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# Thermodynamic performances of thermochemical recuperation in application for combined cooling, heating and power (CCHP) generation

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## ABSTRACT

Combined cooling, heating and power (CCHP) is one of effective approach to enhance the energy conversion performances, in order to enhance the effective utilization of the waste heat, a thermochemical recuperation based CCHP production method is evaluated by employing methanol decomposition, and two power scenarios are considered of gas turbine (GT) and internal combustion engine (ICE). The newly developed CCHP system are mathematically modeled, the thermodynamic characteristics are evaluated and compared. The results indicate that a considerable high-temperature waste heat realize favorable recovery and produce high-quality syngas, the power efficiency is improved by 7.48%-13.7%, and the adjustment range on cooling/heating-to-power ratio can be evidently extended. Both the improved energy conversion efficiency and operation flexibility are achieved, and provides an alternative way to enhance the waste heat recovery and the CCHP production.

**Keywords:** thermochemical recuperation, CCHP production, thermodynamic evaluation, operation adjustment

## NOMENCLATURE

| *Symbols* | |
|---|---|
| *HHV* | Higher heating value |
| *m* | Mass flow rate |
| *R* | Ration |
| *P* | Electric power |
| Q | Heat |
| $\eta$ | Efficiency |

## 1. INTRODUCTION

The issues of energy depletion and environmental pollution are significant for society sustainable development, more efficient and clean conversion technologies are urgent[1]. Combined cooling, heating and power (CCHP) system has been widely employed to evidently improve the energy utilization efficiency and meet the diverse energy demand[2].

In the typical CCHP system with the prime movers of gas turbine (GT) and internal combustion engine (ICE), and mainly use the absorption refrigeration technology to recovery the waste heat[3]. While for the practical application, the heating and cooling output is strongly depended on the turbine operation as the serial connection of waste heat recovery, it is difficult to match the simultaneously varied energy loads and result in a large amount waste heat loss[4].

In this work, the concept of thermochemical recuperation is employed for CCHP production, before enter into the refrigeration, the high temperature is first used to drive a endothermic reaction of methanol decomposition, and the produced syngas direct fed into the turbine as the gas fuel and enhance the waste heat utilization. Another advantages of thermochemical recuperation for CCHP is the operation flexibility to adjust the valid energy output.

In section 2, the thermochemical recuperation concept and CCHP system are developed, section 3 presents the main results and discussion on system thermodynamic and off-design performances, the main conclusions are summarized in section 4.

## 2. APPLICATION OF THERMOCHEMICAL RECUPERATION ON WASTE HEAT RECOVERY

### *2.1 Concept of thermochemical recuperation for CCHP*

In the typical distributed energy system for CCHP production, favorable performance of energy conversion can be achieved as the released waste heat with the carrier of exhaust gas (usually above 400℃) is recovered, mainly by the absorption refrigerator for cooling and common heat exchange for heating, which contributes to satisfying the divers energy demands.

For the practical application, the cooling/heating process directly connect power block in serials, while it is difficult to overcome the off-design operation issue with the changing energy load and different cooling-to-power ratio. In this work, a new method of thermochemical recuperation on methanol decomposition is employed and evaluated, as shown in Fig. 1, which provide an alternative way to enhance the waste heat recovery and optimized the system energy production.

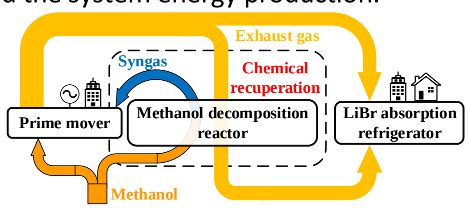


Fig 1 layout of the *thermochemical recuperation*

The methanol is used as the fuel for CCHP production and also the reactant for thermochemical conversion, by using the waste heat to drive the methanol decomposition at the temperature of 250-350℃ as Eq. 1, the produced syngas can be then utilized as the high quality gaseous fuel with an increased heat value.

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

The waste heat of the exhaust gas realizes diverse application and then reduce its exhaust temperature to about 200-250℃, the produced exergy loss within the absorption refrigeration can be decreased as lower heating temperature difference. Moreover, regarding to the high temperature waste heat, driving an endothermic thermochemical reaction of methanol decomposition is also a reasonable solution to improve its energy quality.

### *2.2 Flowsheet of the thermochemical recuperation based CCHP system*

Based on the novel method of thermochemical recuperation, the newly developed CCHP system is proposed and shown in Fig. 2, and two scenarios are considered with the prime mover of gas turbine (GT) and internal combustion engine (ICE), respectively.

