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Integration of a novel renewable energy-fired CCHP integrated with an indirect solar-driven biogas reforming unit at high water steam condition[#]

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ABSTRACT

Conventional biogas-driven distributed energy systems concern the cascaded utilization of thermal energy; however, the chemical energy in the fuel is lost during the combustion process. To solve the problem, this paper designs a novel renewable energy-fired CCHP integrated with an indirect solar-driven biogas reforming unit at high water steam condition, which is capable to make full use of both chemical and physical energy; also, the issues of high consumption of fossil fuel for biogas digester thermal insulation can be addressed by a novel combination of low concentration ratio of trough solar collectors. By performance comparison, the new design achieves a high net solar-to-electric efficiency of 19.71% which is higher than the optimal power efficiency (~16.00%) of a trough solar thermal power generation system. Besides, the new design can save 116.5 kg/h of natural gas (100%) compared with the conventional one. The new design broadens the possibility of the complementary use of multiple renewable energy sources.

Keywords: biogas reforming, distributed energy system, chemically recuperated gas turbine, solar energy, latent heat recovery

1. INTRODUCTION

Climate change and energy depletion are the two serious problems of the modern era [1]. Seeking efficient energy utilization methods may be the ultimate solution [2]. Combined heating and power system (CHP) or CCHP (Combined cooling, heating and power system) have been widely identified as promising technologies with high energy utilization efficiency, low pollutant emission, and strong flexibility [3, 4]. As biogas is abundant in reserves and widely dispersed, the feature agrees well with the application of distributed energy supply technologies [5-7].

The configuration of distributed energy systems varies in different regions differences, and it relies on the ambient conditions. In cold regions, Basrawi et al. [8] developed a biogas-fired CHP in which biogas is firstly combusted for power generation and then for thermal preservation in the digester. In the subtropical area, the ambient temperature is usually high; therefore, the required heat in the biogas digester is low. It is worth noting that the cold demand rises due to the high ambient temperature. Based on this, Chen et al. [9] proposed a biogas-fired CCHP in which the production of heat, cooling and power can be satisfied. Though CCHP has already achieved a better condition for a cascaded way of use in physical energy. Nevertheless, chemical energy is still lost in the biogas combustion process.

To make full use of biogas chemical energy. Jin et al. [10] aims to utilize chemical energy by introducing a reforming reaction. This principle offers a guide for the efficient use of biogas and solar energy. Concentrated solar heat can be used to drive a biogas reforming process. Rathod et al. [11] used a catalyst reactor based on foam type Ni assisted with Al_2O_3 and a 16 m^2 solar concentrating collector was employed for supplying this heat. The dry reforming process is prone to carbon deposition.

Relevant studies indicate that adding suitable water steam has a large potential to ease the risk of carbon deposition [12]. Based on this, Han et al. [3] proposed to use solar energy-driven biogas steam reforming reaction, and the solar energy is converted to the chemical energy of syngas. Syngas is further used to achieve heat, cooling and power supply. While application of high

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concentration ratio solar dish collectors will aggravate the burden of investment. Zhang et al. [13] adopts high-temperature flue gas from the gas turbine to drive the reforming process in the power cycle, which avoids the reliance on the high concentration ratio of solar thermal technologies.

The power cycle based on chemically-recuperated technologies boosts thermal efficiency by increasing the energy level of turbine flue gas. In the biogas-fired CCHP, digester heat demand is extremely high, especially in cold regions; therefore, low-and-mid temperature heat is lacking though power generation rises if chemically recuperated gas turbine cycle is applied.

The integrated performance improvement for biogas-fired CCHP is to combine the chemically recuperated gas turbine cycle and low concentration solar collector. In this way, a low concentration solar collector will only ensure stable production of water steam at a temperature of about 170 °C. The addition of a large amount of water steam before combustion will increase the water concentration in the flue gas. This measure makes a possibility of latent heat recovery for digester thermal insulation.

