International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 250

Heat Current-based Energy Management Platform for Analysis and Optimization of Gas-Steam Combined Cycle-based Cogeneration System

Chen Xi, Zhao Tian, Qun Chen*

* Department of Engineering Mechanics, Tsinghua University, Beijing, China, chenqun@tsinghua.edu.cn

ABSTRACT

Performance improvement of gas-steam combined cycle cogeneration (GSCCC) system has huge potential for energy conservation but puzzles researchers due to the implicitly coupled properties. Through the thermo-electric analogy method, this contribution builds the heat current model of a HRPG system and derives its heat transfer and conversion constraints. Benefiting from the heat current model, the linear topology equations could be separated from implicit nonlinear constraints, and hence a more stable hierarchical solution scheme for system simulation is developed. On this basis, the reasonable matching relation between parameters under off-design working conditions is achieved using the genetic algorithm. Experiment results with energy management platform shows the gas consumption could be decreased by 0.45%.

Keywords: Gas-Steam Combined Cycle-based Cogeneration System, Energy Conservation, Heat Current Method.

NONMENCLATURE

A	heat transfer area, m^2
C	coal consumption, g/kWh
K	heat transfer coefficient, W K^{-1} m^{-2}
Q	heat transfer rate, W
R	thermal resistance, K W^{-1}
T	temperature, K
W	power, W
m	mass flow rate, kg s^{-1}
ε	thermal-motive force, K
GSCCC	gas-steam combined cycle cogeneration

1. INTRODUCTION

Performance improvement of GSCCC system under off-design working conditions is an attractive issue for energy conservation[1]. However, previous contributions mainly concentrate on the optimization of individual components and subsystems[2], while others optimize the whole system with some simplifications of heat transfer processes[3], which consequently cannot accurately reflect the influences of local heat transfer processes on the overall system performance. Therefore, an efficient model construction and computation method for the performance analysis and optimization of complex heat recovery-based power generation systems s is highly desired.

This contribution focuses on a typical GSCCC system and proposes a standardized method to analyze and optimize its overall operational performance. First, applying the thermo-electric analogy method builds the heat current model of the system to reflect the global heat transfer and conversion laws, and utilizing the circuit principle clarifies its governing equations. On this basis, this contribution developed a new iterative solution scheme, which fulfills the model computation without solving any implicit nonlinear equation. Finally, taking the gas consumption as optimization objective, the optimal matching relations of operating parameters under variable working conditions are discussed and experimentally validated.

2. PHYSICAL MODEL OF A GSCCC SYSTEM

Figure 1 gives the schematic diagram of a typical GSCCC system, which consists of economizers (EC), evaporators (EV), superheaters (SH) as well as reheaters (RH) in a heat recovery steam generator, feed water pumps (P), feed water valves (V), a turbine (T) which involves three cylinders, a fuel gas heater (FGH), a turbine cooling air heater (TCA), a sealer cooler (SC), a condenser (C), a cooling water pump (CP) and a cooling tower (CT). Besides, to further improve the global efficiency and satisfy the industrial as well as domestic requirements, the plant also supplies heat, cold and steam to outside users, which is achieved by heat supply exchanger (HS), steam extraction from turbine (HE) and

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

four absorption refrigeration units (REF-Ws & REF-Ss), respectively.

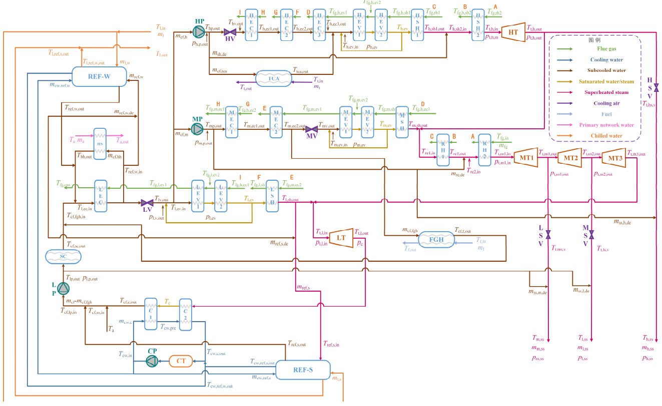

Fig. 1 Sketch of a typical GSCCC system

For the counter-flow heat exchanger with constant property fluids such as economizer and superheater, Chen[4] defined a new thermal resistance based on the inlet temperature difference of fluids and derived the corresponding calculation expression:

$$R=\frac{T_{h,in}-T_{c,in}}{Q}=\frac{G_c\exp\left(\frac{KA}{G_h}\right)-G_h\exp\left(\frac{KA}{G_c}\right)}{G_cG_h\left(\exp\left(\frac{KA}{G_h}\right)-\exp\left(\frac{KA}{G_c}\right)\right)} \tag{1}$$

where $T_{h,in}$ and $T_{c,in}$ are the inlet temperatures, G_h and G_c are the heat capacity rates of hot and cold fluids, respectively. Q is the heat flow rate, R is the thermal resistance, K and A are the heat transfer coefficient and heat transfer area of heat exchanger, respectively. The linear relation shown in Eq. (1) is similar to the Ohm's Law, thus the heat transfer process would be presented by the heat flowing through the thermal resistance under the influence of the inlet temperature difference between hot and cold fluids as shown in Fig. 2.

