SolarPACES 2023, 29th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Solar Fuels and Chemical Commodities

https://doi.org/10.52825/solarpaces.v2i.757

Published: 24 Jul. 2024

Thermal Performance Assessment of a Novel Hybrid Reactor for Solar Thermochemical Processes

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Abstract. Solar thermochemical conversion processes offer a promising pathway for converting sunlight into clean, sustainable, and carbon-neutral fuels. A solar chemical reactor is one of the most essential components that utilizes concentrated solar energy to drive chemical reactions. In this study, a novel hybrid solar reactor is designed, fabricated, and tested to assess its thermal performance for the purpose of studying the solar thermochemical conversion processes in Thailand for the first time. It was performed under different heating modes regarding solar heat and/or electrical heat, with the aim to support day-and-night operation and variations in solar radiation conditions. The reactor was experimentally tested under on-sun, off-sun, and hybrid conditions using air as a heat transfer fluid. As a result, with one kW_{th} solar thermal power input absorbed, the solar reactor achieved high temperatures exceeding 500 °C from the hybrid system while the reactor absorption efficiency was found to be 4%. The reactor demonstrated the possibility and reliability of performing solar thermochemical conversion processes under day-and-night and unstable solar radiation conditions.

Keywords: Hybrid Solar Reactor, Concentrated Solar Power, Solar Fuels

1. Introduction

Solar energy represents a promising renewable energy source worldwide, owing to its abundant availability and eco-friendliness [1]. Solar resource is estimated to exceed other energy sources by a factor of thousands when assuming perfect conversion efficiency [2]. Thailand, recognizing the significance of renewable energy, has been actively pursuing methods to harness this sustainable energy source. Thailand's average high solar radiation density is estimated at 1875 kWh/m^2-year [3]. In Thailand, solar power is mostly used for generating electricity, primarily using non-concentrating solar power systems. Alternatively, it is worth noting that concentrating solar power (CSP) is a promising method of harnessing solar energy, which is more efficient than non-concentrating solar power systems [4]. CSP technologies are the parabolic trough, linear Fresnel, dish/engine, and central receiver [2]. They can provide very high-temperature heat, which can be utilized for driving solar thermochemical conversion processes [5].

Solar thermochemical processes represent a technology that can convert solar energy into chemical fuels [6]. This process involves a solar reactor to carry out a chemical reaction with the supply of concentrated solar energy [7]. Solar reactors can be categorized according to the heating methods related to direct and indirect heating. Indirectly heated solar reactors separate light from the reaction zone, which results in no soot or particles sticking to the transparent windows. This can help to stabilize the operation of the reactor over a long period [8]. The present solar reactor prototype is designed based on the indirect heating concept for radiative heat, consisting of a tube containing the reactant, which is placed vertically inside. It was designed to accommodate a variety of feedstock types, operating modes, thermochemical processes, and solar radiation conditions. In addition, it is necessary to optimize the reactors corresponding to such conditions to maximize the absorption of solar radiation, minimize heat losses, and ensure efficient mass transfer in solid/gas reactions involving reactants and catalysts. Solar reactors with hybrid heating are attractive to solve the issue of unstable solar radiation conditions [7, 9, 10]. For this reason, this study aimed to design and fabricate the hybrid solar reactor, which can be heated by solar heat and/or electrical heat to drive endothermic thermochemical conversion processes.

Therefore, in this study, we designed, fabricated, and tested a hybrid solar chemical reactor to experimentally evaluate its performance for the purpose of developing solar thermochemical conversion processes in Thailand. The reactor design and thermal performance were addressed. Temperature measurements and reactor performance were determined during on-sun, off-sun, and hybrid conditions.

2. Solar hybrid reactor design

The solar chemical reactor design and fabrication imply using high-quality materials to ensure the reactor's robustness and efficiency. Figure 1 shows the cross-section of the solar tubular reactor with housing made of stainless steel. The design of this solar reactor was inspired by indirectly-irradiated solar chemical reactor concepts [11], which comprise a tube inside the reactor where the chemical reaction takes place. This tube is made of alumina with excellent thermal and chemical stability, high mechanical strength, and good corrosion resistance. More details on the solar reactor design were reported in previous work [12].