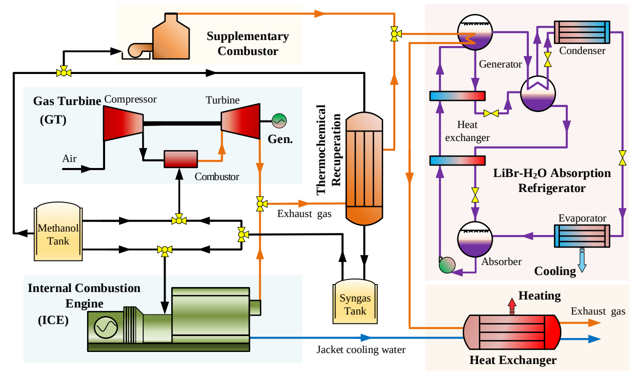


Fig. 2 System integration of CCHP and thermochemical recuperation

The system mainly consists of the power generation unit, thermochemical recuperation block, absorption refrigerator, heat exchanger and auxiliary combustor. In the GT scenario, the exhaust gas from the turbine is first drive the thermochemical reaction, and then utilized to produce cooling and heating energy subsequently through the process of LiBr-$H_2O$ absorption refrigeration and heat exchange, respectively. With respect to the ICE scenario, partial of waste heat will be released with the form of jacket cooling water at the temperature below 100℃, and thus results in a quite different cooling and heating energy output ratio.

The thermochemical recuperation block and absorption refrigerator system can be operated under the serials or parallel mode, which contributes to adjusting the system energy output characteristics and enhancing the system operation flexibility. Additionally, with the assistance from the auxiliary combustor, the varied energy demand of user can be fully satisfied including the surplus cooling and heating condition.

### 2.3 System modelling

The new CCHP system broaden the waste heat recovery method and enhance the system operation characteristics. In this paper, a small scale distributed energy network is considered with the power capacity of 650 kW, by referring the Pratt & Whitney gas turbine and GE JMS internal combustion engine, the main the main parameters of the system are listed in Table 1. In addition, a double-effect absorption refrigerator is adopted with the COP of 1.2, and the released jacket cooling water is directly used as the heating resource with the temperature of about 90℃.

Table 1 Main parameters of the system

| Parameter | Value |
|---|---|
| $\eta_{e,GT}^{nom}$ (650 kW) | 21.2% |
| $\eta_{e,ICE}^{nom}$ (650 kW) | 39.4% |
| $T_{Dem}$ | 200℃ |
| $T_{Colding}$ | 7-12℃ |
| $T_{Heating}$ | 90℃ |
| $COP_{Cold}$ (double effect) | 1.2 |

The system thermodynamic performances will be comprehensively investigated, the system power efficiency $\eta_e$, overall energy efficiency $\eta_{th}$ and the fuel saving ratio $R_{saving\_fuel}$ are selected as the basic criteria, as expressed by following:

$$\eta_e = P / (m_{methanol\_TR} \times HHV_{methanol}) \quad (2)$$

$$\eta_{th} = (P + Q_{heating} + Q_{cooling}) / (m_{methanol\_TR} \times HHV_{methanol}) \quad (3)$$

$$R_{saving\_fuel} = (m_{methanol} - m_{methanol\_TR}) / m_{methanol} \quad (4)$$

## 3 Results and discussion

The gas turbine and internal combustion engine based CCHP are typical employed for the distributed energy supply, and the thermochemical recuperation support a more favorable waste heat recovery. The system thermodynamic performances both under the on-design and off-design conditions are evaluated.

### 3.1 System on-design thermodynamic evaluation

Under the designate condition, the high-temperature waste exhaust gas is first recovered to produce syngas and used as the power fuel, the system power efficiency is thus increased by 13.68% and 7.48% for the GT and ICE scenarios, respectively. The second stage exhaust gas with the reduced temperature is then used for cooling and heating, the system overall energy balances are summarized in Fig. 3. For the GT-based system, the recuperated thermal energy accounts for 25.07% of the waste heat, and the rest is also enough for later cooling and heating, the corresponding system power and energy efficiency reach to 23.4% and 78.53%, respectively. While for the ICE-based case has a quite different performances, as its relative higher power efficiency and distinct structure design, the amount of high-temperature waste heat is evidently reduced which limits the capacity for cooling production, and both the final exhaust gas and the jacket cooling water support the heating production. Generally, compared with the typical CCHP, system energy efficiencies nearly keep stable, while the waste heat realizes upgrade and used for power generation with reasonable quality, it is critical for energy cascade utilization for the energy system.

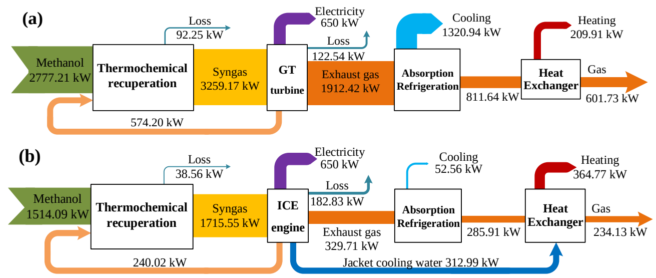


Fig. 3 Energy balance of thermochemical recuperation based CCHP system: (a) GT scenario, (b) ICE scenario.

