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Performance analysis of a polygeneration system for methanol production and power generation with solar-biomass thermal gasification

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Abstract

By using the cotton stalk as the feedstock, a polygeneration system for generating methanol and power with solar thermal gasification of biomass is proposed in this work. The endothermic reaction of biomass gasification is driven by the high temperature solar thermal energy with the range of 800~1200℃. The flat-plate solar collector and the parabolic trough solar steam generator are used to preheat biomass and generate steam as gasification agent, respectively. The thermodynamic performance of the polygeneration system is investigated. The compressed syngas, produced by the biomass gasification, is used to produce methanol via the synthesis reactor. The un-reacted gas is used for power generation through a combine cycle power unit. The results indicate that the methanol output rate and the output power in steady operation condition is 41.56 kg/s and 524.88 MW, respectively, and the maximum total exergy efficiency is 49.50% when the solar gasification temperature is 900℃. Furthermore, the highest exergy efficiency of the optimized scheme by recycling partial un-reacted syngas for methanol production reaches to 50.69%. The above studies provide a feasible way to exploit the abundant solar energy and biomass in the Western China.

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Keywords: solar energy; biomass; gasification; polygeneration system; performance analysis

1. Introduction

Methanol is one of clean liquid fuels, which can be regarded either as a hydrogen storage compound or petroleum alternative [1]. Traditionally, the syngas that is used to produce methanol is mainly derived from the coal gasification or natural gas reforming [2]. Nevertheless, the excessive use of non-renewable fossil fuel should not be advocated, and the use of biomass as gasification feedstock is a promising approach.

However, the common gasification technologies need inner biomass combustion or oxidation reaction to provide the heat [3]. This kind of technology makes the gasification costly and the H_2/CO ratio of syngas still lower. The high-temperature solar thermochemical technology is an alternative solution, the biomass gasification is driven by the concentrated solar energy with steam as gasification agent. Moreover, the solar-biomass gasification mode is a feasible way to upgrades the quality of solar energy and syngas, and solar energy can be stored by converting into chemical products.

The main motivation in this paper is to propose a polygeneration system with solar-biomass thermal gasification, to evaluate the system thermodynamic performance and to identify the influence of solar gasification. Furthermore, the effect of the recycle ratio (defined by the sum molar ratio of the fresh and un-reacted syngas to the fresh syngas) on the system performance with optimized scheme is investigated.

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Nomenclature

W the output power
E the exergy

Subscript
poly polygeneration system
sol solar
bio biomass
CH_4O methanol

2. Description of the polygeneration system

The solar and biomass polygeneration system for methanol production and power generation with the syngas is illustrated in Fig. 1. The cotton stalk and steam are selected as the feedstock and the gasification agent, respectively. The flat-plate solar collector is equipped for removing the surface moisture of biomass and the saturated steam is produced by the parabolic trough solar steam generator.

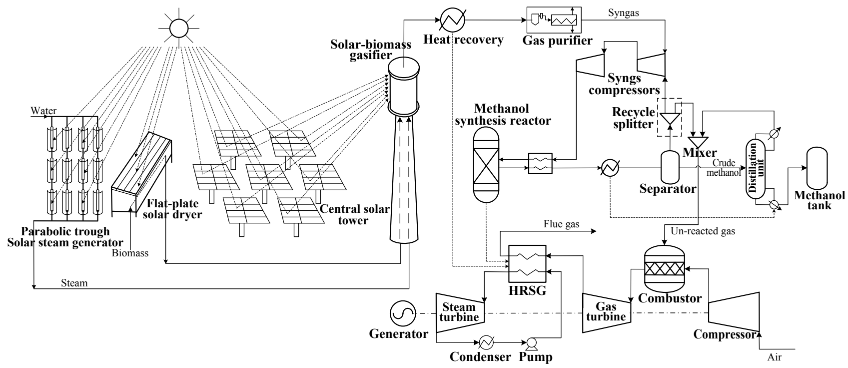


Fig. 1. Flowchart of polygeneration system based on solar-biomass gasification

The dry biomass and steam are fed into the solar-biomass gasifier, and the heat is provided by the central solar tower, the heating method is different from common gasification technologies. The raw syngas is produced by gasification with temperature of 850℃ and pressure of 1.8 MPa, and then flows into the process for cooling and purification. The qualified fresh syngas is fed into the methanol synthesis reactor (H_2+ 0.5CO → 0.5CH_4O, $\Delta_r H_{298K}$ = -64.07 kJ/mol) after compressed to 10 MPa. The exit stream is the mixture of the crude methanol and un-reacted syngas, and the crude methanol after separation will be pumped into the distillation unit for achieving the required quality (> 99.9 wt.%). The gas after separation and the flash gas released from the distillation unit will be mixed, which is viewed as un-reacted gas and used as fuel for power generation via an advanced combined cycle unit.