This solar reactor comprises three main sections. According to Figure 1, the upper section of the reactor is where the reactants are fed. The reactor's top has a tube inserted into a stainless-steel tube, allowing the gas reactants to enter the tube toward the chemical reaction zone. K-type thermocouples are installed around the reactor to measure the temperature at each point. Additionally, one thermocouple is installed in the middle of the tube to measure the reactor cavity temperature. The upper section also features two tube cooling systems to cool down the tube when it operates for long durations. The middle section of the reactor has an aperture with a 30 mm diameter at the front that allows concentrated solar power entering the reactor. The focal point is set in the middle of an alumina tube to reach high temperatures for the chemical reaction. The reactor cavity is filled with insulation to maintain high temperatures during the solar thermochemical process. Furthermore, the reactor features electric heat sources from two U-tube electric heaters with one kWe capacity in total on both sides of the tube to increase the temperature, particularly during unfavorable weather conditions or overnight operations. The reactor shell has a cooling system to maintain the reactor's temperature and prevent melting. The lower section of the reactor is similar to the upper section, featuring a tube cooling system, a middle hole for the outlet products to flow out of the tube, and another tube on the side of the bottom section for the gas phase product entering a gas analyzer to analyze gas products compositions. As seen in Figure 1, the reactor temperatures (T_1-T_6) were measured at different positions of the reactor. Note that the thermocouple T_1 was placed at the focus.

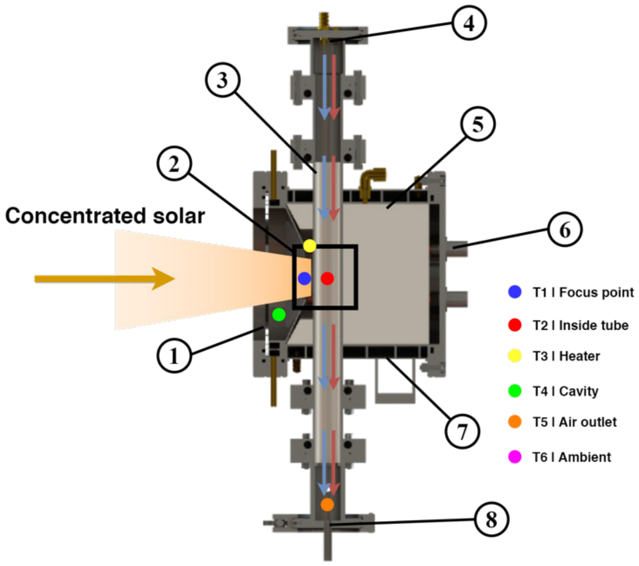

Figure 1. *Schematic diagram of the cross-section of the hybrid solar reactor: (1) glass window, (2) reaction zone, (3) alumina tube, (4) reactants inlet, (5) insulation, (6) heater, (7) reactor's shell, (8) products outlet.*

3. Hybrid solar reactor setup and methods

Figure 2 illustrates the setup of the solar reactor system used in this experiment. The set-up is located on the rooftop of the lab building at KMITL Prince of Chumphon Campus to receive sunlight. The system consisted of a manual tracking heliostat measuring 2x2 m and about 3 m high, which reflected sunlight to a Fresnel lens (1.05x1.4 m) with a focal length of 1.2 m. The concentrated solar power was directed to a tubular cavity receiver in the reactor with very high solar intensity, rapidly increasing the temperature. In addition, two 500 W electrical heaters were supplied to heat the reactor during unstable conditions of solar DNI (direct normal irradiation), demonstrating the hybrid system. Once the reactor reached the targeted temperature, a heat transfer fluid (air) was fed into the reactor, and its heating performance was evaluated.