### 3.2 Off-design evaluation on power efficiency improvement

The system capacity is designed according to the energy load and the prime movers are critical, by considering the different gas turbine with the power capacity of 0.5-300 MW, typically, the gas turbine with a large scale capacity usually has a higher power efficiency. The power efficiencies of the gas turbines with or without thermochemical recuperation process are evaluated and compared under the designate condition, as shown in Fig. 4.

After the process of waste heat recovered by thermochemical recuperation, the power efficiency is evidently enhanced with the increase ratio of 12.89-14.22%, and correspondingly results in a remarkable reduction on fuel consumption, as summarized in Fig. 4.

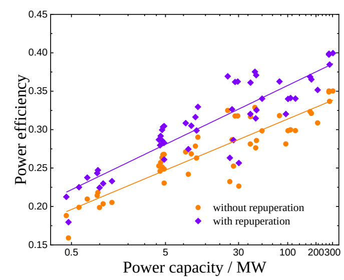


Fig. 4 Potential on efficiency improvement of gas turbine

The CCHP system energy output should be matched with the user's load, and power ratio need to be adjusted and change the cooling and heating output simultaneously, while with the varied power ratio, the off-design system thermodynamic performances are significantly changed. Without consideration of cooling and heating production, the power efficiencies of GT (referring the adopted 650 kW gas turbine) and ICE scenarios are shown in Fig. 5. Under the conditions of high power ratio, the two scenarios achieve reasonable increase. Whereas, with the lower power ratio (i.e., below 50%), the efficiency improvement is relative slight with power efficiency increased by about 3.37%-13.7%. Although the high-temperature waste heat is abundant, with the less fuel requirement and reduced exhaust gas temperatures, the thermochemical recuperation ratio and affect the efficiency improvement.

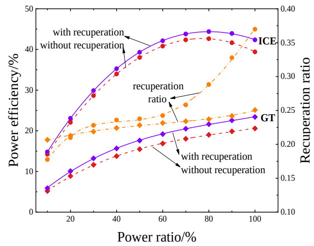


Fig. 5 Power efficiency improvement with varied power ratio

3.3 Enhanced operation flexibility for CCHP production

The utilization method of the waste heat is extended in the developed new CCHP system, instead of the strong serials connection with the previous turbine/engine, more original produced useless cooling or heating energy can be effectively converted to the electricity, and the energy output ratio is shown in Fig. 6.

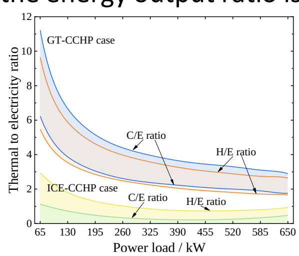


Fig. 6 Varied cooling/heating-to-power output ratio

With the given gas turbine and engine, the cooling/heating to power output ratio will be adjusted in a wider range under different power condition. For the GT scenario under 100% power ratio, the cooling/heating to power output ratio is 1.73-2.92 and 1.67-2.67, respectively, and during the full power load variation, the favorable adjustment range is also presented. Regarding to the ICE scenario, shows a quite different characteristics, depend on the reduced thermal amount of the exhaust gas, the output ratio is relatively lower, and the heating capacity is evidently higher than the cooling as a part of low-temperature waste heat stored in the jacket cooling water. Generally, the flexibility on energy generation of the proposed system is remarkable improved, and provides opportunity to achieve efficient utilization and well satisfy the transient energy demand.

By considering the practical operation which determined based on the varied demand of the cooling/heating to power ratio, the system performances are then discussed as shown in Fig. 7 with the consideration of full power output.

The thermochemical recuperation is become one of adjust route. By comparison, the ICE scenario has a favorable energy conversion efficiency than the ICE scenario, while its reasonable adjustment range only presented with a small heating/cooling-to-power ratio of 1.0. For the GT scenario with a higher operation flexible, it can be well adjusted with the energy ratio below 3.0, and has capable of realize the qualified waste heat fully recuperated and enhance the waste heat conversion.

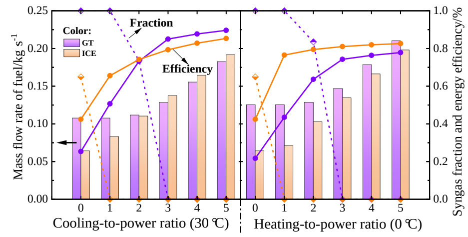


Fig. 7 Recuperation performances with varied energy ratio

## 4. CONCLUSIONS

In this work, based on the thermochemical recuperation concept, a modified CCHP is investigated, and the main conclusion are summarized as follows:

(1) The thermochemical recuperation is one of promising solution to upgrade the waste heat quality and the power efficiency can be increased by 16.49% and reduce the reasonable fuel consumption.

(2) The cooling/heating-to-power ratio of the CCHP system can be extended with different power load, and evidently improve the system operation flexibility.

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