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Thermodynamics evaluation of a solar-biomass power generation system integrated a two-stage gasifier

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Abstract

A new solar-biomass power generation system that integrates a two-stage gasifier is proposed in this work, in which two types of solar collectors are used to provide solar thermal energy with different levels for driving the biomass pyrolysis (about 643K) and gasification (about 1150K), respectively. The qualified syngas produced is fed into the combined cycle system for power generation. The thermodynamic performances of the proposed system are improved with the overall energy efficiency of 26.72% and the net solar-to-electric efficiency of 15.93%. The exergy loss during the solar collection and gasification is reduced by 19.3% compared with the scheme of using one-stage gasifier.

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Keywords: solar energy, power generation, two-stage gasifier, hybrid

1. Introduction

Various renewable energies, including solar energy and biomass, are viewed as alternatives for the alleviation of the current energy and environment concerns. Moreover, the technical route of solar thermochemical is promising to deal with the low energy density and intermittent nature of solar energy [1-3].

The concentrating solar energy as the heat source of the high-temperature process can be used to drive the biomass-steam gasification, in which the solar thermal energy is converted into the chemical energy. Therefore, the solar energy is easily converted to valuable chemicals and low-carbon footprint transportation fuels [4-6].

In this work, the biomass gasification process is divided into two stages of biomass pyrolysis and char gasification. A two-stage gasifier is integrated in the proposed solar-biomass power generation system.

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Nomenclature

A	Energy level
E	Exergy
HHV	High heat value
m	Mass flow rate
P	Power
η	Efficiency

The line-focus solar collectors (LFC) and the point-focus collector (PFC) are used to provide the solar thermal energy for driving the gasification process, and the system thermodynamic performances are investigated.

2. System description

2.1. Physical Properties of Biomass

The corn straw is an abundant herbaceous biomass resource in China, which is selected as the gasification feedstock. The biomass sample of corn straw is collected as follows.

The pyrolysis experiment of corn straw is firstly conducted, by a program-control electrical furnace, with the temperature of lower than 673 K, the tar yield ratio can reach 19.5% as reported in Table 1. The chemical composition as air-dry basis of the biomass sample and the char (solid product from pyrolysis) are determined and summarized in Table 2.

Table 1. The product yield of pyrolysis / wt.%

	Tar	Water	Char	Gas
Corn straw	19.50	22.13	38.26	20.11

Table 2 Chemical compositions of the biomass sample

Sample	Proximate analysis / wt.%				Ultimate analysis / wt.%					HHV/ MJ·kg-1
	M_{ad}	A_{ad}	V_{ad}	FC_{ad}	C_{ad}	H_{ad}	N_{ad}	S_{ad}	O_{ad}	
Corn straw	3.94	7.1	69.56	19.39	41.49	6.05	2.35	0.19	38.88	16.51
Char*	0.36	18.65	22.81	58.18	59.28	3.90	4.60	0.25	12.96	25.67

* produced by pyrolysis

2.2. System description

The new solar-biomass power generation system consists of a solar-assistant biomass gasification subsystem and an advanced Brayton–Rankine combined cycle with a SGT-900 type gas turbine, as illustrated in Fig. 1. During the gasification process, the biomass pyrolysis is firstly conducted to yield tar and char with the temperature of lower than 673 K. Subsequently, the processes of tar crack and char gasification are carried out, at the temperature of higher than 1000 K, for producing syngas.

The biomass gasification reaction heat is provided by the concentrating solar energy. The LFC is used to drive the pyrolysis and generate the steam as the gasification agent, meanwhile the PFC with the beam-down concept is employed for providing the gasification reaction heat. The system operation parameters and the design condition are listed in Table 3.

Table 3. Main assumptions of the system

Items	value
Gasification temperature & pressure	1150K/18bar
Pressure ratio (π)	15.3
Gas turbine inlet temperature (TIT)	1422K
Primary steam temperature & pressure	764K/56bar
Low-pressure steam temperature & pressure	533K/6.9bar
DNI	765 W/m^2
Collection temperature & efficiency of LFC	643K/51.70%
Collection temperature & efficiency of PFC	1150K/38.71%

After the condensation and clean-up, the solid particles of ash and other corrosion compositions, like H_2S, etc., are removed from the syngas produced. The qualified syngas as the gas fuel is fed into the power generation unit. The HRSG and the steam turbine installed employ the dual-pressure system without a reheat steam configuration.