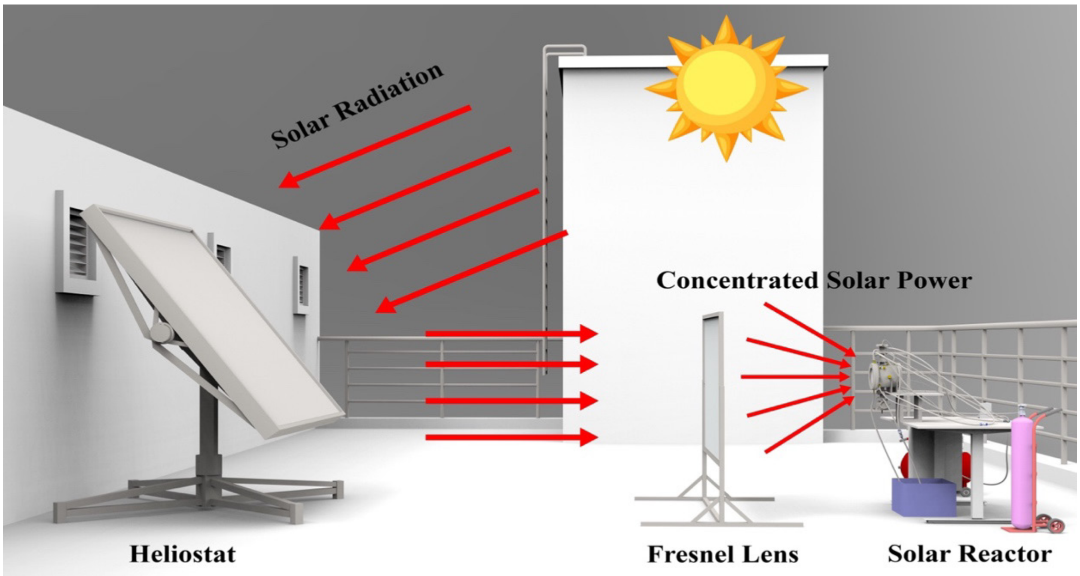

Figure 2. *On-sun solar reactor set-up.*

The reactor's thermal performance was assessed with on-sun, off-sun, and hybrid heating modes. During on-sun heating, a shutter was used to control the solar intensity passing through the Fresnel lens. This enabled the reactor to be heated throughout the entire reactor volume. Cooling water was employed to protect the reactor's components and maintain the materials' properties. During heating up the reactor, the shutter was opened progressively to receive the concentrated sunlight. In the hybrid heating method, the electrical heaters were turned on during unfavorable weather or low DNI conditions to keep the reactor operating. Operating parameters were recorded with an automatic data logger system to monitor the time evolution of temperature, DNI data, and air flow-rate. Off-sun heating was similar to the on-sun methods, except that the electrical heater was only utilized as the heat source instead of solar heat.

4. Results and discussion

4.1 On-sun heating

Figure 3 shows the temperature profiles of the solar chemical reactor along with DNI during on-sun heating for 120 mins. Overall, it was found that the reactor can achieve temperatures from concentrated sunlight above 560 °C regarding the focal point area (T_1). A fluctuation in T_1 was encountered due to a change of the focal point resulting from a delay in the manual solar tracking. The heating process was slow due to low solar power input (1 kW_{th} maximum at DNI of 1000 W/m^2). This led to the temperature inside the tube (T_2) being below 300 °C. During on-sun testing, the DNI was relatively high, above 950 $W/m^{2,}$ thanks to the clear sky in the summer season, and then it decreased slightly with operating time. The temperature at cavity (T_4) was similar to T_2 (below 300 °C). The temperature at the outlet (T_5) was above 200 °C after 80 min, even if it was far from the reaction zone, due to convective heat transfer in the reactor. The ambient temperature (T_6) was found to be 38 °C.

