Suitable technology developments for Batch Hydrothermal Liquefaction operation driven by solar energy

Eduardo Bautista-Peñuelas

Centro de Investigaciones en Óptica A.C. Unidad Aguascalientes Pról. Constitución 607, Fracc. Reserva Loma Bonita, CP 20200. Aguascalientes, Aguascalientes, México.

***Abstract-* In this paper, the working principles of different technologies are described. The main goal is to detail the instruments in the literature that can achieve a hydrothermal liquefaction operation to obtain biofuels from different biomass sources. This objective can be reached using solar energy as the main source, however different technological systems need to be coupled to drive these processes with only solar energy consumption. This feasibility study seeks to provide information on suitable solar technology, tracking systems, and reactor developments to drive hydrothermal operations in a suitable prototype design. Future work aims to operate modular hydrothermal batch systems to determine the feasibility and robustness of the operation with the main goal of describing prototype design performance and scalability in operation to produce industrial volumes of biofuel fabrication reducing environmental impact through this technological implementation.**

***Keywords:* Hydrothermal liquefaction, solar concentrating energy, biofuels.**

I. INTRODUCTION

Fossil fuels have suffered a constant depletion in recent times, the higher energy needs for social growth and the increase in environmental contamination challenges generate the need for alternate energy sources that must be sustainable and low-cost. The main objective is to keep society's needs and at the same time reduce global warming [1].
The first step is to determine a renewable source for sustainable fuel production. This question has become urgent in recent years [2] and one source of interest is biomass waste for this fuel production needs. The main characteristic of biomass waste is that is considered a renewable source since this kind of source grows in hand with population increments. Biofuels produced from biomass as the main source are named second-generation biofuels, the latter are considered renewable fuels [2].
One of the methods that is drawing attention is the thermochemical methods, these are divided into thermochemical and biochemical methods [3]. Thermochemical methods are divided into direct combustion, pyrolysis, and hydrothermal process. Hydrothermal process depends on the operation temperature at temperatures between 280° to 370° and (10 to 25 MPa) is often referred to as Hydrothermal liquefaction [3].
Hydrothermal methods require a significant amount of energy to carry out these reactions. Traditionally the energy is obtained through fossil fuel use. These kinds of fuels generate greenhouse gas (GHG) emissions, and consequently increase the ambiental impact of these process [4]. The main idea is to use concentrating solar energy to drive Hydrothermal reaction, at first sight, to produce environmentally clean biofuel using biomass wastes. In second sight this method produces a storage solar energy method on stable products like bio-oil produced from hydrothermal liquefaction.
Most of the studies in the literature are developed in batch reactor systems due to problems like pressure and sealing problems. For a full-scale application, it is used a continuous-flow operation scheme for biomass processing [5]. The reactor employed for HTL operation depends on the type of operation and are batch reactor and continuous flow reactor.
In the literature batch reactors had better quality products while continuous flow systems produced higher bio-crude yields. Control systems and monitoring are easier in batch configurations, compared to continuous reaction systems. Batch systems have found several applications in research terms, but they require to expand for bio-crude yield maximization or incorporate powerful heaters [5].
High reaction times are not desirable in standard batch reactors because repolymerization process has a chance to increase and decrease the final bio-oil yield [5]. For this reason, lower reaction times are needed and for solar reactions, the income solar flux needs to be high. Another consideration of the batch systems is the reactor headspace. This space needs to be purged but for major hydrothermal systems can represent an incremental operation cost [5].

Concentrated solar energy and concentrated solar power technologies manage mechanical and optical elements to concentrate solar radiation on small zones (focal point technology). Active solar tracking systems are needed to manage solar tracing on concentrating solar energy operations which is indeed considered mandatory [6].

In this study, a review of several technologies for batch solar-enhanced hydrothermal liquefaction systems is described. The main goal is to explore in the literature if exists backup technology to integrate and develop a solar-enhanced hydrothermal liquefaction (SEHTL) system, focusing on batch reaction operations. This is done to obtain batch hydrothermal technology at a low scale and continue to develop this technology to obtain a degree of maturity in this technology to obtain a full-scale HTL bio-oil production starting with low-scale designs.

II. METHODOLOGY

Solar hydrothermal systems are required to overcome different technical and operational challenges, the final idea is to obtain a conceptual system focusing on existing technologies. The main concern is to utilize developed technology because this ensures that these processes are suitable, new technology requires development, validation, and demonstration. Driven solar hydrothermal process with existing technology ensures that the technology is validated and works under certain schemes, even so coupling optical elements, control schemes, and climatic models to evaluate the relevance of this technology for solar hydrothermal and if a certain combination can ensure lead a successful hydrothermal liquefaction operation.

