International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0209

THERMODYNAMIC EVALUATION OF A SPECTRAL SPLITTING HYBRID PROTOTYPE FOR CASCADING SOLAR ENERGY UTILIZATION

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ABSTRACT

Full-spectrum solar energy utilization has drawn widespread attention for cascading solar energy utilization. A spectral splitting approach is described and a prototype is originally presented. Innovatively, the full-spectrum solar energy is first split and then concentrated onto photovoltaics and solar thermochemical reactor. In this case, the irreversible loss would be expected to be reduced. Here, thermodynamic evaluation of prototype is conducted. The monocrystalline silicon photovoltaics and methanol decomposing are adopted. The results show that the solar-to-electricity efficiency would be 37% in the hybrid system, 19% higher than individual concentrating solar photovoltaics and 9% higher than individual solar thermochemical system. An optimal working spectral range is about 280-1100nm for the silicon photovoltaics. The proposal of hybrid approach of solar photovoltaics and endothermal reaction leads to a feasible strategy for cascading solar energy utilization.

Keywords: Cascading solar energy utilization, hybrid prototype, full spectrum, spectral splitting approach

1. INTRODUCTION

Solar energy has played a prominent role in the renewable energy supply, accounting for about 21% of renewable power in 2018. [1] At present, the research hotspots of solar energy are how to achieve efficient and low-cost utilization. Full-spectrum solar energy utilization provides a possibility and attracts attentions of researchers and governments. For example, Bermel et al. [2] points out the combination of tandem photovoltaics (PV), thermoelectrics and mechanical Rankine cycles can harvest the full spectrum of sunlight and minimize the cost of solar energy. US Department of Energy has put forward a research plan of full-spectrum solar energy utilization in 2013 [3].

Regarding the full-spectrum solar energy utilization, the spectral splitting hybrid system is commonly considered as a promising approach of cascading solar energy utilization. [4] In details, by using spectral splitting technology, the incident solar radiation is split into ultraviolet, visible and infrared spectra. The split visible radiation is concentrated onto photovoltaics to excite electrons and converted into electricity. Meanwhile, the split ultraviolet and infrared radiations are cast to receiver and directly converted into solar heat at medium-high temperature or chemical energy. [5]

For example, Tang et al. [6] used a spectrum selective nanofluid to absorb ultraviolet and infrared spectrum, the absorbed solar energy was further converted into chemical energy by driving a thermochemical reaction. At the same time, the un-absorbed visible spectrum illuminated photovoltaics and was converted into electricity. As a result, the solar energy conversion efficiency would be expected to be approximately 31.5%. Widyolar et al. [7] developed a spectral splitting hybrid prototype and tested on-sun up to 600 ^oC. The full-spectrum solar energy was converted into photovoltaic electricity and high-temperature solar heat. In addition, the test results demonstrated the feasibility of two-stage collector design. Liang et al. [8] designed and fabricated a SiO2/TiO2 interference thin film. Adopting this film, the overall energy and exergy efficiencies of the hybrid system can increase by 4.94% and 1.03%, compared with individual system.

Furthermore, our previous works [9] has proposed a spectral splitting hybrid system, converting full-spectrum solar energy into electricity and chemical energy of solar fuel. In addition, a spectral splitting parabolic trough concentrator has been designed which can concentrate, split and homogenize sunlight, synchronously. In this paper, the prototype of hybrid system is presented, and the thermodynamic performance is investigated.

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).
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2. SPECTRAL SPLITTING HYBRID PROTOTYPE

2.1 Description of prototype

Prototype mainly consists of solar photovoltaic/ thermochemical component, power component and auxiliary component. By using solar photovoltaic/ thermochemical component, the incident solar energy is first converted into electricity and solar thermal fuel. Here, the methanol decomposition is adopted, and then the produced solar thermal fuel is the mixture of hydrogen and carbon monoxide. According to the type of solar thermal fuel, a solid oxide fuel cell (SOFC) is employed to convert the chemical energy into electricity in the power component. The auxiliary component provides the pump power, recovers the waste heat, records the experimental data, and so on. It is emphasized that the solar photovoltaic/thermochemical component is key. As depicted in Fig. 1, it includes spectral splitting parabolic trough concentrator, concentrating solar photovoltaics (CPV) and solar thermochemical reactor.

Spectral splitting concentrator: It is comprised of above-mirror and sub-mirror. Both mirrors are parabolic trough and have same focus length. The above-mirror has a layer of selective film, which can reflect visible spectrum with high reflectance and penetrate ultraviolet and infrared spectra with high transmittance. The sub-mirror has an ultrathin silver coating, by this silver coating, all radiations reaching the sub-mirror can be reflected with high reflectance. The detailed parameters are list in Table 1.

