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Enhanced demand response flexibility of applying thermochemical recuperation in a combined cooling, heating and power system

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ABSTRACT

Combined cooling, heating and power (CCHP) system is a promising distributed energy system, which is usually installed close to the terminal user and satisfies the diverse energy supply. Whereas, the demand-response characteristics is critical for the system feasible and efficient operation. In this work, an alternative adjust method based on the thermochemical recuperation is developed for optimizing the CCHP production, the exhaust high-temperature gas from the prime mover is first used to drive the endothermic reaction of methanol decomposition before the absorption refrigeration, thereby the exhaust waste heat realizes the enhanced cascade utilization and improves its energy level by transited into the chemical form. Both the thermodynamic performances and the flexible demand response characteristics of the system were also comprehensively investigated. Regarding to the case studies of building application in China, two scenarios of the gas turbine and the internal combustion engine as the prime movers are considered, the system thermal efficiency for CCHP production is increased by 0.82%-13.71% accompanying with a considerable fuel saving. Furthermore, the system is able to automatically adjust the recuperation thermal ratio based on the simultaneous changed terminal energy loads, the operation flexibility of source-demand matching is thus enhanced and optimized. The reasonable operation characteristics approve this promising method to achieve efficient waste heat recovery and feasible multi-energy production.

Keywords: thermochemical recuperation, flexible demand response, CCHP, case study

NOMENCLATURE

Symbols	
FRR	Fuel recuperation ratio
FSR	Fuel saving ratio
HHV	Higher heating value
m	Mass flow rate
P	Electric power
Q	Thermal heat
TCR	Thermochemical recuperation
η	Efficiency

1. INTRODUCTION

With the rapidly growing and reliable requirement of the energy demands in modern society, flexible multi-energy provision becomes more urgent [1]. Typically, as the distributed energy network, combined cooling, heating and power system (CCHP) usually installed closed to the terminal end-user, apart from the diverse energy products supply, the operation flexibility has potential to be enhanced by comparing to the large-scale centralized energy system [2].

In the typical CCHP system, the waste heat released from the prime mover of gas turbine (GT) or internal combustion engine (ICE) directly drives the absorption refrigeration and heat exchanger subsequently, with the production of the cooling and heating energy. CCHP system comprehensively considers the various energy

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supply and cascade utilization in practical application, which is cost-efficient and environment-friendly. Whereas, due to the issues of frequently changing and unpredicted energy demands, the precise regulation of the CCHP production is a huge challenge [3].

Wu et al. [4] proposed a novel CCHP system integrated with an organic Rankine cycle and solar thermal utilization, which broadened the range of electric-thermal provision and realized an evident energy saving. As for this concern, Feng et al. [5] investigated the load matching performance between the CCHP production and the user requirement, and result shows that following electricity load strategy encompasses a wider scope of users than following thermal load. Zhou et al. [6] developed hybrid demand-side controller to handle the complexity of building demand prediction with supervised machine learning method, and with implementation of the proposed approach, the peak power of the grid importation can be reduced by 61%.

Based on the internal configuration optimization, thermochemical recuperation (TCR) is an alternative way to recover the high-temperature waste heat by driving the endothermic chemical reaction (e.g., methane reforming [7] and methanol decomposition [8]). After the TCR process, the waste heat can be readily stored in the medium of syngas which could be utilized in further CCHP utilization, moreover, the CCHP production has potential to be well adjusted and enhance the system operation flexibility [9]. Meanwhile, different from the typical waste heat direct utilization by absorption refrigeration, TCR process optimizes the waste heat recovery and reduces the temperature difference with the heat transfer, irreversible loss can be decreased and improves the system thermodynamic performances.

Under the system practical operation, the relationship between the energy supply and demand is complicated, especially for the different terminal end-users. The novel method of TCR has potential to improve the output condition and readily responses the energy demand. In order to explore the detailed TCR operation characteristics and energy matching feasibility for the CCHP system, the cases of building type energy user are adopted and considering the different climate zones of China.

In section 2, the principle of thermochemical recuperation and CCHP system are introduced, and flexible operation of the novel system is presented in section 3. In section 4, based on the GT and ICE scenarios, the main results of the system recuperation characteristics and flexible demand response are discussed, and the main conclusions are summarized in section 5.

2. SYSTEM DESCRIPTION AND MODELLING

The waste heat utilization in CCHP system is significantly important, and the thermochemical recuperation process is adopted as an alternative way to optimize the CCHP production. In this section, this new concept and specific application are introduced.

