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Industrial Steam Waste Heat-Driven Polygeneration System Integrating GTCC and Methanol Reforming for Hydrogen, Cooling, Heat and Power

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ABSTRACT

Traditional gas-fired combined heat and power (CHP) plants are plagued by high transmission loss to off-site heat users and irreversible loss when driving absorption chillers (heat source ⩽200 ℃). To alleviate these challenges, this study proposes a novel hydrogen-cooling-heating-power poly-generation energy system driven by industrial steam waste heat. This innovative system utilizes methanol as feedstock, whose reforming temperature (200-300°C) aligns closely with industrial steam temperatures. It is integrated with gas-steam combined cycle power generation and the thermochemical process of methanol reforming. The waste heat from 300°C industrial steam is utilized to drive hydrogen production through methanol reforming, achieving cascade energy utilization. The industrial steam is split for material and energy coupling with the methanol reforming unit. One stream is mixed with methanol as a reactant and enters the reformer, while the other provides the heat for the endothermic reforming reaction. The industrial steam waste heat is further recovered through absorption refrigeration for cascaded utilization. The overall utilization efficiency of industrial steam is enhanced. Under the designed operating conditions, the energy efficiency and exergy efficiency of the system reach 73.60% and 61.37%, respectively. Electricity, hydrogen, cooling, and heat are simultaneously generated by the integrated design, minimizing energy waste and alleviating thermal mismatch. This study provides an innovative solution for the efficient utilization of industrial steam in power plants.

Keywords: GTCC, industrial steam, MSR, absorption refrigeration, integrated systems

NONMENCLATURE

Abbreviations	
GTCC	Gas turbine combined cycle
MSR	Methanol steam reaction
DEARC	Double effect absorption refrigeration cycle

1. INTRODUCTION

With the continuous growth of the global economy, the surge in energy consumption has led to increasingly severe environmental pollution problems [1]. Gas turbine combined cycle (GTCC) technology is recognized as a pivotal component of clean power systems [2], owing to its high thermal efficiency, low emission characteristics, and operational flexibility [3]. According to recent data, natural gas consumption accounts for 29% of the total energy consumption [4], and the efficiency of advanced GTCC systems exceeds 64% [5], significantly surpassing that of traditional coal-fired systems [6]. As a primary application form of GTCC, the combined heat and power (CHP) system enhances overall energy efficiency by simultaneously generating electricity and heat energy [7]. However, the utilization of 300 °C medium-temperature industrial steam suffers from significant challenges. If this steam is transmitted to off-site users, substantial heat losses will occur during long-distance pipeline transportation, accompanied by high infrastructure operation and maintenance costs [8]. Conversely, when used for nearby absorption refrigeration [9], notable irreversible loss may arise from temperature mismatch between the steam and the driving heat source (⩽200℃).

Previous research on steam utilization focused on pipeline optimization [10], organic Rankine cycle (ORC) power generation [11], and absorption refrigeration

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[12]. Nevertheless, effective solutions to the temperature mismatch issue remain unsolved. Meanwhile, hydrogen energy, as a clean energy source, has attracted extensive attention [13]. However, its large-scale application is restricted by high storage and transportation costs. Methanol, with abundant sources, convenient storage and transportation, and a high hydrogen-to-carbon ratio, has become an ideal hydrogen storage carrier [14]. The steam reforming reaction of methanol (MSR), which occurs at 200–300 °C [15], is highly compatible with the steam temperature of GTCC, offering a novel approach for waste heat utilization.

In response to these challenges, a hydrogen-cooling-electricity-heat cogeneration system is proposed through the incorporation of GTCC with methanol reforming and absorption refrigeration. The core innovations of this system are as follows:

(1) Through steam diversion, a dual coupling of material and energy between GTCC and MSR is achieved. One part of the steam is utilized as a reactant in the reforming reaction, while the other directly drives the highly endothermic chemical reaction. By this mechanism, low-grade thermal energy is converted into high-grade synthesis gas chemical energy, and thermal loss is significantly reduced.

(2) The temperature of industrial steam is decreased after heating the methanol reforming process, which is further used to drive a double-effect absorption refrigeration cycle (DEARC), enabling the cascade utilization of waste heat.

