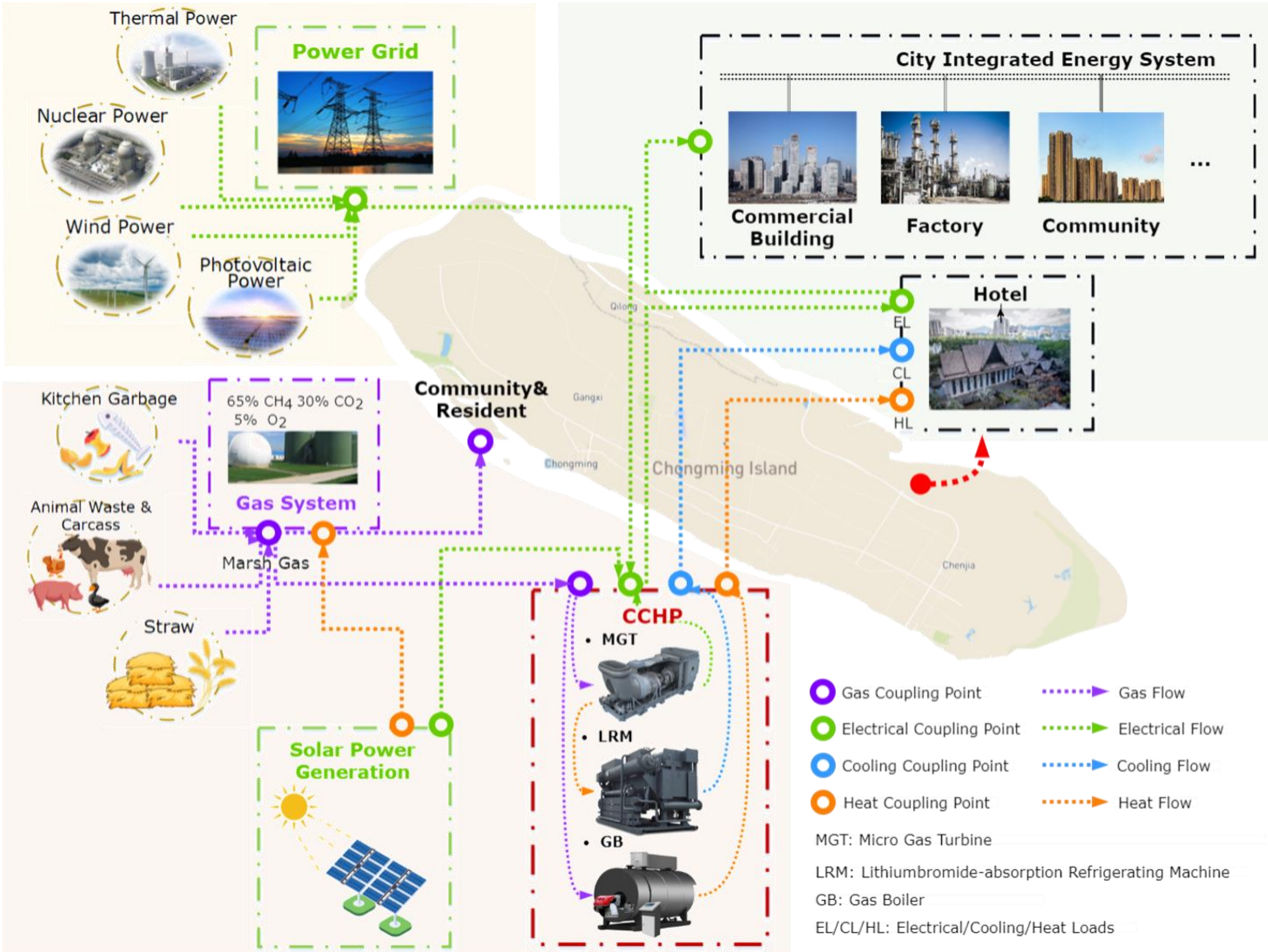


Fig. 1. Schematic diagram of the CCHP system on Chongming Island

where the power generation unit (PGU) provides electricity and at the same time, cooling and heating demands can be satisfied by recovering waste heat from the PGU [6, 7]. Different climate conditions, different areas and different demands of users make the system various. And micro-scale or small-scale CCHP systems are now become more popular than large-scale CCHP systems because of the higher flexibility and the fluctuation demands of users like hospital, hotel and so on [4, 5]. The optimization of the configuration and operation strategy of CCHP system is the key to improve the performance and has been studied widely.