Concentrating solar photovoltaics: It locates at the homogenous focus spot of above-mirror, as a result, the secondary optical element is not demanded in the front of photovoltaics. In addition, the imbricated photovoltaic technology is adopted to weak the effect of concentrating sunlight condition on the junction and contact voltage loss. The monocrystalline silicon photovoltaics M-Si is manufactured and implemented in the prototype. Furthermore, considering the impaired effect of high temperature on the photovoltaic efficiency, a heat sink is fixed at the photovoltaic back to control the operation temperature. The detailed parameters are also list in Table 1.

Solar thermochemical reactor: It locates at the focus spot of sub-mirror and intercepts all the sunlight from sub-mirror. Benefiting from coating of reactor, the intercepted sunlight is absorbed and converted into solar heat. In the inner of reactor, the catalyst ($Cu/ZnO/Al_2O_3$) is filled and the endothermal reaction of methanol decomposition is conducted and driven by solar heat about 250 °C. The detailed parameters are shown in Table 1.

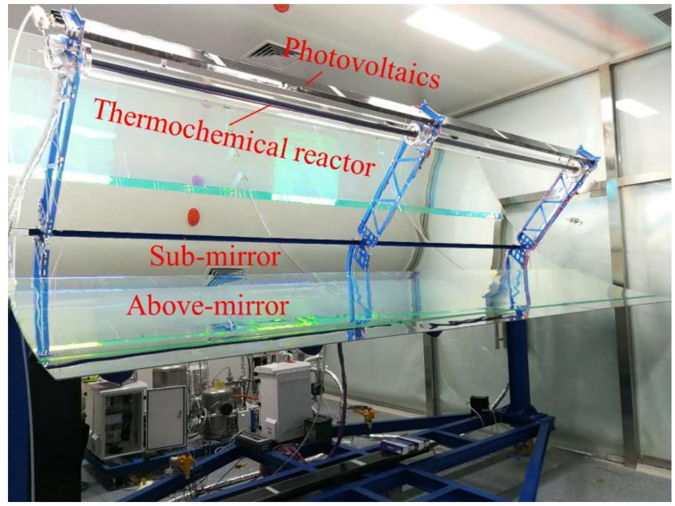

Figure 1. Photo of the prototype of hybrid system

Table 1. The geometric dimensions and optical parameters

Items	Values	Items	Values
Spectral splitting concentrator		**Photovoltaics and heat sink**	
Aperture of the sub-mirror	2550 mm	Width	125 mm
Focus length of the sub-mirror	850 mm	Thickness of the heat sink	30 mm
Clearness of the above-mirror	0.98	Intercept factor	0.958
Clearness of the sub-mirror	0.98	Effective length	0.92
Solar thermochemical reactor		Clearness of the covered glass	0.98
Diameter of the covered glass	102 mm	Photovoltaic absorptance	0.98
Clearness of the covered glass	0.98	Emissivity of the covered glass	0.9
Intercept factor	0.958	Direct normal irradiation	900 $W \cdot m^{-2}$
Effective length	0.95	Global horizontal irradiation	1000 $W \cdot m^{-2}$

2.2 Flow diagram of prototype

Figure 2 depicts the schematic flow diagram of spectral splitting hybrid prototype. The incident solar energy in the full-spectrum is split into the “solar photovoltaic” spectral band energy and “solar thermal” spectral band energy by using spectral splitting concentrator. The “solar photovoltaic” spectral band energy is concentrated on the surface of photovoltaic panel to excite and generate electron-hole pairs. Incident spectral energy is converted into electricity. However, in this process, part of spectral energy is also converted into photovoltaic heat caused by inner recombination loss. A heat sink is mounted beneath photovoltaic panel to collect this waste heat releasing from photovoltaics. The “solar thermal” spectral band energy is cast to the coating of reactor. The solar energy received by reactor is directly converted into solar heat, and this part solar heat drives the endothermic reaction of hydrocarbon fuel in the reactor. The conversion of spectral energy into chemical energy of solar syngas is realized. Subsequently, this part of chemical energy is converted into electricity in the SOFC. As a result, the full-

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spectrum solar energy can achieve a high-grade conversion.

By means of pump, the cooling hydrocarbon fuel first flows into heat sink to cool the photovoltaics, and then a reasonable operation temperature of photovoltaics can be controlled. This cooling process acts as the preheat process of reactant, and hydrocarbon fuel is heated. Subsequently, the heated hydrocarbon fuel flows into thermochemical reactor, involves in the endothermic reaction and produces solar syngas. That is, the low-grade photovoltaic heat can be converted into high-grade chemical energy of solar syngas, and this is an upgrade process of photovoltaic heat. It is worth noting that the mixture leaving from reactor contains solar syngas and some unreacted fuel. Part of solar heat is carried by the mixture in the form of sensible heat. Thus, an exchanger is employed at the outlet of reactor to reutilize this part solar heat. Ultimately, this mixture is injected into condenser #2 and separated to be solar syngas and unreacted reactant in the separator. The solar syngas is stored for further power, and the unreacted reactant is injected into reactant tank.