By coupling GTCC, MSR, and absorption refrigeration, efficient industrial steam utilization with cascade waste heat recovery is achieved. Electricity, hydrogen, cooling capacity, and domestic hot water are simultaneously generated, minimizing energy waste. The system is modeled and evaluated from a thermodynamic perspective. Additionally, we explore the influence of key parameters on the system performance. Our study provides an innovative solution for the efficient and low-carbon utilization of industrial steam in GTCC power plants.

2. DESCRIPTION AND EVALUATION MODEL OF THE NEW SYSTEM

2.1 The schematic of the proposed system

An integrated poly-generation system is proposed in this study, utilizing medium-temperature steam waste heat from GTCC to drive methanol reforming and absorption refrigeration, as illustrated in Fig. 1. The latest 9HA gas turbine of General Electric is selected as the reference GGCT plant [16]. The MSR system and DEARC system are developed following References [17,18].

Natural gas is used as the feedstock for the reference GTCC plant, which is configured with a gas turbine (GT), a triple-pressure reheat heat recovery steam generator (HRSG), and a steam turbine (ST). Initially, Natural gas and compressed air are combusted in the combustion chamber (CC) to produce high-temperature/pressure flue gas that expands in the GT for power generation, then enters the HRSG to produce superheated/saturated steam, which drives the ST for additional electricity. Industrial steam extracted from the GTCC is divided into two streams. One stream serves as the reactant for methanol reforming reaction, while the other provides thermal energy for the reaction. The latter is subsequently utilized for driving the absorption refrigeration unit, enabling cascaded temperature utilization and reducing irreversible loss.

The main parameters of the integrated system are listed in Table 1.

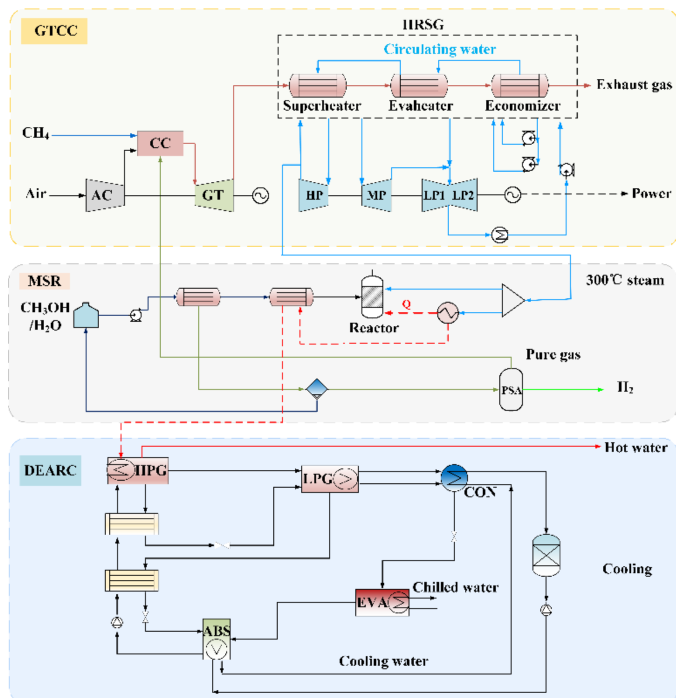

Fig. 1 Schematic diagram of the proposed system

Table 1. The main parameters of the integrated system

Parameters	Value
GTCC	
Ambient temperature (°C)	15
Ambient pressure (bar)	1.0
Pressure ratio	25.8
Gas turbine isentropic efficiency	0.92
HP turbine isentropic efficiency	0.89
IP turbine isentropic efficiency	0.92

LP turbine isentropic efficiency	0.9
HP inlet steam temperature (°C)	625
Reheat temperature (°C)	615
MSR	
reaction pressure (bar)	15
reaction temperature (°C)	250
Water/methanol ratio	1.0
Syngas inlet pressure of PSA (bar)	15
Condense temperature (°C)	25
DEARC	
High pressure (kPa)	93
Low pressure (kPa)	7.78
HPG temperature (°C)	153.51
LPG temperature (°C)	93.35
Evaporator temperature (°C)	5.0
Condenser temperature (°C)	41
Absorber temperature (°C)	38.4

2.2 Reference system

The reference system is composed of independent GTCC-DEARC module and MSR module. Medium-temperature steam extracted from the GTCC is utilized to directly drive the refrigeration module. The schematic diagram of the reference system is shown in Fig. 2.