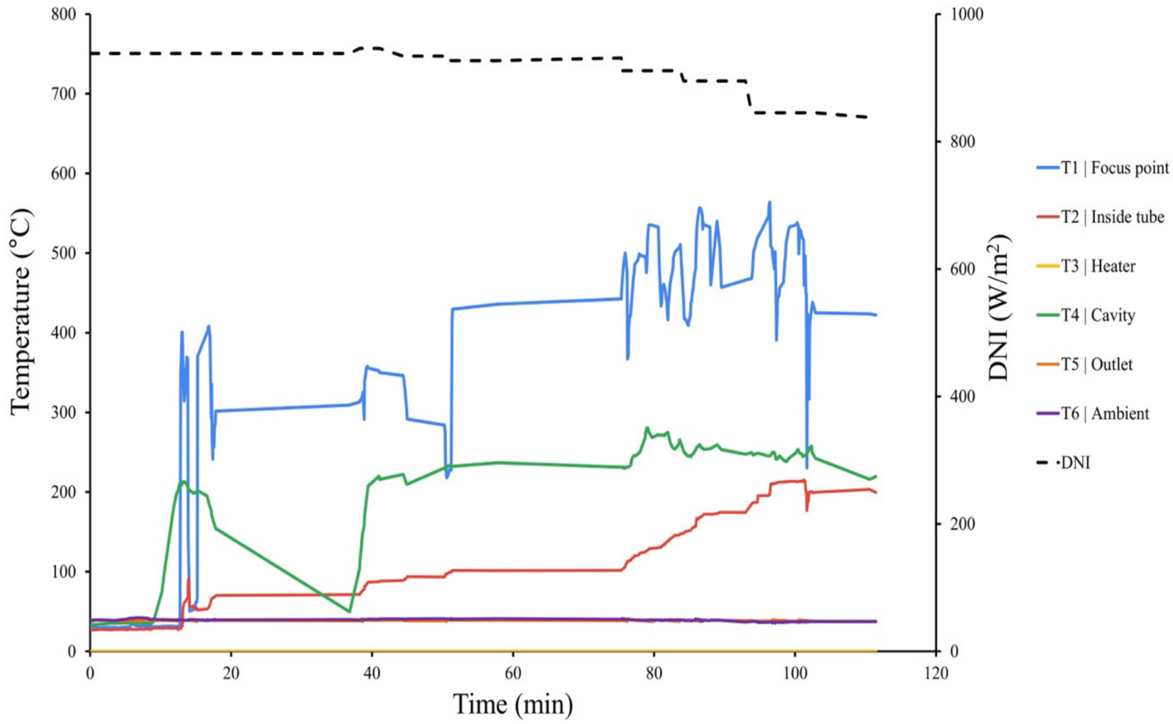

Figure 3. *Solar reactor temperature profile during on-sun heating.*

4.2 Off-sun heating

The solar reactor was electrically heated with 500 W input (half of the heater power capacity) during off-sun heating (Figure 4). The temperature evolution of the focal point (T_1) was compared with the inside tube (T_2). The temperature gap between T_1 and T_2 increased gradually with time, with T_1 reaching 300 °C and T_2 above 200 °C after 120 min. The gap between the two temperatures indicated temperature gradients in the reactor due to heat losses. Therefore, it is crucial to increase the reactor temperature by reducing heat losses, such as by adding more insulation in the reactor or reducing natural convection in the experimental area.