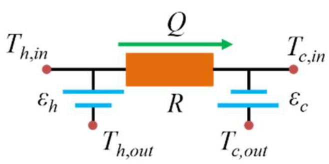

Fig. 2 Heat current model of heat exchanger

In Fig.2, $T_{h,out}$ and $T_{c,out}$ are the outlet temperatures of hot and cold fluids, respectively. The two additive thermal-motive forces, ε_h and ε_c, represent the differences between the inlet and the outlet temperatures of fluids, respectively, which actually reflect the energy conservation relation.

$$\varepsilon_h=T_{h,out}-T_{h,in}=Q/G_h \tag{2}$$

$$\varepsilon_c=T_{c,in}-T_{c,out}=Q/G_c \tag{3}$$

On this basis, according to the developed heat current method[5], the heat current model of the whole GSCCC system is constructed as shown in Fig. 2.

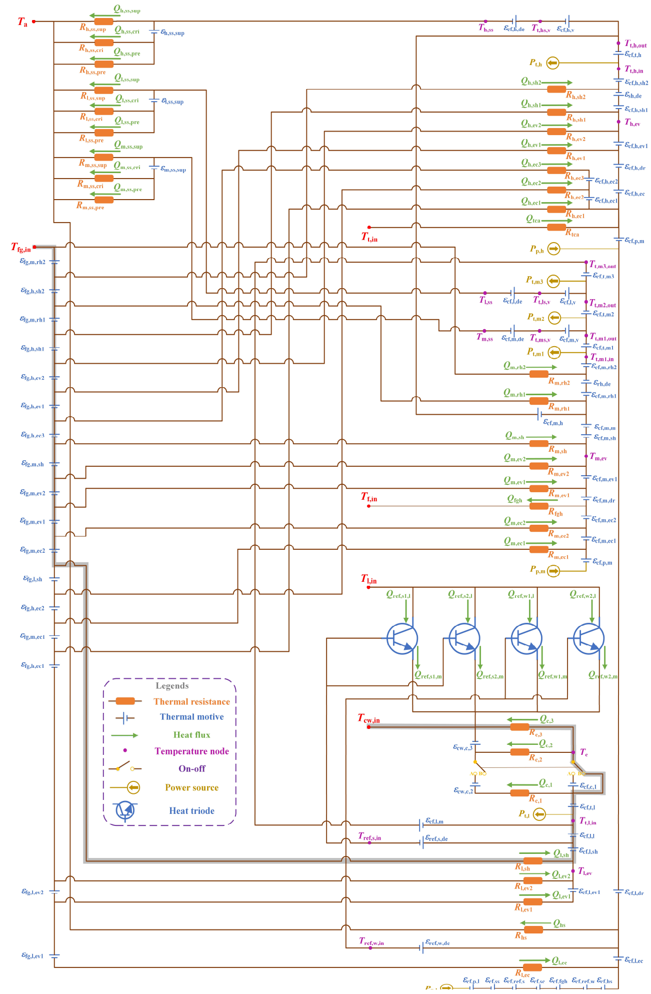

Fig. 3 Heat current model of GSCCC system

Figure 3 demonstrates the heat transfer and heat-to-work conversion processes in the whole system. Based on the heat current model, applying the circuit principle, i.e. Kirchhoff's circuit and voltage law, could derive the integral governing equations of the system. For instance, the KVL equation corresponds to the branch specially marked in Fig. 3 is

$$\begin{aligned}&T_{fg,in}-\varepsilon_{fg,m,rh2}-\varepsilon_{fg,h,sh2}-\varepsilon_{fg,m,rh1}-\varepsilon_{fg,g,sh1}-\varepsilon_{fg,h,ev2}\\&-\varepsilon_{fg,h,ev1}-\varepsilon_{fg,h,ec3}-\varepsilon_{fg,m,sh}-\varepsilon_{fg,m,ev2}-\varepsilon_{fg,m,ev1}-\varepsilon_{fg,m,ec2}\\&-Q_{l,sh}R_{l,sh}+\varepsilon_{cf,l,sh}+\varepsilon_{cf,l,l}-\varepsilon_{cf,t,l}-Q_{c,3}R_{c,3}=T_{cw,in}\end{aligned} \tag{4}$$

Due to the length restriction of the conference article, the other governing equations are omitted. As shown, the introduction of thermal resistances helps decouple the implicit nonlinear properties in heat transfer processes and consequently divides linear topology equations from the governing equations of GSCCC system, which provides a new computation idea of hierarchical solution.