2.1 Principle of thermochemical recuperation

Typically, the waste heat from power generation unit is released with the carrier of exhaust gas, which is mainly recovered and approves the CCHP production, diverse energy demands is thus well satisfied. However, apart from the unfavorable temperature matching within the high-temperature exhaust gas (usually above 400 ℃) recovery by directly driving absorption, and results in more irreversibly loss, the subsequent cooling and heating production are strongly depended on the previous power generation as the varied exhaust gas release, the operation flexibility is thus weaken under the off-design operation. Therefore, in this work, thermochemical recuperation based on methanol decomposition (about 250-350 ℃) is considered to realize cascade utilization of the waste heat, as Eq. 1.

$$CH_3OH \rightarrow CO + 2H_2,\quad \Delta_r H_{298K} = 90.14\ \mathrm{kJ/mol} \qquad (1)$$

In this novel CCHP system, methanol can be directly fueled for CCHP production, and also decomposed by recuperating the high-temperature waste heat to produce high quality syngas which is reasonable fuel to approve the prime mover operation, as shown in Fig. 1. Hence, both considerable efficiency improvement and favorable fuel saving are achieved. Besides, with the adjustable thermochemical recuperation level, flexible cooling/heating to electricity ratio could be achieved to satisfy various user energy loads.

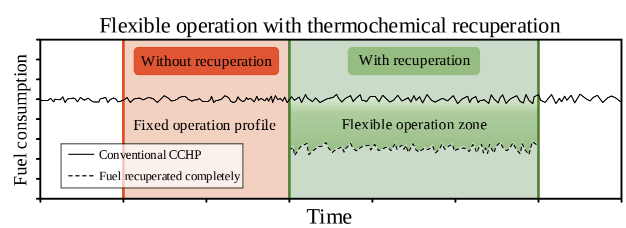


Fig. 1. Concept of adjustable thermochemical recuperation level

2.2 Flexible system operation with thermochemical recuperation

The CCHP system integrated with thermochemical recuperation is promising to achieve efficient cascade utilization, and the system flowsheet is presented in Fig. 2, which mainly consists of a power generation unit, a thermochemical recuperation block, an absorption chiller, a heat exchanger and a complementary combustor. By considering the practical application, both gas turbine (GT) and internal combustion engine (ICE) are considered.

The exhaust gas after the power generation is first recuperated by the thermochemical module by deploying the endothermic reaction of methanol decomposition, and then drive a double-effect LiBr-H_2O absorption refrigeration for cooling and heat exchanger for heating, subsequently. While, as for the ICE scenario, part of waste heat will be taken into the jacket cooling water, that below 100 ℃ and used to supply heating. Meanwhile, in this system, with the assistance of complementary combustor, the surplus heating/cooling energy demand can be provided to satisfy the system stable operation. In addition, thermochemical recuperation and absorption refrigeration can be switched to the serials or parallel model, in order to realize flexible cooling/heating to power output and reliable system operation.

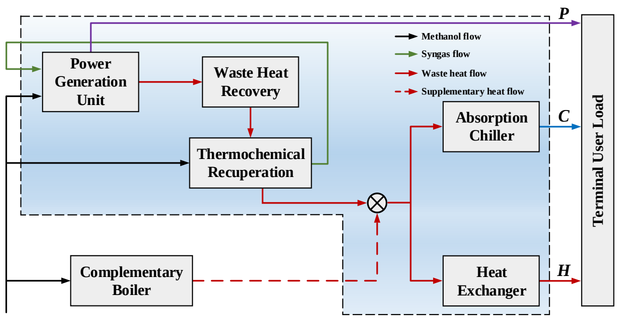


Fig. 2. Configuration and flowsheet of the proposed system

To obtain direct insight of the flexible energy output performance of the advanced CCHP system, a dimensionless energy matching map is drawn based on the operational characteristics of the prime mover, as shown in Fig. 3. The matching map can be divided into 6 sub-regions: (1)-(6). Therein, the load demands can be satisfied, meanwhile, part of waste heat could be recuperated when the demands located in sub-region (4). Furthermore, redundant energy will be produced in surplus lower cooling/heating to power demand in sub-region (5) and could be stored in chemical form. However, the temperature of exhaust gas below 200 ℃ cannot be recuperated by driving the thermochemical reaction as shown in sub-region (6). Meanwhile, with respect to surplus thermal heat demands, an auxiliary combustor is considered to maintain system flexibility in sub-region (3). The load demand is less than the system's minimum output in sub-region (1) and (2), accordingly, the terminal demand is satisfied by the external energy.