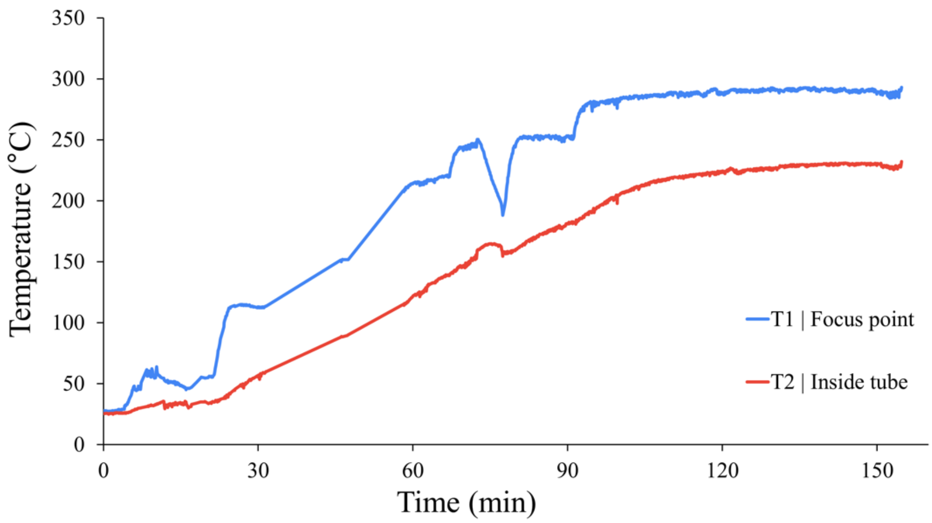

Figure 4. *Solar reactor temperature profile during off-sun heating.*

4.3 Hybrid heating

Figure 5 shows the temperature evolutions during the hybrid heating test (solar + electrical heat) of the solar reactor along with DNI values for 120 min. The hybrid heating system demonstrated improved performance, with the maximum temperature at the focal point (T_1) reaching 668 ºC, closely followed by the temperature in the reaction zone (T_2) at 545 ºC. Notably, the temperature rise was more rapid in the hybrid heating system compared to the system solely reliant on solar heat, chiefly because the global power input was roughly doubled. These findings highlight the enhanced thermal capabilities and efficiency of the hybrid heating approach. Thus, the additional heat source from the electrical heater was found to be beneficial for supporting the solar reactor with declining DNI.

In addition, in this test, air working fluid (6 NL/min) was also fed in the reactor for 20 min after 90 min duration to evaluate the reactor heating performance. As a result, the temperature inside the alumina tube (T_2) dropped reasonably to approximately 450 ºC at the expense of an increase in the outlet air temperature (T_5) above 100 ºC.

