Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 2089 – 2094

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

A novel CHP-HP coupling system and its optimization analysis by genetic algorithm

Shushuo Kang[a,b], Lin Lu[b]*, Hongqiang Li[a]*, Guoqiang Zhang[a]

[a] *College of Civil Engineering, National Center for International Research Collaboration in Building Safety and Environment, Hunan University, Changsha, Hunan, 410082, China*

[b] *Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong*

Abstract

Combined heating and power system has been applied widely due to its energetic and environmental characteristics. Heat pump system is also regarded as a promising energy-saving and environment-friendly technology. This paper proposed a novel coupling system by integrating the combined heating and power system with the heat pump system. The performance characteristics of the novel coupling system are investigated by the Aspen plus software based on a case system. The results show that the energetic efficiency and exergetic efficiency are 142.2% and 22.6% respectively, increasing by 3.9% and 3.7% respectively, compared with the ones of reference system. In order to make the novel coupling system more practical, the multi-objective optimal model is developed based on the primary energy saving ratio, carbon dioxide emission reduction ratio and annual total cost saving ratio simultaneously. The key parameters, such as the capacity of power generation unit and the outlet temperature from the heat pump, are optimized by genetic algorithm so as to maximize the comprehensive performance.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Combined heating and power system; Heat pump; Integration system; Performance analysis; Multi-objective optimization.

1. Introduction

Combined heating and power system (CHP), in which waste heat is utilized, is a popular alternative to conventional system due to its environment-friendly, operation cost saving and energy-saving characteristics. Heat pump (HP) is also regarded as a promising technology, especially ground source heat pump, which utilizes renewable energy as its heating source, and shows much higher coefficient of performance (COP). Therefore, the coupling system which consists of the CHP and HP can perform better.

* Corresponding author. Tel.: +86 731 88821040; Fax: +86 731 88821004.

E-mail address: vivien.lu@polyu.edu.hk, lhq@hnu.edu.cn.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

doi:10.1016/j.egypro.2017.03.588

Based on the principle of temperature grade counterparts and heat transfer mechanism, a novel coupling system, with difference from common integration approach, was proposed [1].

In order to make the novel coupling system more practical, it is necessary to optimize its design and operation strategy. The typical optimization algorithms used in CCHP systems are usually linear programming and non-linear programming, while there are some other optimization methods such as sequential quadratic programming, Lagrangian relaxation, particle swarm and genetic algorithm (GA) [2] [3]. More importantly, the objective function in optimization process guides and determines the optimal result in some extent. Usually, the objective function is expressed in different terms of primary energy saving, annual total cost and exergetic efficiency, as well as carbon dioxide emissions [3]. Therefore, in this paper, the multi-objective function which includes primary energy saving ratio (PESR), carbon dioxide emission reduction ratio (CDER) and the annual total cost saving ratio (ATCSR) is constructed and the GA is employed to optimize the key operation parameters of the novel coupling system.

2. System description

The schematic diagram of novel coupling system can be observed in Fig. 1. First, compressed natural gas and air are sent into combustor. After combustion, flue gas with high temperature and high pressure flows into gas turbine to generate power. Then, exit flue gas flows into heat exchanger to reheat the warm water generated by HP-subsystem to meet the requirement temperature. It should be pointed out that the outlet temperature is dropped actively from the required temperature.

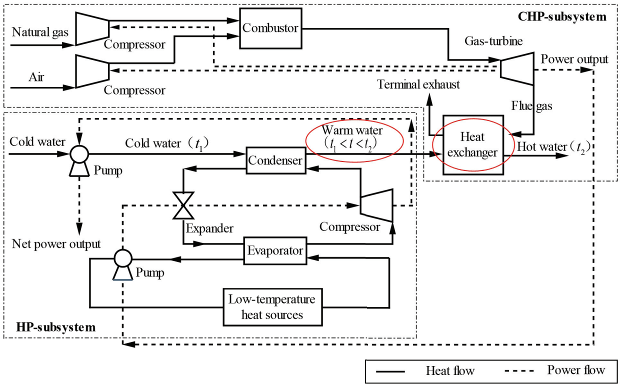

Fig. 1. Schematic diagram of the novel CHP-HP coupling system

The major differences with the reference system are as follows: first, the utilization approach of flue gas from CHP-subsystem is directly used for heating the outlet temperature from HP; second, the HP no longer generates hot water at the required temperature, but generates the warm water instead; and third, the inlet temperature of the cold fluid in heat exchanger is increased.