3. COMPUTATION METHOD FOR GSCCC SYSTEM

This contribution applies the divide-and-conquer algorithm illustrated in reference [5] to simulate the GSCCC system. The unknown variables included in the formulas of thermal resistances are calculated by iteration, the topology constraints could be easily solved by linear matrix calculus. Solving these linear matrix equations offers the heat flow rate of each heat transfer process, which are used to update the iteration variables.

The whole solution procedure involves no calculation of implicit nonlinear equation, and only sixteen variables are solved using the iterative approach, which effectively reduces the dependence on the initial values of unknown variables and thus has good calculation stability. Besides, each iteration solves a linear matrix equation and updates all the iteration variables by substitution, which benefits the calculation speed. Moreover, all the equations solved here are the inherent constraints of system, which also ensures the calculation time and accuracy. Therefore, the heat current method not only helps reduce the number of model equations, but also contributes to decouple the implicit nonlinear relations among the operating parameters of system, which further benefits the model computation.

4. VALIDATION

To validate the method proposed in this article, simulation results of the GSCCC system obtained by heat current method and historical operational data are compared under variable working conditions. Figure 4 shows the simulated net power generations and high-pressure superheated steam pressures obtained by two method, respectively. It can be seen that results obtained from two ways are in good agreement and thus the proposed method is validated.

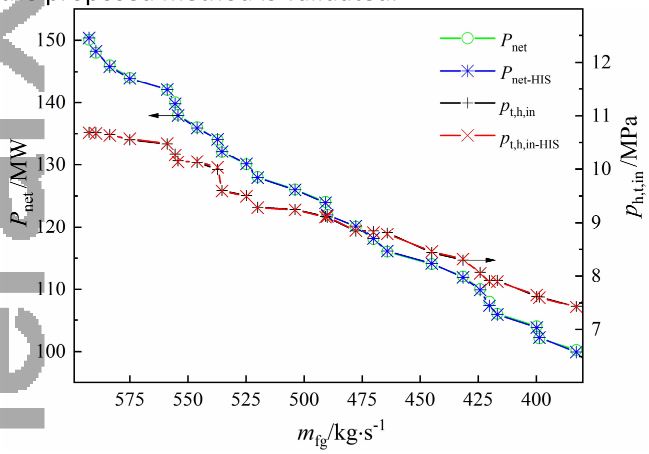

Fig. 4 Validation results with historical data

In the optimization of this GSCCC system, the gas consumption, which reflects the overall efficiency, is used as the optimization objective. With the aid of the genetic algorithm, the optimal matching relationship among operating parameters could be investigated under variable conditions.

5. HEAT CURRENT-BASED ENERGY MANAGEMENT PLATFORM

To promote the practical application of the integrated optimization strategy and increase the operation efficiency of units, an energy management and real-time operation optimization platform is developed based on the existing communication network in the plant. Figure 5 presents the structure of the platform, which consists of following modules: data curation, parameter identification, operation optimization, and information release. When the deviation between optimization results and real-time parameters exceeds the preset critical value, the platform would send alert to administrators to help them make decisions and perform adjustments in the DCS client.

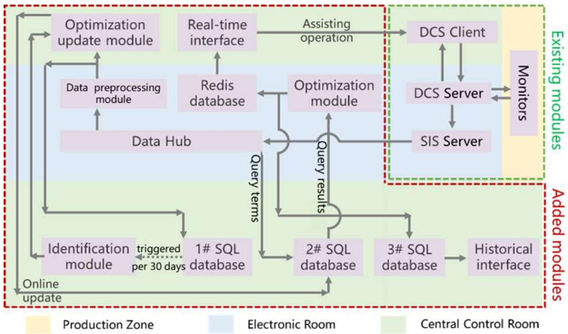

Fig. 5 Framework of energy management platform

6. EXPERIMENTS AND DISCUSSIONS

To validate the proposed integrated energy management system, the authors performed experiments in China Power New Energy Dongguan Cogeneration Power Plant in Guangdong Province of China. Experimental results are shown in Fig. 6, where the reference cases are marked in blue and the optimized cases are marked in orange. In the experiment, the average values of the electrical, steam, cold, and total heat loads are basically kept. Meanwhile, the optimization results present that the mass flow rate of cooling water is required to be kept while the load distribution between the steam and hot water refrigeration units is required to be adjusted by administrators.