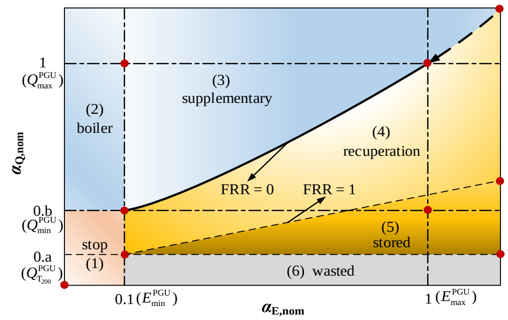


Fig. 3 Dimensionless energy-matching map for CCHP production

With the assistance of thermochemical recuperation, the exhaust waste heat is readily stored in chemical energy and then further efficiently utilized for subsequent CCHP production. Moreover, the flow rate of methanol for the thermochemical recuperation can be well adjusted which approves the flexible energy output and satisfies fluctuant user's energy load.

2.3 System modelling

In this paper, main parameters of the proposed CCHP system are summarized in Table 1. The design power capacity of prime movers is 650 kW_e, which refer to the P&W gas turbine as GT scenario and GE JMS internal combustion engine as ICE scenario, with the nominal power efficiency of 20.14% and 39.4%, respectively. Meanwhile, the cooling production adopts a double-effect absorption refrigerator with the COP of 1.2 and the generation temperature of 150°C, and the jacket cooling water is directly used as the heating source with the temperature of about 90°C.

Table 1 Main parameters of the system

Parameter	Value
Power generation unit	
$\eta_{e,GT}^{nom}$ (650 kW)	20.14%
$\eta_{e,ICE}^{nom}$ (650 kW)	39.4%
Refrigeration/heating	
Solution generation temperature	150°C
Solution evaporation temperature	5°C
Cooling recycle temperature	7-12°C
COP (double-effect)	1.2
Heating temperature	90°C
Thermochemical recuperation	
Reaction pressure	1.05 MPa
Reaction temperature	250°C

The significant operation characteristics and thermodynamic indexes including fuel recuperation ratio

FRR, fuel saving ratio FSR and total energy efficiency η_{th} are selected to evaluate the system thermodynamic performance, as expressed by following:

$$m_{fed\_TR} = m_{PGU,MeOH} + m_{syngas} \tag{2}$$

$$FRR = m_{syngas} / (m_{PGU,MeOH} + m_{syngas}) \tag{3}$$

$$FSR = (m_{fed} - m_{fed\_TR}) / m_{fed} \tag{4}$$

$$\eta_{th} = (P + Q_{heating} + Q_{cooling}) / (m_{fed\_TR} \times HHV_{methanol}) \tag{5}$$

3 CASE STUDY CHARACTERISTICS

In order to explore the demand response characteristics of new CCHP system implemented with the thermochemical recuperation, the real-time building loads are integrated. In this work, four kinds of building including hotel, shopping center, office building and hospital are considered, wherein the building energy, e.g., electricity, cooling and heating, are satisfied by the system. The building model is established as shown in Fig. 4 with the total building area of 17546.12 m^2, and the building height is 29.7 m with 8 floors (4.5 m for the first floor and 3.6 m for the others). In addition, the total window to wall ratio and the shape coefficient are 0.24 and 0.19, respectively.

Fig. 4 The established typical building model

To ambient condition is another factor to influence the user's energy and system operation, based on the local meteorological condition, five climate zones of China are considered. Correspondingly, Harbin (severe cold zone), Beijing (cold zone), Shanghai (hot summer and cold winter zone), Shenzhen (hot summer and warm winter zone) and Kunming (mild zone) are selected as the representative cities, as shown in Fig. 5. Taking Beijing as an example as shown in Fig. 6, the annual solar irradiation is 4770.78 MJ/m^2, meanwhile, the summer temperature is higher than 30 ℃ but the temperature in winter is as low as -10 ℃, which result in large amount cooling/heating energy consumption.