3. Optimization model

3.1. System model

The novel coupling system always consists of power generation unit (PGU), waste heat recovery system, boiler and HP. Here the novel coupling system operates following thermal demand. The electricity from PGU is used for meeting electricity demand. The waste heat of PGU and the heating from HP is utilized to satisfy the heating demand. If the generated heating does not completely satisfy the application, the supplementary boiler needs to be opened to reheat the outlet stream of HP. Similarly, when the amount of electricity generated by PGU is not enough, the additional electricity comes from the grid. However, when there are excess heat or electricity produced, these excess products will be wasted.

In the novel coupling system, the electrical energy balance is expressed as:

$$E_{ij,grid} + E_{ij,\mathrm{pgu}} = E_{ij} + E_{ij,hp} + E_{ij,\mathrm{ae}} \tag{1}$$

where i and j are day and hour, respectively; $E_{ij,grid}$ is the electricity from grid; $E_{ij,pgu}$ is the electricity generated by PGU; E_{ij} is the electricity load of building; $E_{ij,ae}$ is the electricity consumption of the auxiliary equipment; which is related to the supplied heating; the relationship is:

$$E_{ij,ae} = \eta_{ae} Q_{ij} \tag{2}$$

where η_{ae} is the electricity consumption coefficient of auxiliary equipment; Q_{ij} is the heating load demand.

$E_{ij,hp}$ is electricity consumption from the HP, and it can be expressed as:

$$E_{ij,hp} = Q_{ij,hp} / COP_t \tag{3}$$

where $Q_{ij,hp}$ is the heating generated by the HP, and COP_t is the coefficient of performance of the HP, which is related with the outlet temperature of heat pump (t). The relationship can be expressed as:

$$COP_t = 14.518 - 0.2947t + 0.0022t^2 \tag{4}$$

The electricity generated by PGU is variable with load fraction, which can be shown as follows:

$$E_{ij,pgu} = \begin{cases} E_{ij} + E_{ij,ae} + E_{ij,hp} & f_{ij,pgu} < 1 \\ E_{r,pgu} & f_{ij,pgu} \geq 1 \end{cases} \tag{5}$$

where $f_{ij,pgu}$ is load fraction of PGU, which can be expressed as follows:

$$f_{ij,pgu} = E_{ij,pgu} / E_{r,pgu} \tag{6}$$

where $E_{r,pgu}$ is the rated capacity of PGU. The natural gas consumption of PGU, $F_{ij,pgu}$, can be estimated as:

$$F_{ij,pgu} = E_{ij,pgu} / \eta_{ij,pgu} \tag{7}$$

where $\eta_{ij,pgu}$ is the electrical efficiency of PGU and it is expressed as:

$$\eta_{ij,pgu} = 0.1 + 0.4 f_{ij,pgu} - 0.2 f_{ij,pgu}^2 \tag{8}$$

The waste heat of PGU from the heat recovery system, $Q_{ij,r}$, can be calculated as

$$Q_{ij,r} = \eta_r (F_{ij,pgu} - E_{ij,pgu}) \tag{9}$$

where η_r is the heat recovery system efficiency. The heating balance of novel coupling system is:

$$Q_{ij,b} + Q_{ij,r} + Q_{ij,hp} = Q_{ij} \tag{10}$$

where $Q_{ij,b}$ is the supplementary heating from the boiler. Due to the integration characteristic of the novel coupling system, when Q_{ij} and the outlet temperature of HP (t) are determined, the heating generated by the HP can be known, which is shown as:

$$Q_{ij,hp} = Q_{ij}(t - t_1) / (t_2 - t_1) \tag{11}$$

where t_1 is the temperature of cold fluid, t_2 is the required temperature of hot fluid; t is the outlet temperature of HP. When the recovery heating is not enough, the boiler will be opened. The supplementary natural gas consumption to the boiler, $F_{ij,b}$, can be estimated as:

$$F_{ij,b} = (Q_{ij} - Q_{ij,r} - Q_{ij,hp}) / \eta_b \tag{12}$$

When the electricity generated from the PGU is insufficient, the electricity from the grid, $E_{ij,grid}$, is

$$E_{ij,grid} = E_{ij} + E_{ij,hp} + E_{ij,ae} - E_{ij,pgu} \tag{13}$$

The fuel consumption of grid is:

$$F_{ij,grid} = E_{ij,grid} / \eta_e \eta_t \tag{14}$$

where η_e is the electric efficiency of grid; η_t is the transmission efficiency of grid.