In addition, the polygeneration system is further optimized in this study. A part of un-reacted syngas will be mixed with the fresh syngas and then fed into the methanol synthesis reactor after compression. Thus, the operation can be adjusted by changing the recycle ratio.

3. Chemical equilibrium analysis and system evaluation criteria

3.1. Chemical equilibrium analysis

The cotton stalk from Xinjiang in the west of China is selected as the feedstock in this work. The sample's chemical composition is listed in the Table 1, and the total moisture content of raw sample is 35 %.

Table 1. Chemical composition and heat value of the sample

Sample	Proximate analysis / wt.%				Ultimate analysis / wt.%					LHV
	M_{ad}	A_{ad}	V_{ad}	FC_{ad}	C_{ad}	H_{ad}	N_{ad}	S_{ad}	O_{ad}	/kJ·kg^{-1}
biomass	6.78	3.97	68.54	20.71	42.6	5.59	1.28	0.2	39.58	15999

The concentrated solar energy provides the heat for gasification without air or oxygen introduced, thus, the fraction of CO_2 in syngas is lower as compared with common gasification technologies. The H_2/CO ratio of the produced syngas reaches to 1.65~2.29, which can satisfy the requirement of the optimal H_2/CO ratio by adjusting the solar gasification temperature, the process from CO to H_2 can be removed. It is worthy emphasizing that even the composition of H_2 in syngas is excess, it is also utilized by subsequent power generation.

3.2 System evaluation criteria

Exergy analysis is employed for the performance evaluation of the proposed polygeneration system. The total exergy efficiency $\eta_{\text{tot,ex}}$ serves as a basic criterion to evaluate the thermodynamic performance of polygeneration system, which is defined as:

$$\eta_{\text{tot, ex}} = \frac{W + E_{\text{CH}_4\text{O}}}{E_{\text{tot, poly}}} = \frac{W + E_{\text{CH}_4\text{O}}}{E_{\text{sol}} + E_{\text{bio}}} \tag{1}$$

Also, the solar exergy fraction f_{ex} and the output ratio of chemical to power α (based on exergy) are selected to manifest the inlet exergy and outlet product distribution, which can be formulated by:

$$f_{\text{ex}} = \frac{E_{\text{sol}}}{E_{\text{sol}} + E_{\text{bio}}} \tag{2}$$

$$\alpha = E_{\text{CH}_4\text{O}} / W_{\text{p}} \tag{3}$$

One of the advantages of the polygeneration system is the resource-saving as compared with the reference systems for the same methanol and power output. The reference systems employ common biomass gasification technologies for producing methanol and power generation individually. Thus, the exergy saving ratio R_{ex} and the biomass saving ratio R_{bio} are chosen as criterions to evaluate the system's energy reservation potential.

4. Results and discussion

4.1. The result in specific steady operating condition

The polygeneration system is simulated by Aspen Plus with a biomass feed flow rate of 143.42 kg/s (dry-basis biomass of 100 kg/s) and steam of 80kg/s, the gasification temperature and pressure are set to 850℃ and 1.8 MPa. In this gasification condition for the specific biomass sample, the H_2/CO molar ratio of fresh syngas reaches to 2.08 that is closes to the optimal H_2/CO molar ratio. The exergy balance of the ploygeneration system is summarized in Table 2.

Under the steady operation, the methanol output rate and the output power are 41.56 kg/s and 524.88 MW, respectively, and the total exergy efficiency of the polygeneration system $\eta_{\text{tot,ex}}$ is 49.17%. The exergy fraction of solar energy to total input is 36.78%, and the solar exergy received by solar-biomass gasifier up to 840,105.3 kW, which occupies about 84.24% share in the total solar exergy input. Through the integrated utilization of solar energy and biomass, the exergy saving ratio R_{ex} can reach to 23.89% and the biomass saving ratio R_{ex} is up to 51.74%.