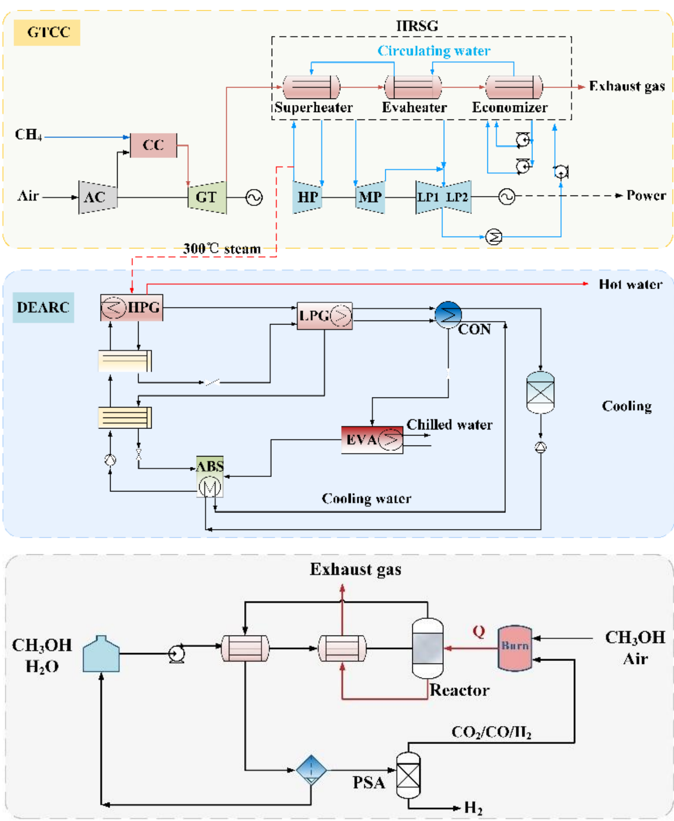

Fig. 2 Schematic diagram of the reference system

2.3 The evaluation criteria

In the MSR reactor, the steam reforming reaction (Eq. (1)) is the dominant reaction, accompanied by side reactions such as methanol decomposition reaction (Eq. (2)) and water-gas shift reaction (Eq. (3)).

The energy balance of the system is calculated as follow:

$$\mathrm{CH_3OH + H_2O \rightarrow 3H_2 + CO_2} \tag{1}$$

$$\mathrm{CH_3OH \rightarrow 2H_2 + 2CO} \tag{2}$$

$$\mathrm{CO + H_2O \rightarrow CO_2 + H_2} \tag{3}$$

The energy balance of the system is calculated as follow:

$$En_{\mathrm{in}} = En_{\mathrm{out}} + En_{\mathrm{loss}} \tag{4}$$

The overall energy efficiency η_{en} is defined by:

$$\eta_{\mathrm{en}} = \frac{En_{\mathrm{H_2}} + P + En_h + En_c}{En_{in}} \tag{5}$$

where $En_{\mathrm{H_2}}$ represents the energy contained in hydrogen, P denotes the generated electricity, En_h is the heat produced by the system, and En_c refers to the cooling generated by the system.

The system exergy efficiency η_{ex} is given by:

$$\eta_{\mathrm{ex}} = \frac{Ex_{\mathrm{H_2}} + P + Ex_{\mathrm{h}} + Ex_{\mathrm{c}}}{Ex_{\mathrm{in}}} \tag{6}$$

where $Ex_{\mathrm{H_2}}$ is the exergy contained in hydrogen, Ex_{h} is the thermal exergy generated by the system, and Ex_{c} is the cold exergy produced by the system.

2.4 Model validation

Compared with references [16–18], negligible discrepancy is found between the simulation herein and the reference model In Table 2, demonstrating its high accuracy and reliability.

Table 2. Model validation

Item	**Design value**	**Simulation value**	**Relative error (%)**
GTCC module			
TIT (°C)	1515.4	1514.88	-0.03
TET (°C)	654.8	655.22	0.06
Gas turbine power (MW)	379.7	374.55	-1.37
Steam turbine power (MW)	151.2	151.2	0
Combined cycle efficiency (LHV, %)	64.1	62.83	-2.02

MSR module			
Reaction temperature (°C)	250	250	0
H_2 mole fraction at reactor outlet (%)	63.2	65.0	2.77
Methanol conversion (%)	99.0	98.82	-0.18
DEARC module			
Absorber temperature (°C)	38.40	38.03	-0.97
Condenser temperature (°C)	41.0	40.92	-0.20
HPG Temperature (°C)	153.5	153.6	0.07
LPG Temperature (°C)	93.5	92.61	-0.95
Circulation ratio	12	11.6	-3.44
COP	1.29	1.29	0