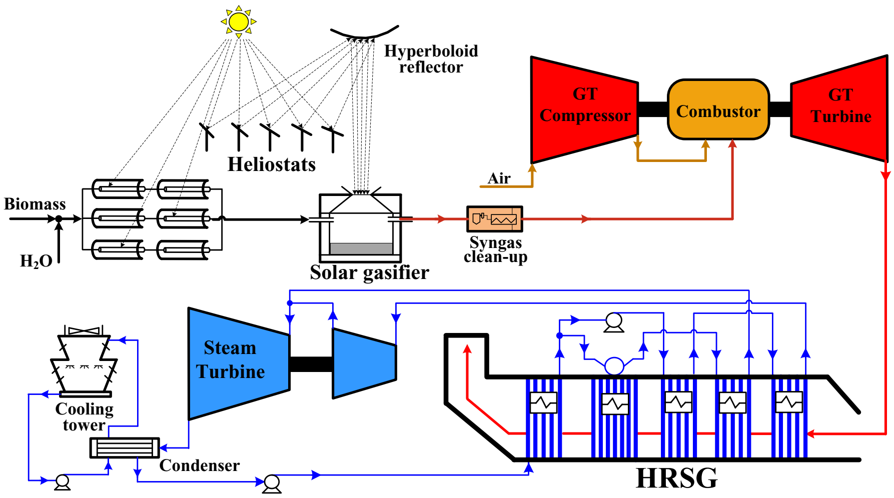

Fig. 1. Schematic diagram of the novel solar-biomass power generation system

2.3. System evaluation criteria

The system energy efficiency η_{sys} and net solar-to-electric efficiency $\eta_{sol\text{-}elec}$ are used as the overall evaluation criteria, which can be formulated as:

$$\eta_{sys} = P / (Q_{solar} + HHV_{bio} \cdot m_{bio}) \quad (1)$$

$$\eta_{sol\text{-}elec} = (P - P_{ref}) / Q_{solar} \quad (2)$$

where, P and P_{net} represent the total generated power of the proposed system and the reference system, respectively; Q_{solar} is the collected solar thermal energy; HHV and m are the higher heat value and the mass rate for the biomass, respectively.

Additionally, the EUD (Energy-Utilization Diagrams) method [7] is employed to investigate the exergy loss of the system, the exergy balance of the energy-conversion process and the energy level can be computed as follows:

$$\Delta E = \Delta H - T_0 \Delta S \tag{3}$$

$$A = \Delta E / \Delta H \tag{4}$$

3. Results and discussion

3.1. Energy level upgrade of the solar thermal energy

In the solar-biomass gasification, the solar thermal energy is used to provide the reaction heat and drive the gasification process. And the EUD for the solar-biomass gasification process is illustrated as shown in Fig. 2. The EUD is used to graphically show the variations in energy quality and energy quantity, the energy donor (A_{ed}) and the energy acceptor (A_{ea}) exist in an energy-transformation process.

For the typical solar-biomass gasification process with high-temperature solar energy introduced (1150K for the case study), the energy level of solar energy can be improved from 0.741 to 0.9 as the energy level of the produced syngas. Whereas, if the gasification process is switched to employ the proposed two-stage solar-biomass gasification technical mode, in which the pyrolysis and the water evaporation processes are driven by the mid-temperature solar energy of 643 K, the energy level of the required solar energy is reduced to 0.68, and more energy level upgrade ratio of the solar energy can be achieved. In addition, compared to the one-stage gasification mode, the proposed system can converted more heat resource of the solar energy into the chemical form, which accounts 9.25% of the required net exergy of the solar thermal energy.

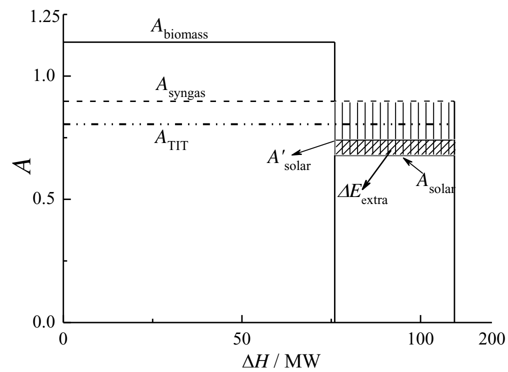

Fig. 2. The EUD diagram of solar gasification process

3.2. Thermodynamics analysis of the system

According to the evaluation criteria, the system performances evaluation with the two two-stage solar-biomass gasification concept under the nominal condition is conducted, the energy and exergy analysis of the proposed system are summarized in Table 4. The solar energy approximates 51.08% of total energy inputs. Correspondingly, due to the inferior collection efficiency of the PFC accompanying with more irreversible loss, the largest energy and exergy losses are produced in the solar collection process, which accounts for 29.48% and 23.48%, respectively.