Exist several challenges for this thermochemical process to be realized with the aid of solar energy as the main energy source. Challenges in receiver/receptor configurations, temperature control, reactor types, and configuration among others. Intermittency of solar radiation leads to the establishment of reliable tracking technology to overcome these problems.

For this work, a literature overview is realized to detect actual and functional technology that can be implemented as a candidate for the solar-enhanced hydrothermal liquefaction process. Design of a functional prototype design may be established throughout available technology to obtain a robust batch operating device for bio-oil obtention.

Hydrothermal liquefaction for bio-oil production requires several control schemes and considerations, thus the discussion is going to be divided into four major elements: Suitable reactor, control and algorithms, optical elements, and wind conditions.

III. RESULTS AND DISCUSSION

Suitable reactor:

Several studies have worked in thermal configurations, mainly focused on pyrolysis reactions. The same as Hydrothermal operations for the pyrolysis process, the yield of the obtained products depends on the reactor temperature, for solar pyrolysis the intermittency of the source throughout the day decreases overall production. The first point of notice is to develop a prototype of a hydrothermal solar system that has full control of operating parameters. This needs to be done to ensure thermal reactor stability and control [7].

Reaction time depends on the reactor (receiver) geometry and the desired reaction time and pressure conditions. Sun tracking is required in the solar-enhanced hydrothermal liquefaction process. The cooling process needs to be considered to allow cooling reactor conditions. If multiple reactors are used the tracker must continue to drive multiple reactions.

An important condition is that the reactor used in a solar hydrothermal prototype design can be operated with the solar resource as a main energy source, hydrothermal batch reactors available for commercial acquisition are batch stainless steel reactors with direct heating through reactor walls to sustain reactions via conduction heat transfer. Is important to analyze if these candidates can drive solar-enhanced hydrothermal reactions without “optical enhancement” elements. Ayala-Cortés, A., et. al., (2022) [8,9] performed hydrothermal liquefaction reactions are carried out in a 25-kW solar furnace. These experiments are driven with a reactor designed to enhance hydrothermal liquefaction conditions (max: 220 bar and 500°C) a batch-reactor prototype 304 stainless steel. This reactor is made without optimum enhanced “optical properties” unlike thermochemical storage-enhanced reactors [10-12]. These optical-enhanced reactors employ window apertures for radiation that enters the reactor cavity. Experiments in [8,9] that use steel reactors of standard fittings with the steel walls of the reactor directly radiated to enhance hydrothermal reactions. The validation of the use of this kind of equipment indicates that commercial steel reactors are candidates for hydrothermal solar technology.

The direct irradiated walls of steel reactors can approach high temperatures [8], it needs to reduce the differences between non-irradiated walls and the direct irradiated face of the reactor. This could produce temperature differences inside the reactor and differences in the biomass conversion that can promote char and other product conversion. An attempt to reduce these differences in external and internal temperatures along steel reactors is to develop a rotational device to reduce temperature differences and improve bio-crude conversion. This can be done to avoid reactor modifications in terms of wall thickness or to incorporate optical transparent elements that need to be validated in a reactor hydrothermal design.

Tracking and collector control/algorithms:

The geometrical design of the collector is important to determine the tracking mechanism to be implemented [13]. The tracker system will trigger the mechanical components where the maximum direct irradiance is and collect the sunlight, the system then will follow the sun's path along the day. Two types of tracking system configurations exist, active and passive systems.

Active systems use motors and gears to follow solar direction, while concentrated focal point technologies are composed of several different components, the type and size of components increment the energy system requirements and complexity. Additionally, the energy consumption of these systems should be less than 3% of the increased energy in the system [6].

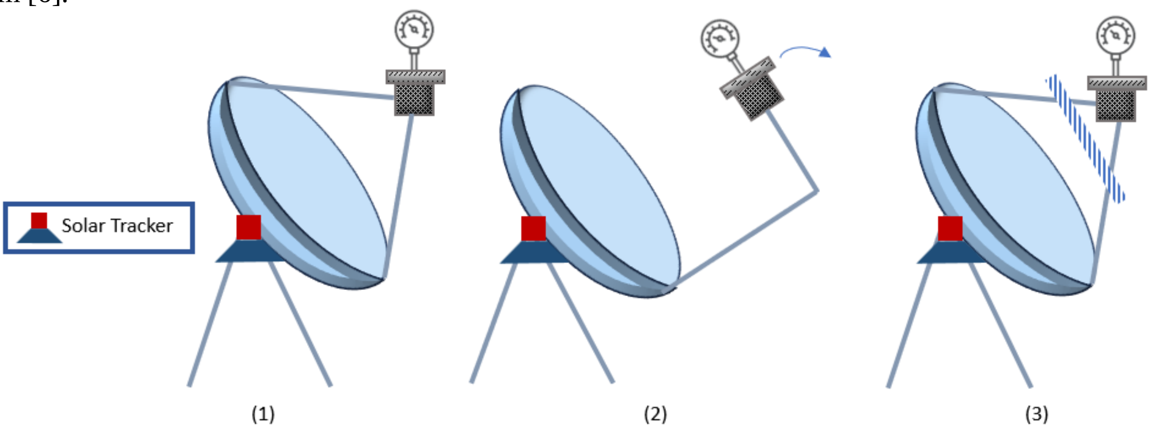

Figure 1. Solar tracker configurations for hydrothermal batch reactors. Solar tracker traditional mount to the parabolic dish (1), Parabolic dish with a controlling axis for reactor manipulation (2), Traditional mount with an attenuator structure, to control the temperature of the receiver (reactor) (3).