In this paper, an IES system is proposed based on CCHP, and a simulation platform was established based on this system. The influence of configuration and operation mode on the system were studied, and through simulation analysis, the optimal configuration and optimal operation mode are obtained.

2. METHODOLOGY

2.1 IES design

Chongming Island of Shanghai has been selected as the study area of this research and the IES experimental area. Chongming Island located in eastern China, which is an alluvial island at the mouth of the Yangtze River. The design of the IES on Chongming Island is shown in Fig.1. This energy system is a typical wind-solar-biomass multi-energy complementary energy supply system. The system has a biogas preparation system based on kitchen waste, breeding manure and straw planting, and uses photovoltaic thermal technology to enhance the gas production performance of the biogas digester. Biogas is supplied to local residents and the CCHP system established by this research group. This CCHP provides the electric, heat and cooling to a comprehensive hotel located in southeast of the island.

Through the annual energy load analysis of this hotel, as shown in Fig. 2, the total capacity of the CCHP for this hotel is 260kW.

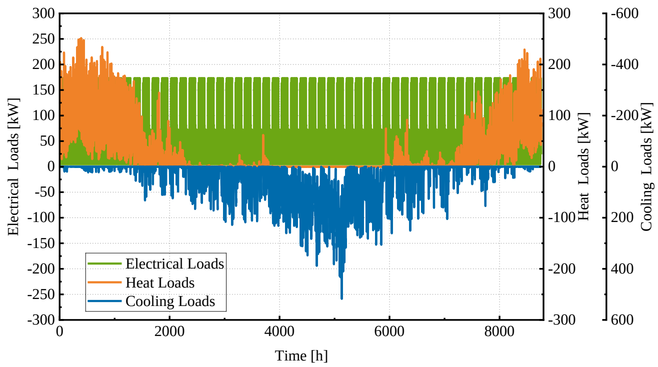


Fig. 2. Annual energy load analysis of this hotel

As shown in Table 1, we can see that the demand of electricity between 50-250kw in a year occupies the proportion about 85% and the cooling load converge on the section below 50kw. The character of this kind of users is that the fluctuation of the loads is small between day and night, the heat and electricity demand is stable.

Table 1 Loads statistics by hours

Segment of the loads/kw	Number of hours of electricity/h	Number of hours of heating/h	Number of hours of cooling/h
0-50	327	5829	3000
50-100	2957	511	1116
100-150	3129	338	777
150-200	1565	204	582
200-250	391	301	599
250-300	267	262	730
300-400	124	415	861
400-600	0	571	704
Above 600	0	329	391

2.1 Decision variables and objective of optimization

The optimization design of the CCHP system is a typical multi-objective optimization problem, and the three parts of economic, energy saving and environmental protection should be optimized at the same time.

Primary energy saving ratio (PESR) is defined as the ratio of the energy saving of the CCHP system compared to SP system and it can be expressed as:

$$\mathrm{PESR} = \frac{F^{sp} - F^{CCHP}}{F^{sp}} \times 100\%$$

where F^{sp} means the total primary energy consumption of the SP system and F^{CCHP} means the energy consumption of the CCHP system

The annual total cost saving ratio (ATCSR) is defined as the ratio of the annual total cost saving of CCHP system compared to SP system and is expressed as:

$$\mathrm{ATCSR} = \frac{ATC^{SP} - ATC^{CCHP}}{ATC^{SP}} \times 100\%$$

where ATC^{SP} means the annual total cost of SP system and ATC^{CCHP} means the annual total cost of CCHP system and can be calculated as:

$$\mathrm{ATC} = C_{eq}R + C_{run} + C_m$$

where C_{eq}, C_{run} and C_m are the cost of initial investment, running and maintaining. R is the recovery coefficient and is influenced by the annual interest rate.

Another objective is the CO_2 emission reduction ratio (CO2ERR) and is defined as:

$$CO2ERR = \frac{CO_2E^{SP} - CO_2E^{CCHP}}{CO_2E^{SP}} \times 100\%$$

where CO_2E^{SP} and CO_2E^{CCHP} are the CO_2 emission of SP system and CCHP system.