It could be found that the average mass flow rate of

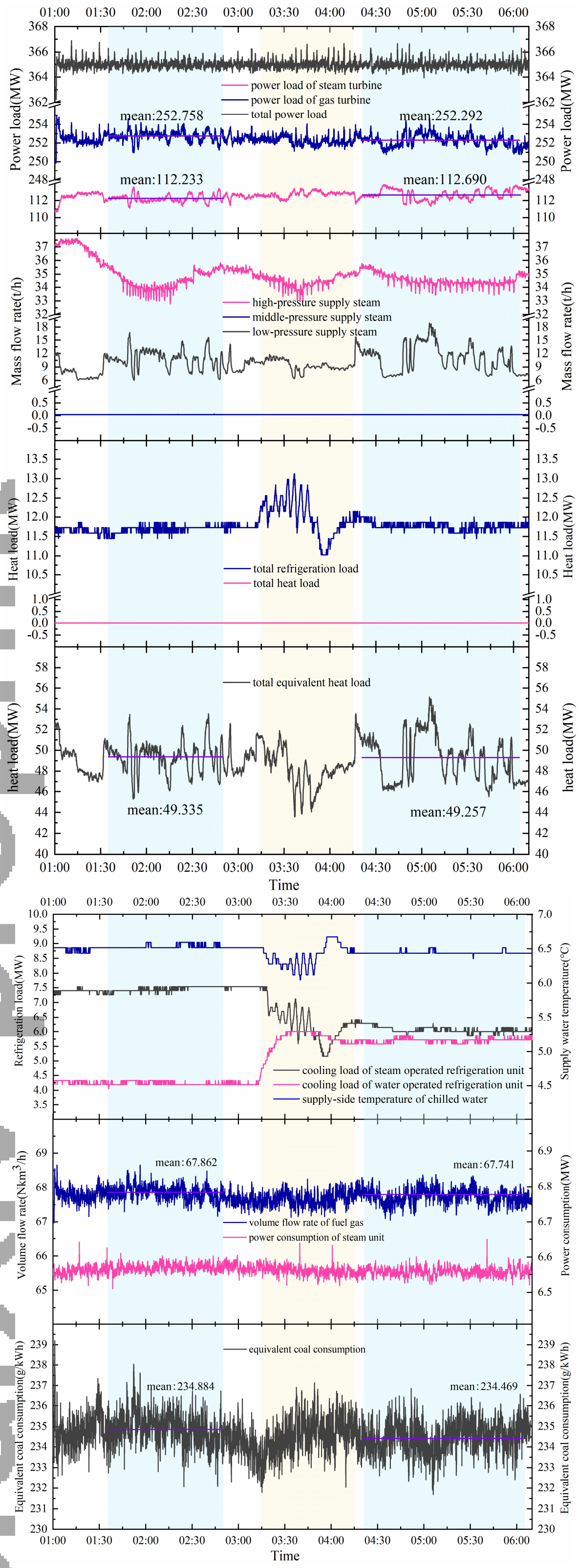

Fig. 6 Experimental results

gas decreases by 121 N m^3/h, and the standard coal consumption of power generation decreases by 0.415 g/kWh. Therefore, the proposed integrated energy management system is proven to be capable of improving the operation efficiency of the GSCCC system.

7. CONCLUSIONS

This paper applied the thermo-electrical analogy technology to build the heat current model of the GSCCC system. Besides, applying the Kirchhoff's voltage law derived their corresponding linear matrix equations. Most importantly, benefiting from the introduction of thermal resistances, the implicit nonlinear constraints of the GSCCC system is disassembled into linear topology equations and explicit nonlinear component constraints. Therefore, this contribution proposed a new hierarchical solution scheme for model computation. Comparison between the simulation results with practical data validates the accuracy of proposed method. On this basis, applying the genetic algorithm achieves the minimum of gas consumption under variable working conditions. Experiment results using the energy management platform show that the gas consumption could be decreased by 0.45% by reasonably matching operating parameters.

ACKNOWLEDGEMENT

The present work is supported by the National Natural Science Foundation of China (Grant No. 51836004).

REFERENCE

[1] Han X, Liu M, Wang J, et al. Simulation study on lignite-fired power system integrated with flue gas drying and waste heat recovery. Energy 2014;76:406-18.
[2] Carapellucci R, Giordano L. A comparison between exergetic and economic criteria for optimizing the heat recovery steam generators of gas-steam power plants. Energy 2013;58:458-72.
[3] Manassaldi JI, Arias AM, Scenna NJ, et al. A discrete and continuous mathematical model for the optimal synthesis and design of dual pressure heat recovery steam generators coupled to two steam turbines. Energy 2016;103:807-23.
[4] Chen Q, Hao JH, Zhao T. An alternative energy flow model for analysis and optimization of heat transfer systems. International Journal of Heat & Mass Transfer 2017;108:712-720.
[5] Chen X, Chen Q, Chen H, et al. Heat current method for analysis and optimization of heat recovery-based power generation systems. Energy 2019;189:116209.