Therefore, the total fuel consumption of the novel CHP-HP coupling system is:

$$F_{\mathrm{n,t}} = \sum\sum(F_{ij,pgu} + F_{ij,b} + F_{ij,grid}) \tag{15}$$

A reference system is used to compare with the novel coupling system. In the reference system, the electricity demand comes from the PGU and the grid. The heat load demand is satisfied by the waste heat, the HP and the boiler. The capacity of PGU, HP and boiler is same as that in the novel coupling system. Moreover, the heating generated by HP is also same as that in the novel coupling system. The difference is that the COP of HP is regarded as the constant, which is lower than that in the novel coupling system;

3.2. Objective function

The primary energy saving rate (PESR) is selected as energy objective. It can be expressed as:

$$\mathrm{PESR} = (F_{r,t} - F_{n,t}) / F_{r,t} = 1 - F_{n,t} / F_{r,t} \tag{16}$$

The carbon dioxide emission reduction rate (CDER) is chosen as environment objective. The amount of carbon dioxide emission can be determined using the emission conversion factors. The emission conversion factor of electricity from grid and natural gas is 968 g/kWh and 220 g/kWh, respectively.

$$\mathrm{CDER} = (F_{r,\mathrm{CDE}} - F_{n,\mathrm{CDE}}) / F_{r,\mathrm{CDE}} = 1 - F_{n,\mathrm{CDE}} / F_{r,\mathrm{CDE}} \tag{17}$$

where $F_{n,CDE}$ and $F_{r,CDE}$ is the amount of carbon dioxide emission of the novel coupling system and reference system, respectively.

The annual total cost saving rate (ATCSR) is used as economy objective. The annual total cost includes the annual investment cost, maintenance cost and annual energy expenses. It can be calculated as:

$$\mathrm{ATCSR} = (\mathrm{ATC}_r - \mathrm{ATC}_n) / \mathrm{ATC}_r = 1 - \mathrm{ATC}_n / \mathrm{ATC}_r \tag{18}$$

where ATC_n and ATC_r is annual total cost of the novel coupling system and reference system, respectively.

In this study, the multi-objective which takes energy, environment and economy into consideration is used to evaluate the system. The objective function is defined to maximize the benefits of novel system:

$$\max = \omega_1 \cdot PESR + \omega_2 \cdot CDER + \omega_3 \cdot ATCSR \tag{19}$$

where $\omega_1, \omega_2, \omega_3$ are weights of $PESR$, $CDER$ and $ATCSR$, which are the same in this study.

4. Case analysis

4.1. Performance analysis

A case system (t =35 ℃, the outlet temperature from HP) is studied. The key operation parameters can be found in Ref. [1][4]. In the novel coupling system, the waste heat is used to generate the domestic hot water from 35℃ to 55℃. However, in the reference system, it always generates the domestic hot water from 5℃ to 55℃. The terminal exhaust temperature in both system is the same (150℃). By the Aspen plus software simulation, the results show that with the same input of natural gas and the output of domestic hot water, the novel coupling system can generate more power (about 669 kW) than reference system. The COP of HP in the novel coupling system is increased to 6.95, while the COP in the reference system is 5.06. The total energy efficiency of the novel coupling system is about 142.2%, and it is higher than that of the reference system, about 138.3%. The total exergy efficiency of the novel coupling system is 22.6%, approximately 3.7% higher than the reference system (18.9%). The cause of exergy efficiency improvement is that the exergy loss in the heat exchanger and HP is reduced.

4.2. Optimization analysis

In order to ensure the validity of novel coupling system modeling and the optimization procedure, a numerical case is studied by selecting a hypothetical buildings demand. The energy load demands are estimated using Design Builder software, which are shown in Fig. 2.

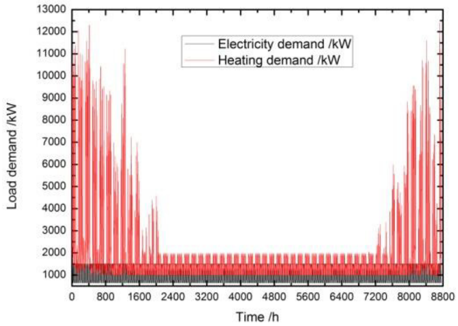

Fig. 2. Load demand

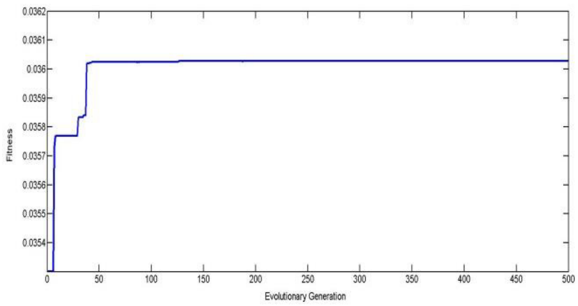

Fig. 3. Optimal process of GA

The characteristic parameters of both systems are listed in Table 1, which are used to compute the fitness in Fig. 3. The cost parameters are presented in Table 2. The GA parameters and the search range of the variables are shown in Table 3.