For a parabolic dish with a batch reactor system, three types of layouts can be implemented and called: Traditional: Reactor as a solar receptor at the center of the focal point spot of the receiver. Independent system: Solar tracking for the dish receiver and a system to center the reactor in the focal point spot of the receiver. Attenuator system: reactor as a solar receptor at the focal point spot with an attenuator to control the temperature (Figure 1).

Traditional tracking systems are dedicated to tracking the sun's path the entire day to obtain maximum system efficiency. For batch hydrothermal liquefaction process, requires that the reactor is heated to a certain operating temperature, sustains a control temperature to ensure a certain holding time, and reduces the temperature to ambient for the collection and separation of products.

Several two-axis tracking systems were developed for multiple applications, photovoltaic concentrating technologies require solar tracking to enhance solar energy in PV applications. Natarajan, S. K., et., al., (2019) [14] reports a two-axis tracking system for a solar parabolic dish collector. The receiver used is a PV panel and has an aperture area of 0.00984 m2. The system described increases the concentration ratio and the surface temperature, in this case, a PV panel.

Active tracking systems require the use of devices such as light-dependent resistors (LDR) to track the sun's position in real-time. Parthipan, J., et., al., (2016) [15] Develop an automatic solar tracking system. It uses light-dependent resistors LDR to track the sunlight position and a PIC (Programmable Interface Controller) controller. This device is fixed in the parabolic dish concentrator and collects maximum solar radiation throughout the day.

Measure the concentration ratio achieved with solar tracking ensures the obtention of maximum flux harvest in the focal point/line of the receiver [16]. Sahu, S. K., et., al., (2021) [17] Presents a novel design on parabolic dish concentrator. The main characteristic is that is a low-cost design with a 12.6 m2 aperture area and a dual-axis manual tracking scheme. It can generate a solar image area of 0.027 m2 and a geometric concentration ratio of 467. The area of 0.027 m2 corresponds to an approximate area of 16.5 cm*16.5cm, several commercially available reactors of similar sizing correspond to approximate volumes of 500 ml reactors, which makes this kind of device fitting for hydrothermal applications.

Yeh, P. Y., et., al., 2011 [18] Propose a dual-axis system that moves the receptor (solar transducer) along the solar path with a fixed concentrating lens configuration. This system is suitable for vertical applications like building walls and consumes less energy due that the heavy concentrating lens and heavy elements don’t require mechanical movement. This work demonstrates that the evaluated system can achieve solar conversion as the conventional systems. The adaptation capacity of the tracking systems to be employed for the solar-enhanced hydrothermal liquefaction process for bio-oil production is remarked.

Optical elements:

Several focal point solar concentrating technologies are available. Know which technology is more suitable for hydrothermal liquefaction in terms of efficiency, cost, technology readiness, and ease of implementation. Xie, W. T., et., al., (2011) [19] Developed a Fresnel collector and evaluated different receivers due to their geometry and analyzed the thermal distribution. Convection heat transfer is considered, and geometric concentration ratio was obtained and tested with 50 mm aperture diameter cavities. It was found that the optical concentration ratio for this experiment is found to be between 279 and 295. High concentration optic ratio favors hydrothermal liquefaction reactions, Natraj, Rao, B. N., & Reddy, K. S. (2021) [20] developed a comparative study between Parabolic dish and Fresnel lens devices and found that the optical concentrating factor is higher for parabolic dish configuration in respect to a Fresnel lens with the same geometrical concentrating factor.

Overall system cost is important to determine viability of proposed designs, Hijazi, H., et., al., (2016) [21] Design a low-cost parabolic dish concentrator and evaluate three dish diameters: 5, 10, and 20 m. This design is constructed based on an appropriate dimensions scheme using an appropriate reflecting surface to be cut from available commercial sheets to reduce overall costs. These insights show that a suitable, low-cost, scalable, and appropriate technology with a high optic concentration ratio is the parabolic dish solar concentrator.

Wind conditions:

Computational fluid dynamics (CFD) is used to evaluate wind load's impact on overall structure, and convection and radiative heat losses on collectors and receiver efficiency. CFD modeling is suitable for probing and understanding the performance of a design without the need for empirical model testing. CFD modeling requires accurate boundary conditions, and material properties as inputs and be a sufficient representation of the actual system [22].