3. RESULTS AND DISCUSSION

3.1 Overall system performance

The thermodynamic performance of the proposed system and the reference system is studied, with consistent energy input. Results are shown in Table 3. In the proposed system, cascade utilization of medium-temperature energy is enabled by coupling with the methanol reforming reaction, whereby low-grade thermal energy is converted to high-grade chemical energy, improving system efficiency. Compared with the reference system, the overall energy efficiency of the proposed system is improved by 1.98%

Table 3. Energy balance between the proposed and reference systems.

Item	Proposed system		Reference system	
	Value (MW)	Ratio (%)	Value (MW)	Ratio (%)
Energy input	**998.39**	**100**	**998.39**	**100**
CH_4	909.71	91.1	909.71	91.1
CH_3OH	88.68	8.90	88.68	8.9
Energy output	**734.78**	**73.60**	**715.11**	**71.62**
Power	489.56	49.03	473.07	47.38
Cooling	138.08	13.83	158.85	15.91
Heating	8.76	0.88	9.23	0.92
H_2	98.38	9.85	73.96	7.41
Energy loss	**263.61**	**26.40**	**283.28**	**28.37**
GTCC				
Flue gas	109.68	10.98	107.74	10.79
Heat transfer	32.10	3.22	29.01	2.90
MSR	13.82	1.38	19.02	1.91
DEARC	107.03	10.72	127.01	12.72
Other loss	0.98	0.10	0.50	0.05
Energy efficiency (%)	**73.60**		**71.62**	

An exergy analysis of the system is conducted based on the second law of thermodynamics, as shown in Table 4. Owing to the coupling of GTCC and MSR as well as the cascade utilization of waste heat, the exergy efficiency of the proposed system is 3.55% higher than that of the reference system.

Table 4. Exergy analysis between the proposed and reference systems.

Item	Proposed system		Reference system	
	Value (MW)	Ratio (%)	Value (MW)	Ratio (%)
Exergy input	**947.35**	**100**	**947.35**	**100**
CH_4	847.87	89.50	847.87	89.50
CH_3OH	99.48	10.50	99.48	10.50
Exergy Output	**581.42**	**61.37**	**547.75**	**57.82**
Power	489.56	51.68	473.07	49.94
Cooling	8.1	0.85	11.52	1.22
Heating	0.63	0.07	0.67	0.07
H_2	83.13	8.77	62.49	6.60
Exergy loss (MW)	**365.93**	**38.63**	**399.6**	**42.18**
GTCC				
Flue gas	6.47	0.68	6.34	0.67
Combustor	231.49	24.44	213.24	22.51
Heat transfer	41.91	4.42	40.73	4.30
MSR	5.23	0.55	30.43	3.21
DEARC	80.35	8.48	108.41	11.44
Other loss	0.48	0.05	0.45	0.05
Exergy efficiency (%)	**61.37**		**57.82**	

3.2 Parametric study

In this section, we investigate the effects of key parameters on system performance.

As shown in Fig. 3, methanol conversion increases rapidly with reaction temperature and then stabilizes near 99%. At lower temperature, the endothermic MSR shows low kinetics and low equilibrium conversion.

When the temperature is sufficiently high, the reaction approaches equilibrium, and the conversion reaches about 99%. Further temperature increase has little additional effect. Increased pressure reduces methanol conversion. This is because MSR increases the number of gas molecules, so elevated pressure promotes the reverse reaction and suppresses conversion.

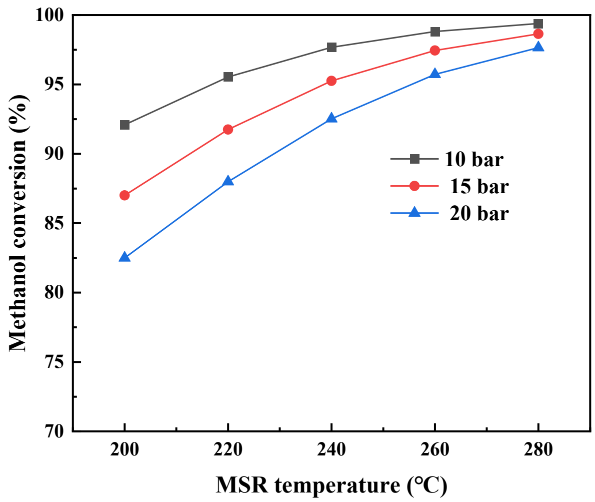

Fig. 3 Influence of the MSR temperature and pressure on methanol conversion

Fig. 4 illustrates the effects of reaction temperature and pressure on system energy performance.