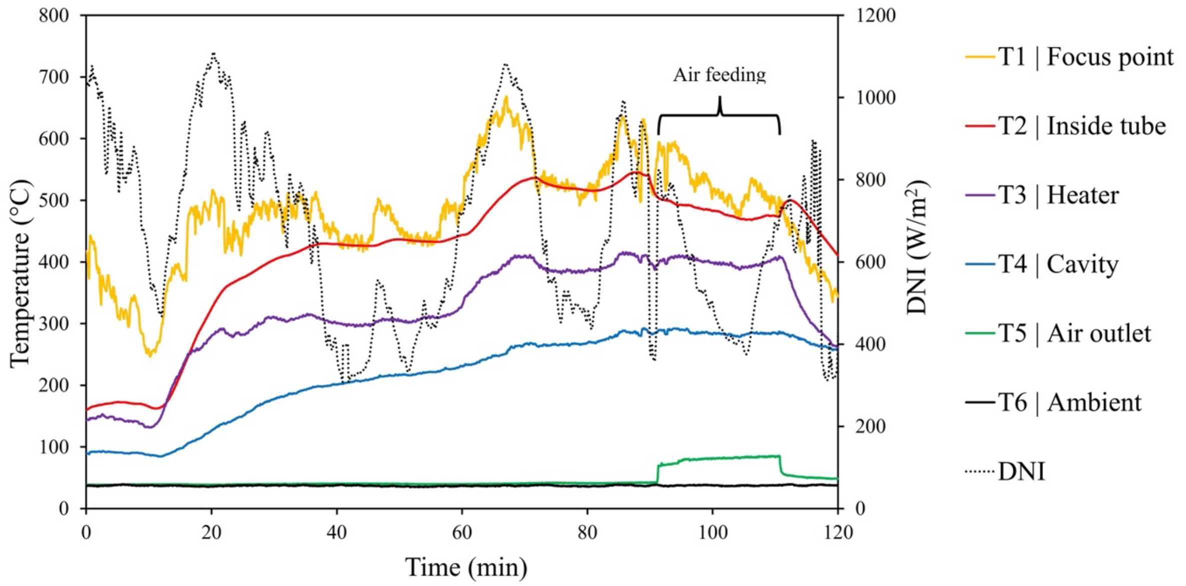

Figure 5. *Solar reactor temperature evolutions during hybrid heating.*

Figure 6 shows the evolution of the input hybrid power (Q_{in}, calculated from the summation of solar power and electrical power), absorbed power ($Q_{abs}= \dot{m}_{air} c_p \Delta T$, calculated from air flow-rate ($\dot{m}_{air}$, NL/min), air specific heat (c_p, kJ/kg/K), and air temperature difference (ΔT, K)), and thermal absorption efficiency as a function of time over 20 min during air feeding. As a result, the hybrid system exhibited an absorption efficiency of around 3-4% over time, with respect to Q_{in} values in the range 1500-2200 W (Figure 6). The absorption efficiency was quite low due to high heat losses, mainly from conductive losses, followed by radiative and convective losses, respectively. A fluctuation in Q_{in}, resulting from unstable solar input, led to an unstable efficiency. However, despite these variations, the amount of power absorbed (Q_{abs}) remained relatively stable at around 65 W. These results suggest the need for further optimization and control measures to improve the stability and overall efficiency of the hybrid heating system.

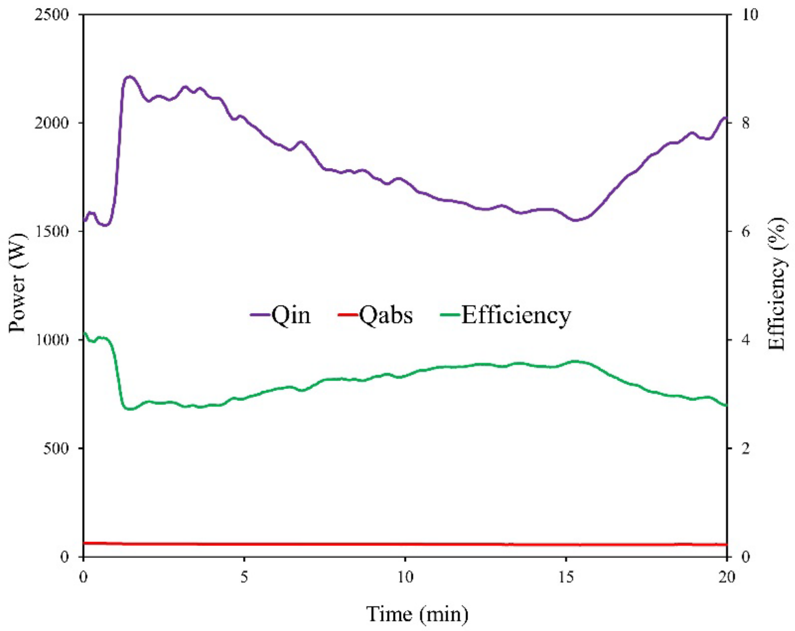

Figure 6. *Thermal efficiency during hybrid heating.*

5. Conclusion

An indirectly-irradiated solar hybrid reactor was successfully designed, fabricated, and tested. Experimental investigation on reactor temperatures and performance during on-sun, off-sun, and hybrid heating was carried out to support solar thermochemical conversion processes. As a result, the reactor can reach temperatures above 500°C for both on-sun and hybrid testing with a solar power input of 1 kW_{th} and electrical power of 1 kW_e. The thermal absorption efficiency was up to 4% at an air-flow rate of 6 NL/min. During on-sun testing, a fluctuation in the temperature of the focal point was encountered due to unstable solar power input. During hybrid testing, the reactor temperatures increased significantly and rapidly, pointing out the important assistance of electrical heating, which is very helpful for the solar reactor operation during unstable DNI. Increasing solar power input and reducing heat losses are required to increase the reactor temperature. Real-time automatic solar tracking is also necessary to keep a stable solar input. Future work will focus on the performance analysis of this solar reactor with thermochemical processes.

Data availability statement

The data presented in this study are available on request from the authors.

Author contributions

Atthawit Saengpradab: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Visualization, Writing- Original draft preparation. **Jirayut Tathong**: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Visualization. **Hattakit Kongsrichay**: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Visualization. **Srirat Chuayboon**: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Visualization, Writing- Reviewing and Editing, Supervision, Project administration, Funding acquisition. **Stéphane Abanades**: Validation, Visualization, Writing- Reviewing and Editing, Supervision.