Combining the three criteria, we can get the objective function U_{obj} as:

$$U_{obj} = \omega_1 ATCSR + \omega_2 PESR + \omega_3 CO_2ERR$$

where ω_1, ω_2 and ω_3 are the three weights of ATCSR, PESR and CO2ERR. To highlight the importance of economic efficiency, choose ω_1 =0.4, ω_2=ω_3=0.3.

Taking the capacity of the micro-gas turbine and the on-off coefficient of the micro-gas turbine as the optimization variables, the weighted average of the above three evaluation criteria is used as the objective function, and use the Particle Swarm Optimization (PSO) algorithm to optimize the variables in the system.

2.2 Configuration plan

The configuration of MGT refers to the number and capacity of MGT according to the performance of MGT on the market. The control strategy refers to the start-stop strategy of each MGT. When the power load is bigger than the capacity or is too small to stop the MGT, the benefit of the system is limited. So, the total capacity of MGT can be divided and allocated to some units with small capacity. The working range of the MGT is wider and the full-load running time is longer by that way.

According to the market research of the MGT, in the configuration plan, four Capstone C65 MGTs were used. The two schemes are shown in Table 2, Scheme1 has no configuration, only one 260kW micro gas turbine is used, while Scheme2 with the configuration plan.

Table 2 Configuration plan of MGT

Scheme	MGT type	Configuration
Scheme1	/	260kw*1=260kw
Scheme2	Capstone C65	65kw*4=260kw

2.3 Operation modes

The power generation unit is the combination of several MGTs and in that way the working range of the MGT is widen and the full-load running time is longer. But there are gaps in the interval of the load supply that are determined by the on-off coefficient. For example, if the MGT group should work in the supply capacity of 0-260kw, but one of the MGTs has to stop in the interval of 0-260kw because of the on-off coefficient and the interval of 0-90kw is the gap. The practical running time will be reduced and there won't be enough power to satisfy the power load. The users will have to buy electricity from the grid and highly rely on it. So, it is important to ensure enough running time to keep the system reliable and independent from the grid.

Specific to the operation of the MGT group, three operation modes of the power generation unit are proposed, these three operation modes can be shown as:

(1) Series type: The load will be allocated to every MGT successively.