Based on this, this paper develops a novel renewable energy-fired CCHP integrated with an indirect solar-driven biogas reforming unit at high water steam condition. The performance comparison is conducted between the current advanced energy systems. Then, the parameters of the new system are analyzed. Finally, some conclusions are made

2. SYSTEM DESCRIPTION

2.1 *Flow chart of the new design*

Fig. 1 shows the flow chart of the novel renewable energy-fired CCHP integrated with an indirect solar-driven biogas reforming unit at high water steam condition. Clean biogas is firstly pressurized in a compressor, and water is vaporized by a trough solar collector. The pressurized biogas mixes with the water steam in a mixer, and the gas mixture is heated in a recuperator. The gas mixture is converted into syngas in a reformer and the syngas is then combusted with air. The high-temperature and pressurized flue gas generates electric power with the assistance of a turbine and a generator. The flue gas from the turbine provides heat for biogas steam reforming. Then, outlet flue gas is further adapted for cooling and heating in an absorption chiller and a biogas digester after releasing heat in the recuperator.

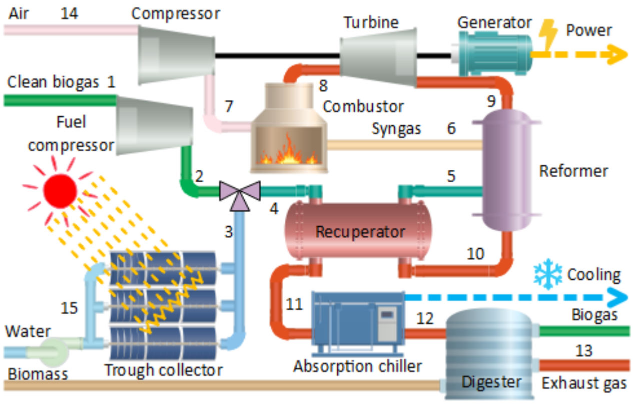
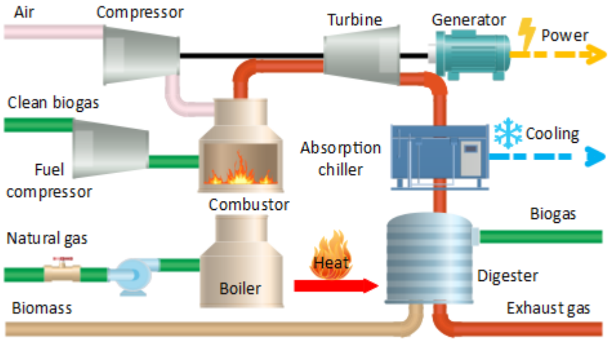


Fig. 1 The flow chart of the novel renewable energy-fired CCHP integrated with an indirect solar-driven biogas reforming unit at high water steam condition

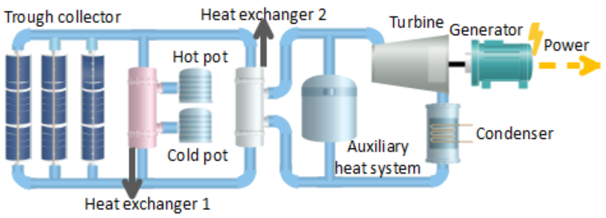
2.2 *Flow chart of the reference designs*

Fig. 2 shows the reference systems: a traditional biogas-fired CCHP and a trough solar thermal power generation system. In the traditional biogas-fired CCHP, clean biogas is firstly pressurized and then combusted with pressurized air in the combustor. The high-temperature and pressurized flue gas is used to generate electric power in a turbine, and then the flue gas from the turbine provides heat for cooling production in the absorption chiller and heat preservation in the biogas digester thermal insulation.

The trough solar thermal power generation system is composed of five subsystems: solar energy collection subsystem, heat exchange subsystem, power generation subsystem, heat storage energy supply system, and auxiliary heat energy function subsystem. Solar collection and heating subsystems focus on direct sunlight, heat the heat transfer medium in the vacuum collector tub, and heat water through the heat exchange subsystem to generate high temperature and pressure steam, thus converting solar energy into electricity.



(a)



(b)

Fig. 2 The flow chart of the reference designs: (a) the biogas-fired CCHP, (b) the trough solar thermal power generation system

3. MATHEMATICAL MODEL AND PROCESS SIMULATION

3.1 Mathematical model

A version of Aspen Plus software is adopted to simulate the new process. The Redlich-Kwong-Soave (RK-Soave) thermodynamic model is selected for the thermal property calculations. In the simulation process, some assumptions are made reasonably to simplify the new system simulation according to the previous studies:

1. Clean biogas is assumed as a gas mixture of 60% CH_4 and 40% CO_2 on a molar basis [7].

2. Pressure drops in pipelines and components are neglected [14].

3. Heat exchangers are adiabatic, heat loss interactions with the environment can be avoided [15].

4. Pump work is ignored due to the addition of limited water [6].

5. Natural gas is assumed to be 100% CH_4 in composition [15].

Biogas steam reforming is the key process in the new system. Gibbs reactor model is adopted to simulate the biogas steam reforming process based on Gibbs free energy minimization [16]. The previous studies compared the results between experimental conditions and simulation results by using Gibbs reactor, and the average relative error is lower than 5% [16]. Thus, the Gibbs reactor model can be used with confidence. The model of the biogas digester thermal insulation was detailed in our previous research [6].