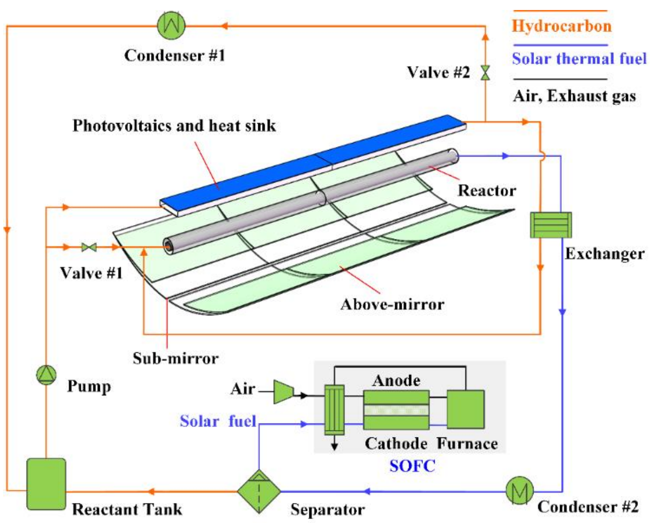

Figure 2. Schematic flow diagram of hybrid prototype

3. RESULTS AND DISCUSSION

3.1 Solar-to-electricity conversion of hybrid prototype

Regarding the hybrid prototype, incident solar energy is categorized as two types. One directly reaches on the above-mirror, concentrated onto photovoltaics and thermochemical reactor to cascade solar energy utilization. The other directly reaches on the sub-mirror, cast onto thermochemical reactor and driving a methanol decomposition. The utilization of latter solar energy is similar to that in the individual solar thermochemical system.

Here, in the individual solar thermochemical system, the flow rate $F_{syngas,solar}$ of produced syngas contributed by solar energy is calculated by

$$F_{syngas,solar} = F_{syngas} \times \frac{Q_{solar,heat}}{Q_{solar,heat} + F_{methanol} \times Z_C \times LHV_{CH4O}} \tag{1}$$

and the solar-to-electricity efficiency $\eta_{individual}$ can be further expressed as

$$\eta_{individual} = \frac{F_{syngas,solar} \times LHV_{syngas} \times \eta_{SOFC}}{AC \times DNI} \tag{2}$$

where F_{syngas} is total flow rate of produced syngas in the thermochemical reactor, $Q_{solar,heat}$ is the amount of solar heat participating in methanol decomposition, $F_{methanol}$ is the flow rate of methanol flowing into reactor, Z_C is the conversion rate of reactive methanol, *LHV* is the lower heat value, η_{SOFC} is power efficiency of SOFC, *AC* is the aperture wide of concentrator, *DNI* is the direct normal irradiation.

In the hybrid system, the produced syngas by total incident solar energy is calculated by

$$\begin{cases} F_{syngas,solar} = F_{syngas} \times \dfrac{Q_{solar,heat} + Q_{cell,heat}}{Q_{solar,heat} + Q_{cell,heat} + F_{methanol} \times Z_C \times LHV_{CH4O}} & , F_{methanol} > F_{cooling} \\ F_{syngas,solar} = F_{syngas} \times \dfrac{Q_{solar,heat} + Q_{cell,heat} \times \dfrac{F_{methanol}}{F_{cooling}}}{Q_{solar,heat} + Q_{cell,heat} \times \dfrac{F_{methanol}}{F_{cooling}} + F_{methanol} \times Z_C \times LHV_{CH4O}} & , F_{methanol} < F_{cooling} \end{cases} \tag{3}$$

where $F_{cooling}$ is the flow rate of cooling methanol in the photovoltaic sink.

The solar energy directly reaching above-mirror is utilized by the spectrum response. With regard to this part of solar energy, considering the photovoltaic electricity P_{PV}, the solar-to-electricity efficiency η_{Hybrid} can be expressed as

$$\eta_{Hybrid} = \frac{F_{syngas,solar} \cdot LHV_{syngas} \cdot \eta_{SOFC} - \left(AC - C_{PV} \cdot DC - W_{PV}\right) \cdot DNI \cdot \eta_{individual} + P_{PV}}{\left(C_{PV} \cdot DC + W_{PV}\right) \cdot DNI} \tag{4}$$

In this paper, the value of Z_C is 0.9. In the cooling process of photovoltaics, the dryness fraction is 1 of methanol leaving from the cooling sink. The temperature difference is about 10 °C between photovoltaics and cooling methanol. The pressure of cooling methanol is 2 bar. In addition, the power efficiency of SOFC with simple form is about 0.42.