Additionally, the heat loss of the stack gas and the steam condensation contribute to the second largest energy loss, which totally take up the proportion of 28.54%. While, for the exergy analysis, the second largest energy loss item is generated in the syngas combustion processes, which accounts for 17.90% of total input.

Whereas, compared with the scheme of using one-stage gasifier, the proposed solar collection system in the work is redesigned with an improvement achieved, the energy loss during this process is reduced by 13.81% and exergy loss by 19.3%.

Table 4. The energy & exergy balance of the system

	Energy analysis		Exergy analysis	
	Energy / MW	Ratio / %	Exergy / MW	Ratio / %
Biomass	136.37	48.92	145.31	59.86
Solar energy	142.38	51.08	97.44	40.14
Total	278.75	100	242.75	100
	OUTPUT			
Generated Power	74.48	26.72%	74.48	31.53
	Energy loss / Exergy loss			
Solar collection	82.17	29.48	56.99	23.48
Gasification unit	-	-	17.25	7.11
Gas condensation	27.27	9.78	16.08	6.62
GT combustor	-	-	43.45	17.90
Gas turbine	13.41	4.81	20.22	8.33
HRSG	-	-	5.53	2.28
Exhaust gas loss	27.27	9.78	2.39	0.99
Steam turbine	0.32	0.11	3.22	1.33
Condenser	52.30	18.76	2.96	1.22
Other	1.54	0.55	0.18	0.07
Total	278.75	100	242.75	100

3.3. System performance

The overall energy efficiency η_{sys} of the proposed system is 26.72%, which can be further improved. Firstly, the hyperboloid reflector and the CPC are used for reflecting sun light downward and improving the concentrating ratio at the expense of increasing the energy loss, which results in a low collection efficiency of the PFC, therefore it can be optimized in the future work. Additionally, the sensible heat recovery of syngas is not to be considered in this work. If a part of sensible heat is reutilized for evaporating the water (gasification agent), the η_{sys} can be improved to 29.48%.

The concentrating solar energy is introduced for driving the biomass gasification, then converted into the electricity with a favorable efficiency $\eta_{sol\text{-}elec}$ of 15.93% under the design condition. $\eta_{sol\text{-}elec}$ is varied with the pressure ratio (π) and the gas turbine inert temperature (TIT) as shown in Fig. 3. Compared with the scheme of using one-stage gasifier, an improvement of 1.16~1.42 percentage point is achieved in this work.

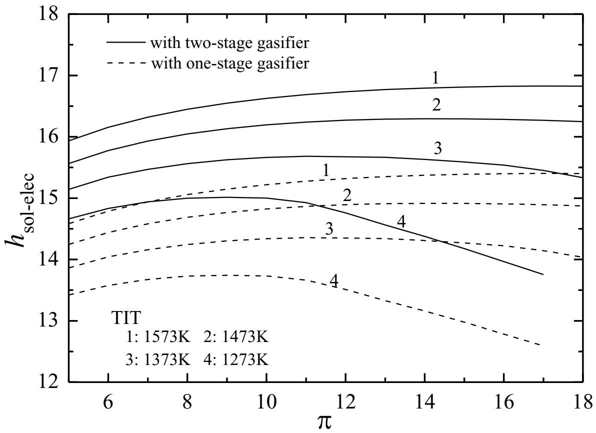

Fig. 3. Variation of $\eta_{sol\text{-}elec}$ versus π and TIT

4. Conclusions

A new solar-biomass power generation system integrates a two-stage gasifier is proposed, and the thermodymics performances of system are evaluated. The main research findings can be summarized as follows:

(1) The energy level of the concentrating solar thermal energy is upgraded to 0.898 and converted to the syngas. by driving the biomass gasification

(2) The total exergy loss produced in the gasification and solar collection of the proposed system is reduced by 19.3%, compared with the scheme with one-stage gasifier.

(3) The system thermodynamic performances are improved, and the overall energy efficiency and the net solar-to-electric efficiency reach to 26.72% and 15.93%, respectively.

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Biography

Qibin Liu is a Professor of Engineering Thermophysics at the Chinese Academy of Sciences (CAS). Dr. Liu’s current research includes: solar thermal power, solar thermochemical technology, and analysis and optimization of energy systems. He has published more than 60 research papers.