Competing interests

The authors declare that they have no competing interests.

Funding

This work was financially supported by King Mongkut's Institute of Technology Ladkrabang (Grant number: 2564-02-08-002 and Grant number: KREF046404).

Acknowledgement

King Mongkut's Institute of Technology Ladkrabang and PROMES-CNRS are gratefully acknowledged for project collaborations.

References

[1] M. Kamran, Chapter 4 - Solar energy, in: M. Kamran, M.R. Fazal (Eds.), Renewable Energy Conversion Systems, Academic Press2021, pp. 109-152.

[2] J.J.C.S. Santos, J.C.E. Palacio, A.M.M. Reyes, M. Carvalho, A.J.R. Freire, M.A. Barone, Chapter 12 - Concentrating Solar Power, in: I. Yahyaoui (Ed.), Advances in Renewable Energies and Power Technologies, Elsevier2018, pp. 373-402.

[3] N. Chimres, S. Wongwises, Critical review of the current status of solar energy in Thailand, Renew. Sust. Energ. Rev. 58 (2016) 198-207. https://www.doi.org/10.1016/j.rser.2015.11.005.

[4] Z. Wang, Chapter 1 - Introduction, in: Z. Wang (Ed.), Design of Solar Thermal Power Plants, Academic Press2019, pp. 1-46.

[5] T. Kodama, S. Bellan, N. Gokon, H.S. Cho, Particle reactors for solar thermochemical processes, Sol Energy 156 (2017) 113-132. https://doi.org/10.1016/j.solener.2017.05.084.

[6] S. Chuayboon, S. Abanades, An overview of solar decarbonization processes, reacting oxide materials, and thermochemical reactors for hydrogen and syngas production, Int. J. Hydrogen Energy 45(48) (2020) 25783-25810. DOI: 10.1016/j.ijhydene.2020.04.098.

[7] S. Rodat, S. Abanades, H. Boujjat, S. Chuayboon, On the path toward day and night continuous solar high temperature thermochemical processes: A review, Renew. Sust. Energ. Rev. 132 (2020) 110061. https://www.doi.org/10.1016/j.rser.2020.110061.

[8] N. Piatkowski, C. Wieckert, A. Steinfeld, Experimental investigation of a packed-bed solar reactor for the steam-gasification of carbonaceous feedstocks, Fuel Process. Technol. 90(3) (2009) 360-366. https://www.doi.org/10.1016/j.fuproc.2008.10.007.

[9] H. Boujjat, S. Rodat, S. Abanades, Solar-hybrid Thermochemical Gasification of Wood Particles and Solid Recovered Fuel in a Continuously-Fed Prototype Reactor, Energies 13(19) (2020) 5217. https://www.doi.org/10.3390/en13195217.

[10] H. Boujjat, S. Rodat, S. Chuayboon, S. Abanades, Experimental and numerical study of a directly irradiated hybrid solar/combustion spouted bed reactor for continuous steam gasification of biomass, Energy 189 (2019) 116118. DOI: 10.1016/j.energy.2019.116118.

[11] X. Wang, S. Abanades, S. Chuayboon, J. Zhang, J. Wei, Solar-driven chemical looping reforming of methane over $SrFeO_{3-\delta}$-$Ca_{0.5}Mn_{0.5}O$ nanocomposite foam, Int. J. Hydrogen Energy 47(79) (2022) 33664-33676. https://www.doi.org/10.1016/j.ijhydene.2022.07.241.

[12] A.Saengpradab, J. Tathong, H. Kongsrichay, S. Chuayboon, An innovative solar reactor for thermochemical conversion process: concept design, fabrication, and temperature test, Conference Proceedings The 4th International Conference on Informatics, Agriculture, Engineering, Sciences and Technology: IAMBEST 2023, King Mongkut’s Institute of Technology Ladkrabang, Prince of Chumphon 2023, pp. 142.