Table 2. Exergy balance of the polygeneration system

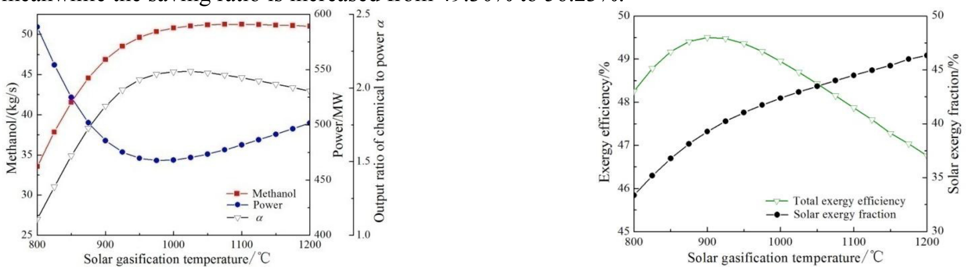
	Items	Exergy / kW	Fraction /%
Inlet	Biomass inlet	1,714,575.29	63.22
	flat-plate solar dryer	5,154.83	0.19
	parabolic trough solar steam generator	152,048.91	5.61
	Central solar tower	840,105.30	30.98
	Total	2,711,884.33	100
Outlet	Methanol production	808,567.01	29.82
	Power generation	525,062.39	19.36
Loss	Total exergy loss	1,378,254.93	50.82

Besides, a combined cycle unit is employed for the utilization of the un-reacted syngas, also the sensible heat of the raw syngas heat and the reaction heat of methanol synthesis can be effectively used. The total power generated by gas turbine and steam turbine is 569.6 MW with an overall exergy efficiency of 58.64%, and 44.54MW power is used.

According to the preliminary devices investment estimate, the total cost of the polygeneration system is $1,099 million. And the subsystem cost of biomass-solar gasification, methanol synthesis and power generation account for about 46.53%, 7.11% and 36.36%, respectively.

4.2. The effect of solar gasification temperature on polygeneration system

The effects derived from the changing of the solar gasification temperature in the range of 800~1200℃ on products output and system performances are investigated. As illustrated in Fig. 2. (a), the methanol production increases rapidly from 37.85 kg/s to 50.79 kg/s lower than 1000℃, then keeps relatively stable. The methanol output can reach to the maximum production of 51.25 kg/s at 1100℃. But the trend of the power output is opposite, and the generated minimum power decreases to 467.69 MW at 975℃. The highest total exergy efficiency is 49.50% at 900℃, and the solar exergy fraction keeps rising from 33.37%. Meanwhile, the exergy saving ratio deceases from 24.14% to 18.67%, meanwhile the saving ratio is increased from 49.30% to 56.23%.



(a) (b)

Fig. 2. The effect of solar gasification temperature on polygeneration system

In addition, the polygeneration system can be optimized by using partial un-reacted syngas for methanol production. Even the conversion ratio of methanol synthesis reaction is kept decreasing because the H_2/CO ratio of syngas is deviate from the optimal value, the methanol output rate can be improved. The highest total exergy efficiency can reach to 50.69%, which is higher than 49.50% as the peak efficiency of previous system. Here, the recycle ratio should not be higher than 1.54. If the recycle ratio is more than the value, the added methanol output cannot compensate the loss of power, and lead to the exergy efficiency decreasing.

Conclusions

A novel polygeneration system with solar-biomass thermal gasification for methanol and power generation is proposed, which provides a feasible way for exploiting the abundant renewable energy in the Western China. The solar energy quality can be upgraded by converting into chemical fuel in this polygeneration system. The system is evaluated by exergy analysis, adjusting the solar gasification temperature, the maximum methanol output is 51.25 kg/s at 1100℃ and the peak total exergy efficiency reaches to 49.50% at 900℃. Furthermore, the system performance can be improved by optimizing the recycle ratio.

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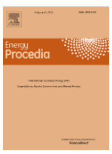

Biography

Qibin Liu is an Associate 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 50 papers, and received the best paper award of The 3rd International Green Energy Conference (Sweden) in 2007.