3.2 Evaluation criterion

Energy efficiency is defined as:

$$\eta_{\mathrm{th}}=\frac{W_{\mathrm{net}}+Q_{\mathrm{h}}+Q_{\mathrm{c}}}{Q_{\mathrm{b}}+Q_{\mathrm{n}}+Q_{\mathrm{sol}}} \qquad (1)$$

where W_{net}, Q_{h}, and Q_{c} are the net electric power, heating and cooling outputs produced by the system respectively. Q_{b} and Q_{n} are chemical energy input of biogas and natural gas. Q_{sol} is the solar energy input for generating water steam.

Considering the different energy levels of different energy, exergy efficiency is further used to measure the system, and exergy efficiency is defined as:

$$\eta_{\mathrm{ex}}=\frac{W_{\mathrm{net}}+E_{\mathrm{h}}+E_{\mathrm{c}}}{E_{\mathrm{b}}+E_{\mathrm{n}}+E_{\mathrm{sol}}} \qquad (2)$$

where E_{h} and E_{c} are heat exergy and cooling exergy output, respectively. E_{b}, E_{n} and E_{sol} are biogas exergy, natural gas exergy and solar exergy, respectively.

To indicate the relative power generation performance of the solar heat contribution in the new system, net solar-to-electric efficiency is further used to measure the system, net solar-to-electric efficiency is defined as:

$$\eta_{\mathrm{sol}}=\frac{W_{\mathrm{new}}-W_{\mathrm{ref}}}{W_{\mathrm{ref}}} \qquad (3)$$

where W_{new} and W_{ref} are power generation of the new system and the biogas-fired CCHP.

4. RESULTS AND DISCUSSION

4.1 Design point analysis

Table 2 presents the thermodynamic performances in the new design and reference designs. In the new design, the flue gas is firstly to provide heat for biogas steam reforming; thus, the thermal energy in the flue gas can be converted into chemical energy in the syngas. In this way, the chemical energy and physical energy of biogas can be all used effectively, η_{th} can reach 97.42%, and η_{ex} can reach 41.83% in the new system. However, the biogas-fired CCHP only concerns the biogas's physical energy. Therefore, η_{th} and η_{ex} are 66.47% and 17.83% in the conventional biogas-fired CCHP. The collected solar heat is used for water evaporation in the new design; nevertheless, the solar energy is used for power generation in the conventional trough solar thermal power generation system. η_{sol} in the new design reaches 19.71% which is higher than the power efficiency (16.00%) in the trough solar thermal power generation system.

Table 2 The thermodynamic performances of the new design and the reference designs

Item	Reference design

	New design	Biogas -fired CCHP	Trough solar thermal power generation system
Energy input (kW)	5080.9	4107.2	2593.1
Biogas	2487.8	2487.8	-
Solar energy	2593.1	-	2593.1
Natural gas	-	1619.4	-
Energy output (kW)	4464.1	2730.2	414.9
Power	1186.9	675.5	414.9
Cooling	1014.9	1628.4	-
Heat	2262.3	426.3	-
η_{th}	97.42 %	66.47 %	-
η_{ex}	41.83 %	17.83 %	-
η_{sol}	19.71 %	-	16.00%

In order to further present energy flows in the new system, Fig. 3 presents the energy flows of the new system. In the new design, the energy input includes solar energy for water steam generation and biogas' chemical energy are 1872.2 and 2487.8 kW, respectively. The power, cooling, and heat production are 1186.9, 1014.9, and 2262.3 kW, respectively. The flue gas from the power engine releases 690.5 kW heat in the reformer, the exhaust gas then releases 402.7 kW heat in the recuperator, further releases 845.8 kW heat in the absorption chiller, and finally releases 2262.3 kW heat in the digester.