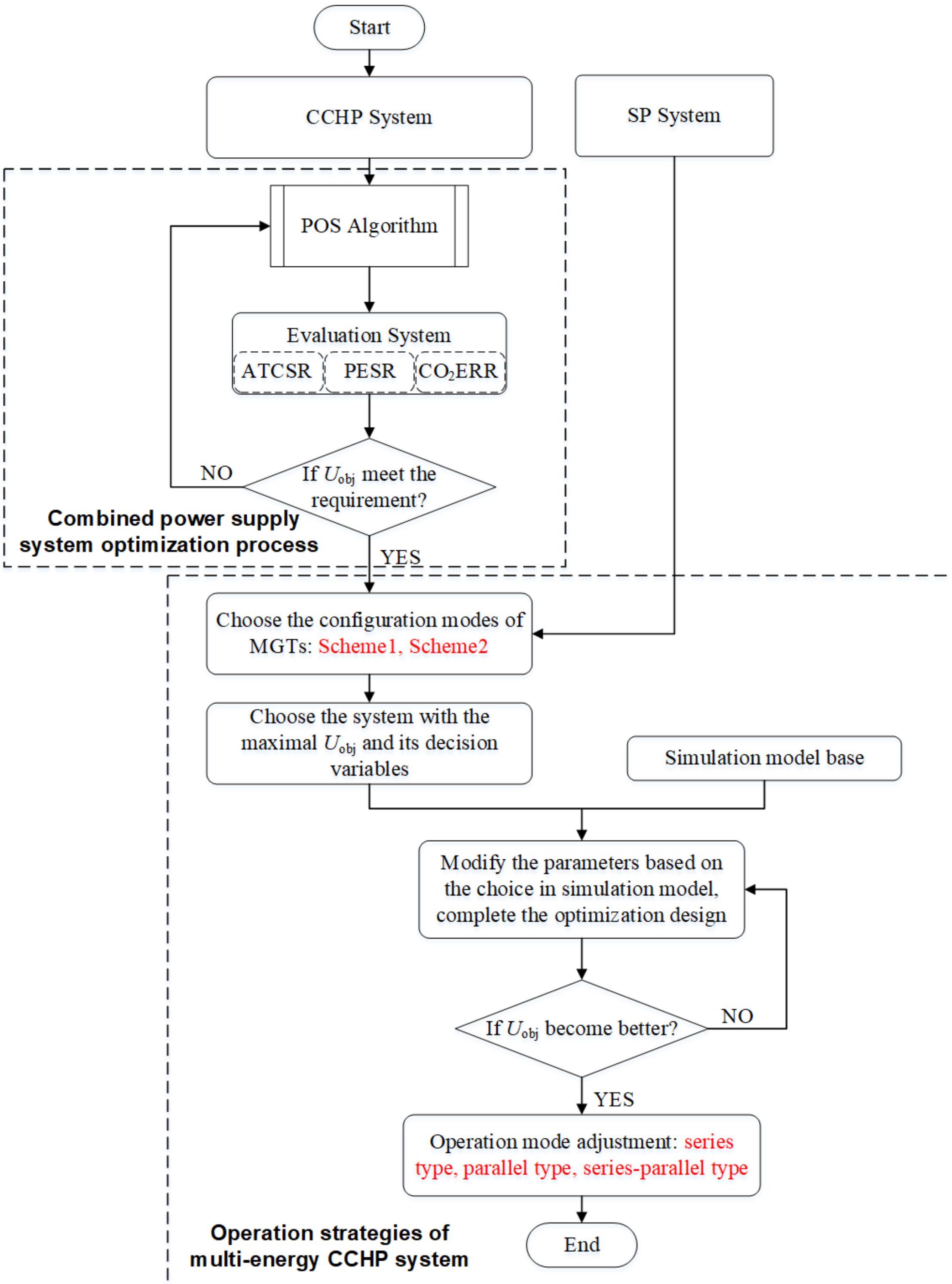


Fig. 3. The optimization procedure of the system

(2) Parallel type: The load will be allocated to all the MGTs equally and the operating parameters of each MGT are the same.

(3) Series-parallel type: Series-parallel type combines the series type and parallel type.

The overall optimization process of the system is shown in Fig. 3..

3. RESULTS

3.1 Optimization of parameters

Taking the annual total hourly load data of cooling, heat and electricity of the hotel into the PSO algorithm, and using MATLAB as the simulation platform, combining the results of the optimization and energy-balance equation, can get the installed capacity of the MGT is 250 kw, and the on-off coefficient is set to be 0.41.

3.2 Configuration selection

The optimized results of the system based on the two configuration plans are shown in Table 3. From the economic point of view, ATCSR of Scheme2 reaches up to 17.55% with an increase of 3.23% than Scheme1 that without optimization. From the energy saving point of view, the PERS of Scheme2 reaches up to 29.44%. From the environmental protection point of view, Scheme2 has an increase of 25.53% than Scheme1.

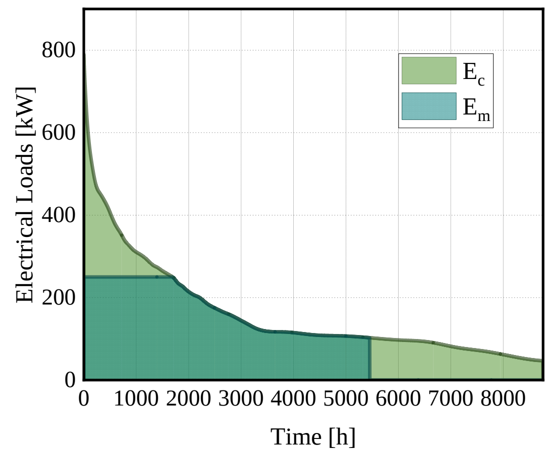
Table 3 Optimized results of the system

Index	Scheme1	Scheme2
ATCSR(%)	14.32	17.55
PESR(%)	28.96	29.44
CO2ERR(%)	12.11	37.64
maxU_{obj}	18.05	27.06
Investment cost (thousand Yuan)	4283.9	4264.7