The "solar photovoltaic" spectral band energy is reflected to concentrating photovoltaics by above-mirror for efficiently generating electricity. Importantly, both the reflected spectrum range λ_L-λ_H nm of above-mirror and concentration ratio C_{PV} of photovoltaics determine the photovoltaic efficiency, the amount of photovoltaic heat. At the same time, the received energy share between photovoltaics and thermochemical reactor is also determined by these two parameters. Fig. 3 depicts the variation of solar-to-electricity efficiency of "solar photovoltaic" spectral band energy with λ_L-λ_H and C_{PV}. It

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is clear that the match between the spectrum range λ_L-λ_H and concentration ratio C_{PV} directly determines the performance of solar energy conversion. Here, the value of λ_H is 1100 nm according to the band gap of M-Si. The suitable value of λ_L is in the range of 280–850 nm, and the feasible value of CPV is in the range of 2–16. Satisfactorily, about 37% solar-to-electricity efficiency is obtained in our prototype.

As shown in Fig. 3, the individual solar thermochemical system has a 28% of solar-to-electricity efficiency, and the individual concentrating photovoltaic system has a 18% of solar-to-electricity efficiency with sufficient cooling and second optical element. By contrast, the enhancement of solar energy conversion in the prototype is prominent and satisfying. It mainly results from that the low-grade photovoltaic heat can be further utilized and converted into high-grade chemical energy of solar fuel. In this case, the amount of photovoltaic heat participating into methanol decomposition is a key factor. As depicted in Fig. 4, excepting for the unavoidable heat loss, all the photovoltaic heat is used to preheat the reactant methanol, and then full-spectrum solar energy has a higher conversion efficiency.

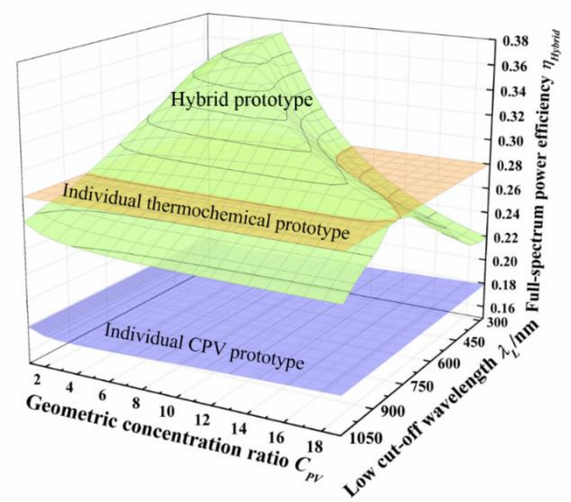

Figure 3. Full-spectrum solar conversion in the hybrid system

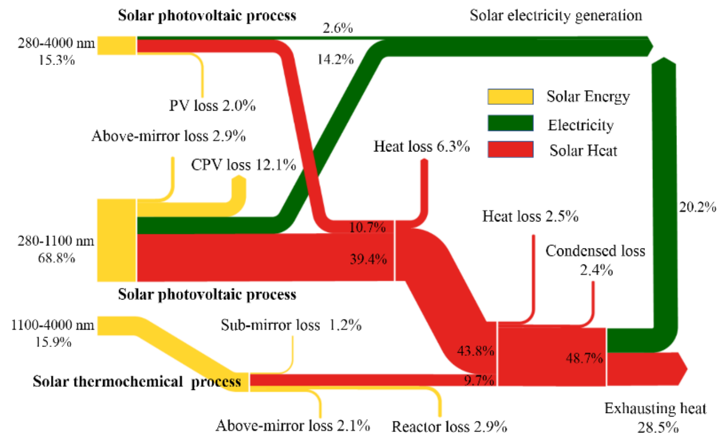

Figure 4. Grassmann diagram for the solar energy transfer

4. CONCLUSIONS

Hybrid prototype synchronously combines individual solar thermochemical and photovoltaic/thermochemical processes. In latter process, the temperature of silicon photovoltaics can reach about 92 °C. The dissipating PV heat participates into solar syngas generation. As a result, the full-spectrum solar energy achieves efficient utilization with the 37% of solar-to-electricity efficiency. Compared with efficiencies of 18% and 20.8% in the individual systems, proposed spectral splitting hybrid approach can provide the possibility of realizing cost-effective solar energy utilization.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the National Natural Science Foundation of China (Grant No. 51590904).

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