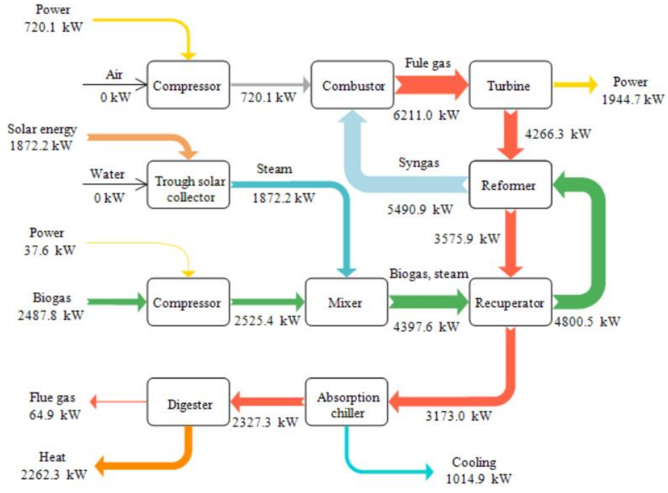


Fig. 3 Energy flows of the new design

4.2 Parametric analysis

Fig. 4 (a) presents the effect of The molar ratio of water steam and biogas (SC) and Turbine intel temperature (TIT) on biogas conversion rate, Fig. 4 (b) presents the effect of SC and TIT on fuel heating value and fuel heating value increase rate. CH_4 conversion rate is always low due to the low reaction temperature. This study introduces high SC to improve the low CH_4 conversion rate. As shown in Fig. 4, for TIT of 980 °C, the CH_4 conversion rate will increase from 20.71% to 88.03%, and the syngas heating value will increase from 2608.3 to 2951.1 kW when SC increases from 1 to 10. TIT has a strong effect on the chemical reaction performance, and methane steam reforming can be strengthened at high TIT. As shown in Fig. 4, when the SC is 10, the CH_4 conversion rate will increase from 68.08% to 88.03%, while TIT rises from 900 to 980 °C.

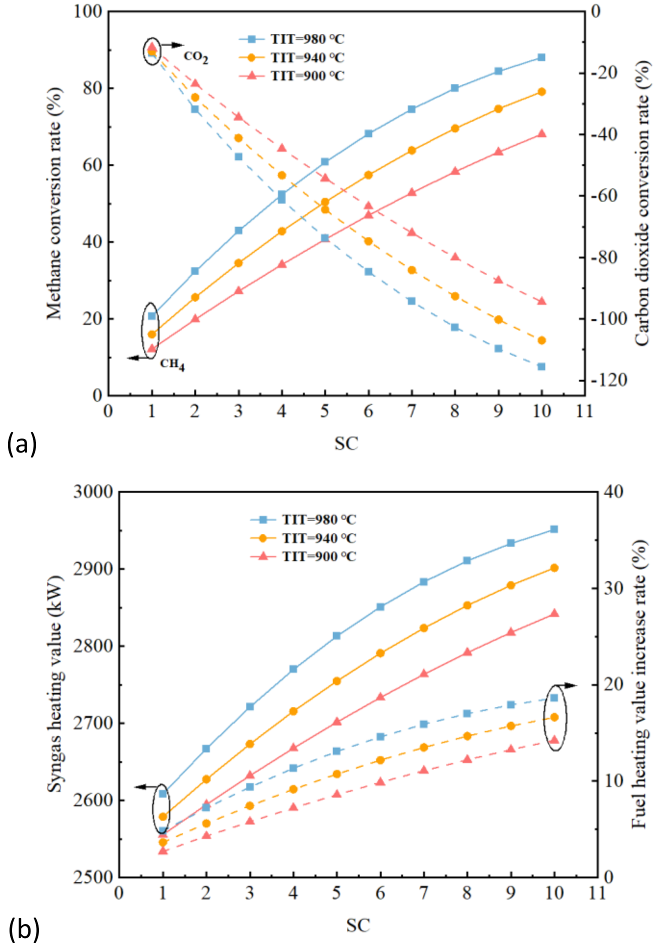


Fig. 4 (a) Effect of SC and TIT on biogas conversion rate; Fig. 4 (b) effect of SC and TIT on fuel heating value and fuel heating value increase rate

Fig. 5 presents the effect of SC and TIT on power generation, cooling and heat. According to the discussion in Fig. 4, higher SC can more effectively convert thermal energy in flue gas into chemical energy in syngas, so that more electrical energy can be produced. As shown in Fig. 5, for TIT is 980 °C, the power generation increases from 792.3 to 1365.1 kW when SC increases from 1 to 10.