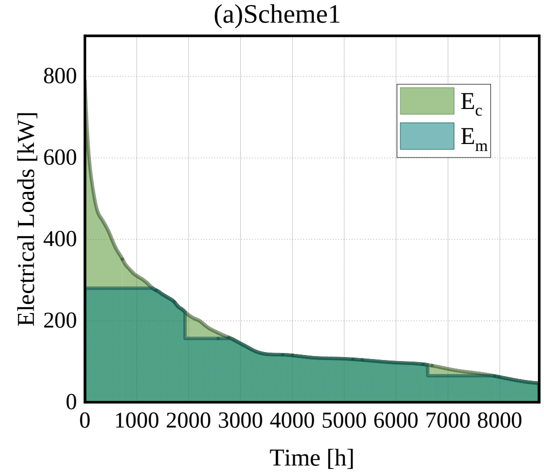
Fig. 4. shows the electrical loads of different schemes. E_c is the power needed for the CCHP system and E_m is the power produced by the MGT units. The shaded area of E_m means the power produced by the MGT while the shaded area of E_c means the power bought from the grid. The MGT will work only about 5000 hours in a year in Fig. 4.(b) while the MGT units will work all the year and the power demanded is more supplied by the MGT units in Fig. 4.(a). So, the configuration optimization of the MGT will also lengthen the operation time of the system and reduce the dependence to the grid.

3.3 Operation mode selection

Take the Scheme2 proposed above as the combining scheme of the PGU, and then discuss the energy load of the hotel. The operation modes of the MGT units have been shown in Section 2.4 and the down load segments in the three modes are shown in Table 4.



(a)Scheme1



(b)Scheme2

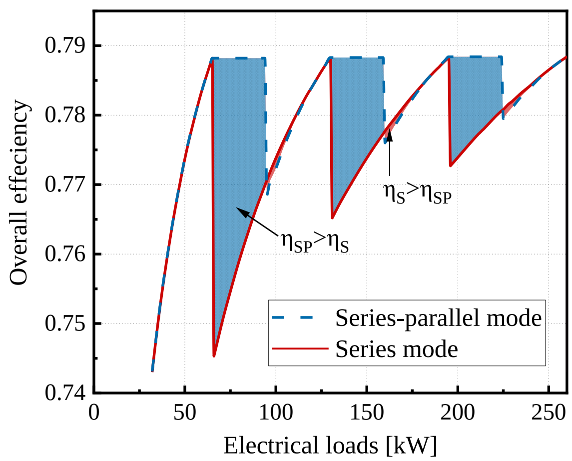
Fig. 4. Electrical loads distribution of different schemes

Table 4 Loads range of shut down in the three modes [kW]

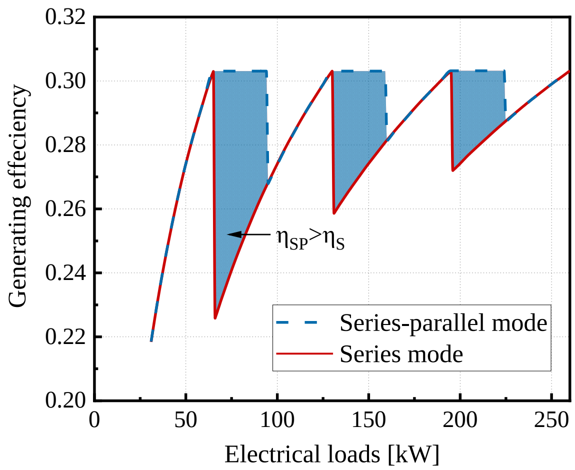
Number of the MGT	Series	Parallel	Series-parallel
1	0-30	0-120	0-30
2	0-95	0-120	0-65
3	0-160	0-120	0-130
4	0-225	0-120	0-195

From Table 4, we can see that parallel type is not suitable for users with low power load and big fluctuation. The operation range of the series mode and series-parallel mode is wide relatively. In the series mode, because of the limit of the on-off coefficient, there is 45% of the load range where the MGT cannot operate at full load. While the series-parallel mode overcomes this difficulty, it is easier to adapt to the fluctuation of the load. The running time is limited because of the starting load and the down load segments of every MGT of series-parallel mode are the shortest which means the working time will be the longest.