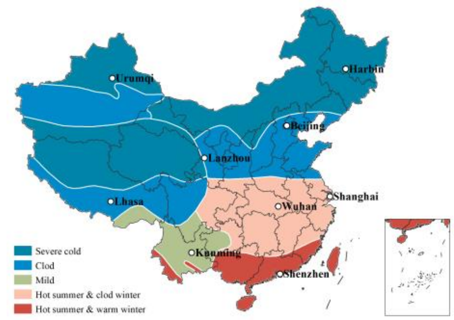


Fig. 5 The five climate zones in China

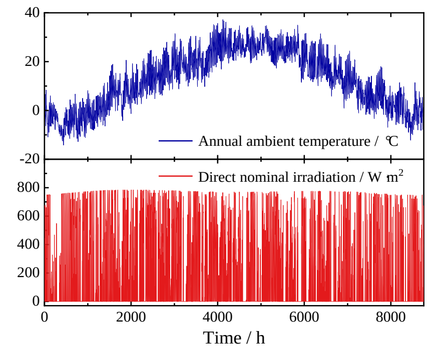


Fig. 6 Annual meteorological conditions in Beijing, China

Meanwhile, the cooling and heating loads are significantly affected by the ambient temperature and the building function. Hence, the building energy demands vary evidently in different climate regions. As shown in Fig. 7, compared with the power load, thermal demands in hotel and hospital are obviously higher, with the largest cooling/heating to power ratio of 7.9 and 5.6 for hotels in Harbin and Shenzhen, respectively. Shopping mall and office building have relatively lower energy demands, especially shopping center.

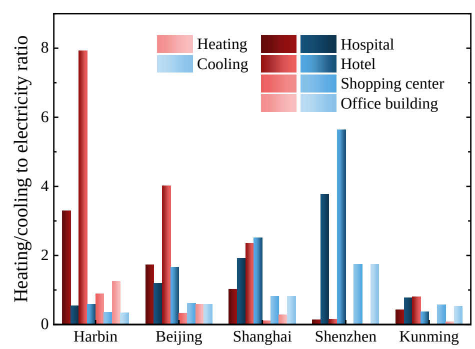


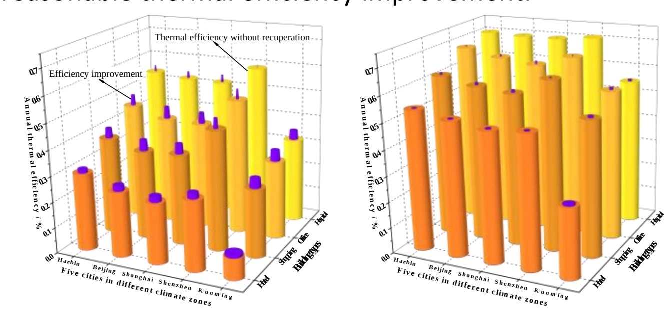
Fig. 7 Characteristics of terminal energy demand in various scenarios

4 RESULTS AND DISCUSSION

Based on the fluctuation of user-side load, the system thermodynamic performance by integrating TCR process and the system flexible demand response characteristics are comprehensively investigated.

4.1 Thermodynamic performance improvement

In typical system operation, the high-temperature exhaust gas is first absorbed by thermochemical recuperation to produce syngas, and average annual efficiency improvement is increased by 0.82%-8.84% in diverse terminal demands for GT and ICE scenario, respectively. For the GT-based system, large amount of waste heat is released with the medium of exhaust gas which provides abundant energy for methanol decomposition. Meanwhile, within the surplus cooling/heating demands in Shenzhen, 9.82%-18.57% part of waste heat is recuperated and thermal efficiency is evidently improved by 2.88%-8.54%. As for the lower energy demands, the largest efficiency improvement is improved by 13.71% for the case of office building in Kunming. With respect to ICE scenario, as its relative higher power efficiency, the released waste heat from prime mover is reduced which limits the recuperation effect. Nevertheless, favorable system operation in mild zone is achieved, and annual fuel recuperation ratios in shopping mall and office building are 0.141 and 0.152 respectively with the increased efficiency of 1.23% and 1.42%. Obviously, within the assistance of thermochemical recuperation, the energy cascade utilization of CCHP system is upgraded and achieve a reasonable thermal efficiency improvement.



(a) GT scenario (b) ICE scenario

Fig. 8 Thermal efficiency improvement with diverse demands

4.2 Enhanced demand response with thermochemical recuperation

The changed energy demands is a critical factor that greatly influences the system operation flexibility, especially under the off-design condition. Meanwhile, system energy output should simultaneously match the terminal loads, the weekly operation performances of the GT and ICE scenarios in the summer, transition and winter seasons are summarized in Fig. 9. Within thermochemical recuperation, as the case of hospital building in Beijing, a large amount of waste heat can be recovered which accounts for a huge proportion in operation time, the average fuel recuperation time ratio in summer, transition and winter seasons are 0.23, 0.937, 0.162 for the GT scenario, respectively, and 0.001, 0.131, 0 for the ICE scenario. Under the various meteorological conditions, the developed system flexibly adjusts the energy production to match the changing terminal user loads and realizes the efficient source-load response effects and the annual recuperation time ratio varies in the range of 41.58%-88.62% in the case of hospital.