Higher SC means more solar energy input, for TIT of 980 °C, the heat increases from 695.7 to 3042.5 kW when SC rises from 1 to 10; however, the production of cooling decreases from 1455.6 to 832.5 kW when SC rises from 1 to 10, because high SC needs more heat for recuperating gas mixture.

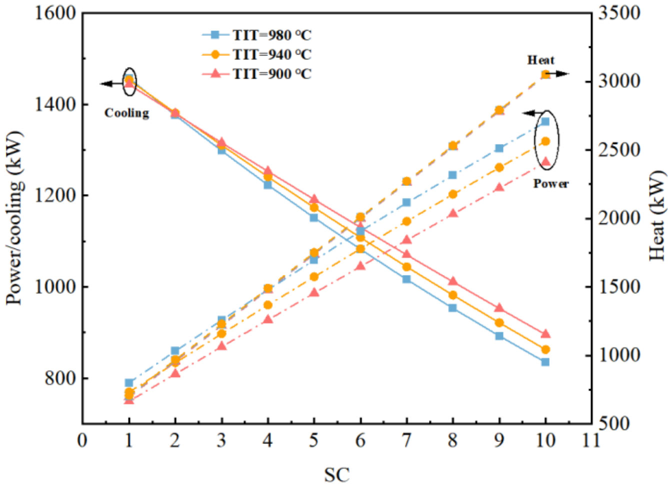


Fig. 5 Effect of SC and TIT on power generation, cooling and heat

Fig. 6 presents the effect of SC and TIT on net solar-to-electric efficiency, exergy efficiency and energy efficiency. As SC increases, electricity generation and heat both increase, but the thermal demand of biogas digester is certain, the excess heat will be wasted when the production of heat exceeds the demand of biogas digester, so η_{th} starts first and then decreases. When SC is 6.2, η_{th} reaches the highest value of 102.74%. As electricity has a higher energy level, η_{ex} is increasing, but it increases slowly. Because of the increase of SC, the solar input is large, so η_{sol} gradually decreases.

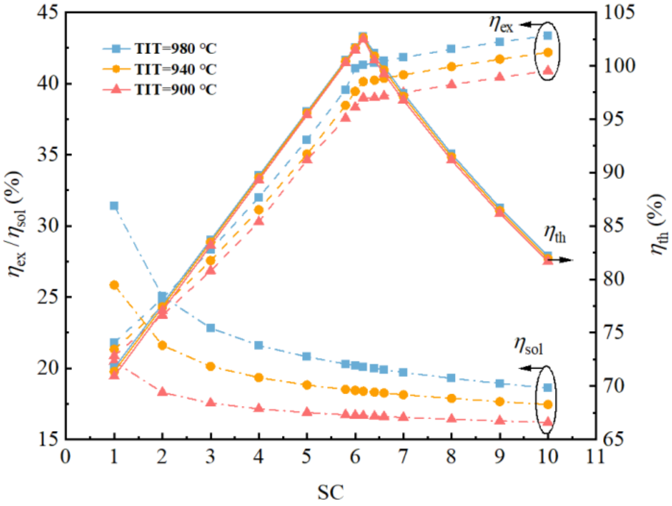


Fig. 6 Effect of SC and TIT on net solar-to-electric efficiency, *exergy efficiency and energy efficiency*

5. CONCLUSIONS

To solve the problem that the chemical energy of the traditional biogas-fired CCHP has not been fully utilized, a novel renewable energy-fired CCHP integrated with an indirect solar-driven biogas reforming unit at high water steam condition has been developed. Some conclusions can be drawn as follows:

(1)By adopting the biogas steam reforming process of using thermal energy in the flue gas, the energy level of thermal energy improves in the power generation process, thus, the new system's exergy efficiency can reach 41.83%, higher than 17.83% of the reference biogas-fired CCHP.

(2) Solar energy involved in biogas steam reforming can effectively improve the net solar-to- electric efficiency. The net solar-to-electric efficiency in the proposed system can reach 19.71%, higher than that of the trough solar thermal power generation system.

(3) SC and TIT have a strong effect on the biogas steam reforming and thermodynamic performance. For TIT of 980 °C, as SC increases from 1 to 10, the methane conversion rate increase from 20.71% to 88.03%, and exergy efficiency increases from 21.73% to 43.27%.

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