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Full chain energy performance for a combined cooling, heating and power system running with methanol and solar energy

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HIGHLIGHTS

- Energy analysis is applied to a CCHP system running with methanol & solar energy.
- Solar energy utilization improve overall efficiency by 4 percentage points.
- Single methanol production + CCHP: less efficient than traditional energy supply.
- Polygeneration + CCHP: save 10% energy in summer and 8% in winter.
- Polygeneration with CO_2 capture + CCHP: save 20–26% energy.

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ABSTRACT

Full chain energy performance is applied to a hybrid combined cooling, heating and power (CCHP) system running with methanol and solar energy. Results show that the overall energy efficiencies of six different cases range from 40% to 50% in summer condition, and 38% to 47% in winter condition. Combined with the traditional methanol production process, the CCHP systems are not energy efficient compared to the traditional energy supply systems from a full chain viewpoint no matter whether the solar energy is utilized. While combined with a polygeneration (PG) or polygeneration with CO_2 capture (PG + CC) process, the CCHP system could achieve obvious improvements in overall energy efficiency due to the benefits from cogeneration and solar energy utilization, and thus could yield a high fossil energy saving ratio in comparison with the traditional energy supply system. The findings presented in this paper indicate that the complementation utilization of solar energy and fossil fuels through thermochemistry reactions is energy efficient and could be one of the potential options to utilize solar energy.

1. Introduction

A combined cooling, heating and power (CCHP) system is the simultaneous production of power, cooling and heat, which is integrated based on the energy cascade utilization principle and usually implemented in a building or in an industrial park [1,2]. The CCHP system, or called tri-generation system, is proven to be a potential option for energy efficiency improvement and CO_2 emission reduction [2–4]. Typically, a CCHP system includes the power subsystem, the cooling/chiller subsystem and the heat recovery subsystem [5–8]. What CCHP employs in the power subsystem includes gas turbines/microturbines, steam turbines, fuel cells, Stirling engines and internal combustion engines [2,3]. Compared with other technologies, the internal combustion engines are a proven technology with a wide range of sizes and the lowest first capital cost [9–11]. High efficiency at partial load operation gives users a flexible power source and allows for emergency or standby power supplies in addition to fast start-up capability and good operating reliability [3]. By far, the internal combustion engines are the most commonly used power generation equipments under 1 MW [3]. And the fuels used for the internal combustion engines are in a wide range and easily available, which include the natural gas, liquid fuels, or the combination of the two fuels [3,11].

The studies about the internal engine based CCHP system can originate from very early time of last century. Since the late 1980s, great interests have been put into the combined heat and power (CHP) systems driven by the internal combustion engines with the emerging of cogeneration systems [12,13]. For example, Fowler et al. [14] developed a CHP system based on natural gas internal combustion engines, and found that the NO_x emissions could be reduced. Bidini et al. [15] presented the performance

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Nomenclature

Abbreviation	
CC	CO_2 capture
CCHP	combined cooling, heating and power
CCS	CO_2 capture and storage
CHP	combined heat and power
COP	coefficient of performance
CPOR	chemicals to power output ratio
FESR	fossil energy saving ratio
IGCC	integrated gasification combined cycle
NBSC	national bureau of statistics of China
PC	pulverized coal power plant
PG	polygeneration
SERC	state electricity regulatory commission
WHB	waste heat boiler
Symbols	
E	energy
EE	energy efficiency
FE	fossil energy
PE	primary energy
Subscripts	
i	sub-process *i*
refer	reference system

and economic analysis of an existing CHP plant with an internal combustion engine, and concluded that electric efficiency was only slightly affected by ambient temperature. During the first several years of this century, many other researches were reported about the techno-economic performance of the internal combustion engine based CHP/CCHP systems [16–18]. Moran et al. [16] made a case study to demonstrate the differences in the system performances of micro-CHP systems driven by a natural gas internal combustion engine and a diesel engine, and found that both systems had similar performance. Ḿıguez et al. [17] proposed a small scale CHP system based on a diesel engine and presented its performance analysis. Kong et al. [18] experimentally investigated a CCHP system, which was driven by a natural gas or LPG fired internal engine. Their test showed that the overall thermal and electric efficiency of the system was over 70%. More recently, given the increasing concern about the global warming, many researchers evaluated the CO_2 emission performance of the CCHP systems based on internal combustion engines [19–25]. Possidente et al. [19] examined experimental analysis of micro-cogeneration system based on internal combustion engine (MCHP), and made energetic, economic and CO_2 emission comparisons between this system and a traditional system, claiming that MCHP was at that moment available on the market and they allowed to reduce primary energy consumption and polluter emissions in comparison to conventional systems. Meybodi et al. [20] performed the impact of carbon tax on internal combustion engine size selection in a medium scale CHP system and reported that the diesel engine based systems was not economical regardless of the operational mode.

The previous studies mainly focused on the internal combustion engines driven by natural gas, diesel, syngas, or LPG. However, with the increasing concern about crude oil shortage and environmental protection, some researches also paid attention to the methanol or other alternative fuel fired internal combustion engines [26–29]. Huang et al. [26] used various blend rates of methanol–diesel fuels for an internal combustion engine and pointed out that the increase of methanol content in the mixture could decrease smoke, CO emissions but increase NO_x emissions. Udayakumar et al. [27] carried out the tests to find out that smoke and NO_x emissions could decrease with methanol fumigation. Song et al. [28] studied the methanol–diesel dual fuel engines and reported that smoke and NO_x was decreased, while CO emissions increased when methanol was added. And study from Sayin et al. [29] showed that the increasing injection pressure and timing in a methanol–diesel blend engine caused to decrease in smoke and CO emissions while increase in NO_x emissions.

As far as what we concern, very few researches have been presented, no matter experimental studies or simulation publications, with respect to the CCHP system incorporating an internal combustion engine running with pure methanol or the combination of methanol and solar energy. However, methanol, as an important alternative fuel [29], is clean and thought to be a potential fuel which can be used in an internal combustion engine [3]. In our previous work, a CCHP system based on an internal combustion engine operating with methanol or the combination of methanol and solar energy was designed and its energy performance had been checked. But no effort has been conducted to the full chain energy analysis of the CCHP system. In this paper, an innovative energy full chain/supply system based on such CCHP system will be presented and the energy performance of the CCHP system from a full chain viewpoint will be analyzed.

2. Methodology

2.1. The scope of full chain energy analysis

The analysis in this paper focuses on the full chain of energy utilization, from exploitation to end users. As shown in Fig. 1, the scope includes the primary energy exploitation & cleaning, transportation, conversion processes, and the secondary energy transportation, conversion and utilization processes. Other processes, i.e., the energy consumption for plant erection, are not considered in this paper.

2.2. Evaluation criteria

The overall energy efficiency is used to evaluate the energy conversion efficiency of the whole energy utilization system, as is defined in the following equation:

$$EE_{overall} = \frac{E_{output}}{PE_{input}} \tag{1}$$

$EE_{overall}$ represents for the overall energy efficiency; E_{output} is the total energy output including electricity, the water for heating, cold water for cooling and hot water whose stream states will be shown in the following sections; PE_{input} is the total primary energy input including the total lower heat value input of coal and the solar energy.

The fossil energy saving ratio (FESR) is defined to represent for the total fossil fuel energy saved in the new energy supply system in comparison with the reference energy supply system assuming the same product outputs, which is shown in the following equation:

$$FESR = \frac{FE_{total,refer} - FE_{total}}{FE_{total,refer}} \tag{2}$$