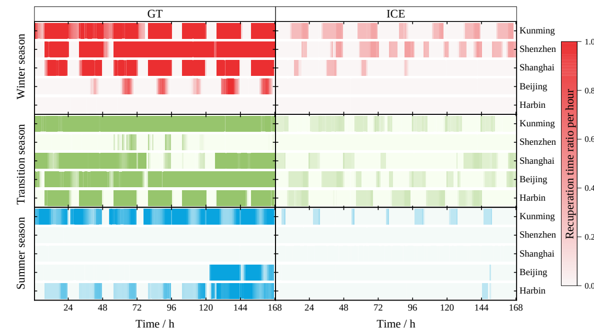


Fig. 9 Weekly ratio of recuperation time ratio for hospital building

Meanwhile, regarding to ICE scenario, it presents a similar recuperation distribution. While with a relatively lower thermal to electricity output ratio, the amount of waste heat that used for recuperation is thus reduced, and the annual recuperation time ratio within the range of 4.43%-12.24%.

4.3 Characteristics of thermochemical recuperation in diverse energy demand

The integrated thermochemical recuperation evidently influences the load matching performance between CCHP production and the user demands, and the characteristics of practical load matching distribution of diverse cases are shown in Fig. 10.

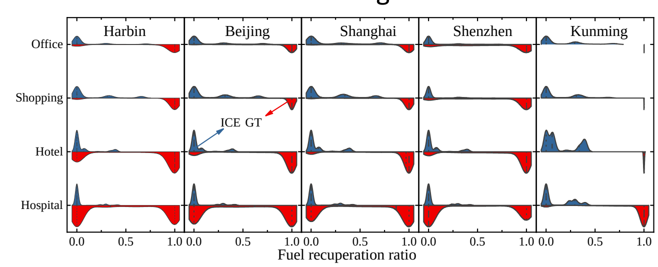


Fig. 10 characteristics of fuel recuperation ratio distribution

Regarding to office and shopping center in mild zone with relatively lower cooling/heating to power ratio based on GT circumstances, almost all the fed methanol is combusted indirectly via the transformation of decomposition where the fuel recuperation ratio (*FRR*) concentrates on 1 and reasonable fuel saving is achieved.

Furthermore, when the thermal to electricity ratio comes to a high level like hotel and hospital, *FRR* mainly allocates around 1 and 0 which results in a normal recuperation effect such as the annual average fuel recuperation ratio is 0.527 of hospital in Beijing.

While the ICE-based system presents a quite different characteristic, under the simultaneous changing terminal cooling, heat and electricity demands, the primary *FRR* distributes around 0 in system operation. However, with the automatic adjustment of recuperation fuel ratio, the system multiply energy output widely adapts to the user demand based on the thermochemical module where the *FRR* distribution mainly appears in 0, 0.319 and 0.652 in shopping center of Beijing. Generally, the proposed system based on this advanced method widely suits the varied terminal demands and efficiently realizes energy cascade utilization and provides a promising way to improve source-load response flexibility.

5 CONCLUSIONS

In this work, the flexible demand response application of a proposed advanced CCHP system based on thermochemical recuperation is investigated. The main conclusions are summarized as flows:

(1) Through the thermochemical recuperation, the system thermal efficiency is increased by 0.82%-13.71% in the hotel, the shopping center, the office building and the hospital in five climate zones in China.

(2) In different climate zones, CCHP system integrated with thermochemical module widely adapts to variable fluctuation of terminal user loads, the annual recuperation time ratios are varied in the ranges of 41.58%-88.62% and 4.43%-12.24% for GT and ICE scenarios, respectively, the flexible response potential is thus realized.

(3) Owing to the automatically changeable recuperation ratio, flexible demand response characteristics is realized. Under relatively lower cooling/heating to power ratio, the methanol fed into GT is combusted indirectly through thermochemical decomposition, and the recuperation fuel ratio in ICE scenario is widely extended, such as the *FRR* distribution is expanded to 0, 0.319 and 0.652 in shopping center of Beijing.

This study provides an alternative pathway to efficiently enhance the system operation flexibility and widely match simultaneous changing user-demands of the distributed energy network.

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