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Performance investigation of a new cooling, heating and power system with methanol decomposition based chemical recuperation process☆

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HIGHLIGHTS

- A new CCHP system with a chemical recuperation process is proposed.
- The system performances are evaluated by deploying it to a shopping center.
- Favorable system annual energy efficiency of 58.05% is achieved.

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ABSTRACT

A novel combined cooling, heating and power system, which mainly consists of an internal combustion engine power block with the capacity of 500 kW_e, a chemical recuperation block, an absorption refrigeration block and a hot water supply block, is proposed to improve the energy conversion efficiency in this work. The high temperature exhaust gas from the internal combustion engine is first used to drive methanol decomposition to produce syngas of CO and H_2 via the chemical recuperation, and the produced syngas is fed into the ICE for power generation. The exit exhaust gas flows into a double-effect lithium bromide-water absorption refrigerator, and finally the rest of the gas sensible heat is used to generate hot water for district heating. The temperature of the exhaust gas reduces to approximately 280 °C by the chemical recuperation process, and the temperature difference between the heat resource and the absorption cooling requirement thereby decreases and leads to lower exergy loss. Numerical simulation results indicate that the developed combined cooling, heating and power system achieves favorable thermodynamic performances, and the matching characteristics between energy production and energy demand can be enhanced. The system annual averaged energy efficiency is increased to 58.05%, and the methanol consumption is reduced to 842.54 tons/year with an annual primary energy saving ratio of 9.75%. Additionally, the system achieves lower annual total cost, i.e., 538.95 k$. The research findings provide a promising method to improve the performances of the combined cooling, heating and power system.

1. Introduction

The combined cooling, heating and power (CCHP) production is considered to be a promising route to improve energy conversion efficiency and alleviate current environment concerns [1]. Currently, CCHP systems have been widely deployed in different sectors, such as residential, official buildings and industrial plants [2].

Different from conventional independent energy supply systems, in the CCHP plant the waste energy from the power generation unit is recovered to drive the integrated heating and cooling systems [3]. The CCHP system reduces cost and environmental pollution by the cascade utilization of energy [4], and achieves a significant improvement of the overall energy utilization efficiency (approximately 70–90%) [5]. Owing to the flexibility in the on-grid or off-grid operation, the CCHP system is considered an indispensable component in an energy supply network.

The CCHP systems mainly consist of a prime mover, a heat recovery system and a refrigeration equipment. Typically, the gas turbine [6] or

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Nomenclature

C	cost
c	cooling
e	specific exergy
E	exergy
h	specific enthalpy
H	enthalpy
HHV	high heat value
i	bank interest rate
m	mass rate
n	system life time
P	electricity
p	price
Q	energy
S	saving ratio
s	entropy
t	time
T	temperature

Greek

η	efficiency

Subscripts

AR	absorption refrigerator
ch	chemical
ER	electric refrigerator
EH	electric heater
HX	heat exchanger
MDR	methanol decomposition reactor
O&M	operation & maintenance
ph	physical
ref	reference
sys	system
th	thermal
0	ambient

internal combustion engine (ICE) [7] is used as the prime mover, and single effect [8] or double effect [9] absorption refrigerators with LiBr-H_2O solution are installed. Apart from natural gas, the thermochemical processes of solar-gasification [10] and solar decomposition [11] provide sustainable and clean fuel for the CCHP system operation. Gao et al. [12] investigated the CCHP system performance variation using gas fuel of different compositions, in addition, biogas-fired [13], solar-assisted [14] and biomass-assisted [15,16] CCHP systems are considered as an acceptable methods to simultaneously use renewable energy resources and improve the energy efficiency of systems.

The CCHP system involves multiple energy conversion processes and diverse energy outputs, and it should match energy demands in the process of practical operations. However, the required thermal and power loads in a building vary with the level of activity and climatic conditions. It is challenging to optimize the CCHP system (e.g., system capacity and operation strategy, etc.) under varying load conditions, and achieve maximum benefits in different applications [17].

Currently, several studies are focusing on improving the thermodynamic performances of the CCHP system [18–21]. Li et al. [18] conducted a comparative study between the absorption and electric compression refrigeration system in terms of the steam transport distance. Wu et al. [19] proposed a new carbon dioxide transcritical power cycle with an absorption refrigeration cycle to recover the waste heat of a heavy-duty ICE and optimized system operation parameters, and more power is generated with a higher recycle efficiency. Kaynakli et al. [20] conducted thermodynamic analysis of a double effect absorption refrigeration system with several heat sources including hot water, hot air and steam. Zhang et al. [21] performed an experimental research on the LiBr refrigeration-heat pump applied in a CCHP system, a stable and flexible operation were achieved, and noted that the average coefficient of performance (COP) of the LiBr refrigeration system reached to 1.20. In addition, the optimization of operation strategies is able to improve system performances in practical applications, and the strategies of following the thermal load (FTL) and following the electric load (FEL) are commonly employed [22,23]. Furthermore, different numerical methods, such as the multi-objective optimization model [24,25], non-parametric stochastic method [26] and mixed integer linear programming model [27], are developed. Zheng et al. [28] proposed a minimum distance operation strategy for CCHP systems. Wang et al. [29] optimized the capacity and operation of a CCHP system using the genetic algorithm based on energy flow, and obtained maximum technical, economic and environmental benefits. As above discussed, several advanced energy cycles and reasonable system operation & control technologies were introduced, and thus thermodynamic performances of the CCHP systems can be enhanced. Nevertheless, existing studies fail to optimize waste heat recovery and reduce the irreversibility, restricting the improvement of CCHP system efficiency.

As a key component, the absorption refrigerator plays a crucial role in utilizing the recovered waste heat and providing cooling energy. The LiBr-H_2O generation temperature is only 150–170 °C, while the temperature of exhaust gas from the ICE or gas turbine, as a heat resource, typically exceeds 400 °C. The large temperature difference between the heat resource of exhaust gas and the temperature requirement in refrigerator inevitably exists, leading to higher exergy loss and worse thermodynamic characteristics. In order to address this issue, a chemical recuperation process is considered to first utilize waste heat by driving a methanol decomposition reaction, and then the exit exhaust gas with reduced temperature is further utilized in an absorption refrigerator, both the temperature differences and the generated exergy loss are thereby decreased. Additionally, the proposed chemical recuperation process enhances the matching performances of energy productions, it provides a different route to coordinate the conflict between the improvement of system efficiency and satisfaction of energy demands from users.

Naturally, the main objectives of this work are to propose a novel CCHP system with chemical recuperation to improve the system thermodynamic performances, and to investigate off-design operation characteristics and economic feasibility. The main contributions are summarized as follows:

(1) A CCHP system with a chemical recuperation process with methanol decomposition is newly developed, and it contributes to improving system energy efficiency and reduce pollution emissions.
(2) The developed CCHP system is deployed in a shopping center, the system exergy analysis and energy conversion evaluation of waste heat recovery are implemented, and the annual energy efficiency and fuel consumption are investigated.
(3) Based on typical weeks in different seasons, the system off-design operation characteristics and energies matching performances are discussed, and the system economic potential is analyzed.

2. CCHP system description

In a typical CCHP system, the waste heat of the exhaust gas from the ICE (with a high temperature of above 400 °C) is directly recovered by a LiBr-H_2O absorption refrigerator and leads to a high temperature difference between the exhaust gas and the refrigeration requirement