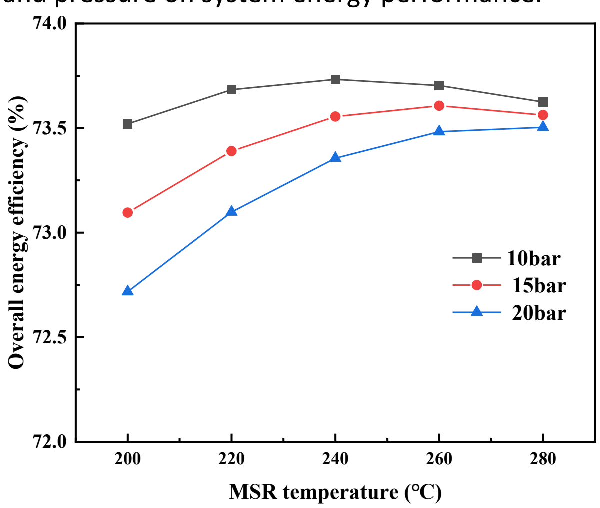

Fig. 4 Influence of the MSR temperature and pressure on system energy efficiency

System efficiency initially increases then decreases with rising temperature. A higher reaction temperature requires more heat while the industrial steam supply is fixed. As a result, less heat is available for the DEARC and the cooling output is reduced. At moderate temperatures, methanol conversion is rapidly improved, so the hydrogen energy output exceeds the cooling loss and efficiency rises. Beyond the certain temperature, conversion is stabilized near equilibrium. Meanwhile, the gains in hydrogen production become smaller than the cooling loss, and efficiency declines. The inflection temperature varies with pressure. It is shifted to a higher value at higher pressure, because equilibrium in the reforming reaction requires higher temperature under elevated pressure.

The impact of water/methanol ratio on the integrated system's performance is presented in Fig. 5. Methanol conversion increases with the ratio, but system energy efficiency does not rise monotonically. As more steam is used as reactant, less remains for refrigeration. When the incremental hydrogen energy falls below the reduced cooling output, the system energy efficiency declines. The peak efficiency of 73.76% is achieved at the water/methanol ratio of 1.2.

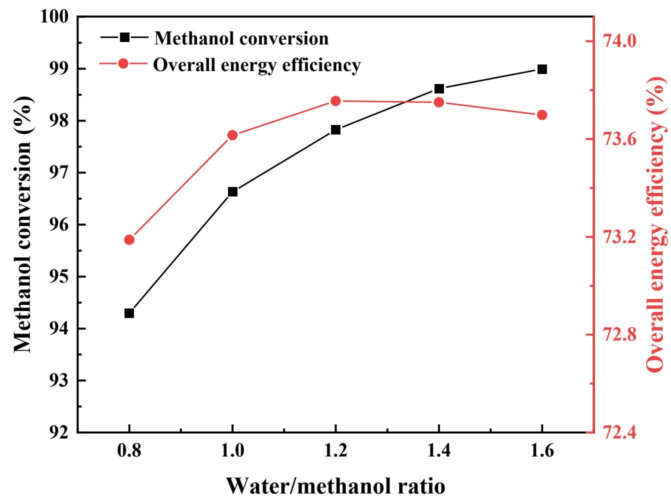

Fig. 5 Influence of the MSR temperature and pressure on system energy efficiency

4. CONCLUSIONS

A poly-generation system driven by industrial waste heat for fuel thermochemical reaction is proposed through the integration of GTCC, MSR, and absorption refrigeration. The thermodynamic performance is investigated, with main findings as follows:

(1) Medium-temperature steam from GTCC is coupled with MSR for hydrogen production, converting low-grade thermal energy into high-grade chemical energy. After heating the reformer, the industrial steam further drives absorption refrigeration. Temperature matching enables cascade utilization of steam waste heat and reduces irreversible losses.

(2) The overall energy and exergy efficiency of the proposed system reach 73.60% and 61.37% respectively under design conditions.

(3) The proposed system achieves a peak energy efficiency of 73.76% at a water/methanol ratio of 1.2

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