Based on the analysis above, the parallel mode is not suitable for the hotel. In order to compare the other two modes in detail, a simulation is carried out under the load between 0 kw to 260 kw. The conditions of overall efficiency and generating efficiency under the two modes are shown in Fig. 5.. Because the two modes are working in the same state under the operating range of the first MGT, the overall efficiency and generating efficiency are the same. But with the adding of the MGT, the overall efficiency and generating efficiency of the series-parallel mode are higher than that of the series mode, and the interpolation is bigger when there is just a new start of a MGT unit. At the same time, the heat supply by the MGT units increase accordingly.



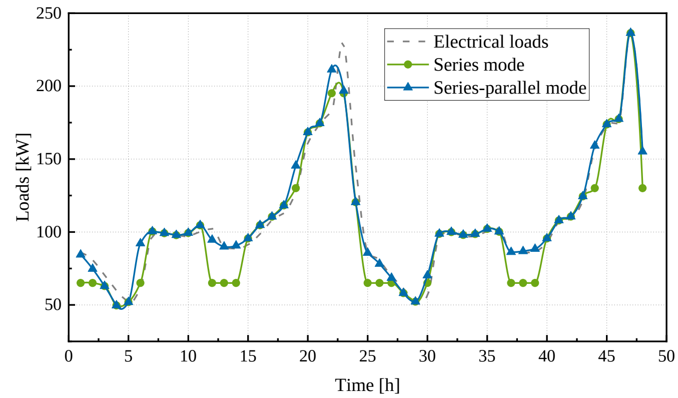
(a) Overall efficiency



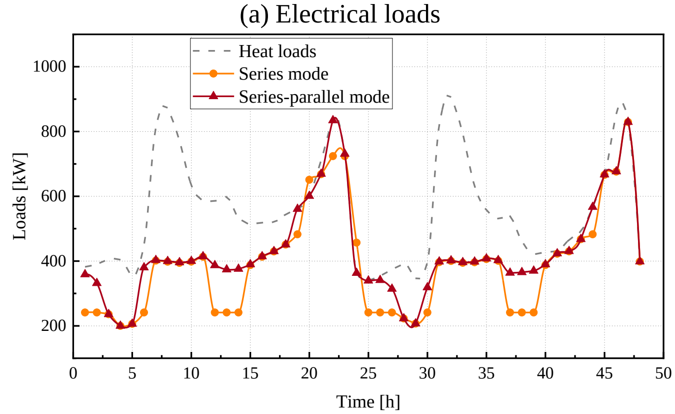
(b) Generating efficiency

Fig. 5. Efficiency under the two modes

A simulation for the hotel has been taken place to show the impact of different modes on the electrical loads and heat loads in different seasons. The results show that there are little differences of the electrical loads supply in spring, summer and autumn of different modes. But in winter, the electrical load is low and the load rate is small, that leads to the shortage of the electrical supply under the series mode but there are some improvements under series-parallel mode. At the same time, the shortage of electrical supply in winter means that there are more MGT started and at the same time the heat supply will be reduced, but under series-parallel mode, the more electrical supply means the more heat produced. Taking the load situation of 2 consecutive days (48 hours) in typical winter as an example, as shown in Fig. 6., the energy supply increases about 9% in winter compared with series mode. Compared with the series mode, there is an increase of 2.97% in electrical supply, and an increase of 6.75% in heat supply. So, the series-parallel mode is more suitable for the energy supply of hotel users.



(a) Electrical loads



(b) Heat loads

Fig. 6. The loads supply under two modes

4. CONCLUSION

This paper set up an IES based on CCHP, and a simulation is established based on this system. The influence of configuration and operation mode on the system is studied, and through simulation analysis, the optimal configuration and optimal operation mode are obtained. Taken the objective function and the running time into consideration, the results show that the optimized system has a better performance in terms of economy, energy saving and environmental protection. Detailed analysis is as follows:

(1) According to the local environment and climate of Chongming Island, an IES suitable for hotel users was established, and the energy flow in the IES was designed.

(2) After the optimization of the configuration, the ability of economy, energy saving and environmental protection of the system have been greatly improved, and the goals of the IES design can be achieved.

(3) For the choice of operation mode, firstly, the efficiency and load satisfaction of the system under different modes are analyzed in detail. Then the final operation mode is determined according to the analysis results, which further improves the performance of the system.

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