Table 1. Characteristic parameters of both systems

Variable	Value
Heat recovery system efficiency /η_r	0.8
Boiler efficiency/η_b	0.8
Electricity consumption coefficient of auxiliary equipment /η_{ae}	0.03
Temperature of cold fluid/ t_1	5
Required temperature of hot fluid / t_2	55
Plant generation efficiency /η_e	0.35
Grid transmission efficiency /η_t	0.92
COP of HP in the reference system/ COP	5.06

Table 2. Cost parameters of the equipments and fuels

Facility	Unit price (Yuan/kW)
CHP system	6800
Boiler	300
Heat pump system	1100
Fuel	Unit price (Yuan/kWh)
Natural gas	0.194
Electricity (6:00:22:00)	0.964
Electricity (23:00:5:00)	0.435

Table 3. GA parameters and search range of the variables

Variable	Value
Population size	40
Evolutionary generations	500
Length of genes	20
Crossover probability	0.75
Mutation probability	0.05
PGU Capacity	[0,2000]
Outlet temperature of heat pump	[5,55]

The characteristic parameters of novel coupling system, energy demands, cost parameters and GA parameters are given firstly. The initial values of variables are coded in binary form. Roulette wheel method is adopted to realize the selection. Single-point crossover is used to preserve the feasibility of offspring generated by crossover. Continue mutation is adopted. If the convergence criteria are satisfied, searching process will be stopped and the optimization results can be obtained. Then, the configuration and operation strategy can be acquired. Otherwise, the search is turned back to the calculation again through selection, crossover and mutation until the optimal criteria are satisfied. According to the optimal process of GA, the rated capacity of PGU and outlet temperature of HP can be achieved to maximize the comprehensive performances, which are 1641 kW and 34.2℃ respectively. The PESR is 3.14%; the CDER is 4.10%; the ATCSR is 3.55%; the comprehensive performance is 3.6%. Therefore, the capacity of other equipments can be calculated, such as the capacity of boiler (2096 kW) and HP (7259 kW).

5. Conclusion

In this paper, a novel coupling system by integrating the CHP and HP is introduced. Then, based on a case, performance characters including energetic and exergetic efficiency are calculated, which are 142.2% and 22.6% respectively, 3.9% and 3.7% higher than reference system respectively. In order to make system more practical, multi-objective optimal model is developed based on PESR, CDER and ATCSR simultaneously. The key parameters are optimized by GA so as to maximize the comprehensive performance. Results show that when the capacity of PGU is selected as 1641 kW and outlet temperature from HP is set as 34.2℃, comprehensive performance of novel coupling system is the best, which is 3.6%.

6. Copyright

Acknowledgements

This study is financially supported by the Joint Supervision Scheme with the Chinese Mainland, Taiwan and Macao Universities from the Hong Kong Polytechnic University through the project G-SB61 and National Natural Science Foundation Project of China (No. 51541603 and No. 51408205).

References

[1] Kang SS, Li HQ, Lei J, Liu LF, Cai B, Zhang GQ. A new utilization approach of the waste heat with mid-low temperature in the combined heating and power system integrating heat pump. Appl Energy 2015;160:185-93.

[2] Wang JJ, Zhai ZQ, You YY, Zhang CF. Particle swarm optimization for redundant building cooling heating and power system. Appl Energy 2010;87:3668-79

[3] Wang JJ, You YY, Zhang CF. Optimization of capacity and operation for CCHP system by genetic algorithm. Appl Energy 2010;87:1325-35

[4] Kang SS, Li HQ, Liu LF, Lei J, Zhang GQ. Exergy analysis of a novel CHP-GSHP coupling system. Appl Therm Eng 2016;93: 308-14

Biography

Kang Shushuo, Male, Ph.D. candidate, Research interests: Building energy system and regional energy technology; E-mail: kss@hnu.edu.cn