Some of these fluid dynamic models are used to evaluate the wind flows over the receiver in solar concentrating technologies. Kim, K., et., al., (2010) [23] performs a study on wind flows over solid particle receivers, these receivers require heat inputs at temperatures up to 1000°C. The main objective was to gain insight into wind effects to understand wind influence on receiver thermic losses. The experimental results show that at certain angles of wind, flow can cause a critical loss in temperature.

For different receiver types and geometry, the local wind conditions play an important role in design performance. This is the case for a condenser that for a specific location, design and orientation with historical conditions and local wind distributions need to be considered to optimize a specific design [24].

Table 1. Suitable technology for solar-enhanced hydrothermal liquefaction systems at batch operation.

Technology	Description
Collector: Parabolic dish focal point	Suitable for hydrothermal operation, mature technology, and low-cost configuration options, and has a higher optical concentration factor than the Fresnel lens [25].
Tracking system: Dual-axis active tracking system	Suitable for parabolic dish option, mature technology, and adaptable algorithm configurations due to intermittency in tracking for reaction time parameters (wide versability).
Receiver: AISI Batch hydrothermal technologies	Demonstrated solar operation, mature technology, different size configurations, and easier to operate than other reactors due to size, shape, and operation regime.
Suitable wind models:	Fluid dynamic model (MFIX simulation model).

Table 1 lists possible candidates for hydrothermal solar enhanced batch operation for bio-fuel production. Several challenges like reactor homogeneity [9] and a wind model proposition to evaluate wind loading on mechanical and structural design need to be considered in a developing prototype phase [20].

IV. CONCLUSIONS

Suitable actual technology for achieving solar-enhanced hydrothermal biomass liquefaction was discussed. From suitable optical collector focal point technology to receiver (reactor commercial systems) suitable devices. Mostly to have sight of the adequate implementation of commercial gadgets and mechanisms to drive hydrothermal liquefaction batch reactions in point focal prototypes to enhance bio-oil production.

There is a great technology diversity, optical elements like parabolic dish concentrators, and Fresnel lenses with commercial AISI batch reactors that are non-optical enhanced and operate through direct heat exchange via reactor wall heating can be a promising alternative. Minor modifications to control systems like sun-tracking mechanisms can be implemented to drive these reactions in a functional prototype design.

Couple new strategies like thermal homogenization of the reactor and wind models over the prototype design can make that convection losses and thermic reactor losses can be considered more effectively. Future work aboard functional prototype design schemes is required, and demonstrative scale efforts needs to be conceived to have a fully operational industrial hydrothermal bio-oil production to have a first step to automate this kind of renewable oil production.

V. ACKNOWLEDGMENT

Eduardo Bautista Peñuelas gratefully acknowledge the support of INCyTEA (Instituto de Ciencia y Tecnología del Estado de Aguascalientes) through "Fondo Estatal de Innovación tecnológica" in its 2023 edition for the partial support of this work.

REFERENCES:

1. Gollakota, A. R. K., Kishore, N., & Gu, S. (2018). A review on hydrothermal liquefaction of biomass. In Renewable and Sustainable Energy Reviews (Vol. 81, pp. 1378–1392). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.05.178
2. Naik, S. N., Goud, V. v., Rout, P. K., & Dalai, A. K. (2010). Production of first and second generation biofuels: A comprehensive review. In Renewable and Sustainable Energy Reviews (Vol. 14, Issue 2, pp. 578–597). https://doi.org/10.1016/j.rser.2009.10.003
3. Toor, S. S., Rosendahl, L., & Rudolf, A. (2011). Hydrothermal liquefaction of biomass: A review of subcritical water technologies. In Energy (Vol. 36, Issue 5, pp. 2328–2342). Elsevier Ltd. https://doi.org/10.1016/j.energy.2011.03.013
4. Sobek, S., & Werle, S. (2019). Solar pyrolysis of waste biomass: Part 1 reactor design. Renewable Energy, 143, 1939–1948. https://doi.org/10.1016/j.renene.2019.06.011
5. Basar, I. A., Liu, H., Carrere, H., Trably, E., & Eskicioglu, C. (2021). A review on key design and operational parameters to optimize and develop hydrothermal liquefaction of biomass for biorefinery applications. In Green Chemistry (Vol. 23, Issue 4, pp. 1404–1446). Royal Society of Chemistry. https://doi.org/10.1039/d0gc04092d
6. Fuentes-Morales, R. F., Diaz-Ponce, A., Peña-Cruz, M. I., Rodrigo, P. M., Valentín-Coronado, L. M., Martell-Chavez, F., & Pineda-Arellano, C. A. (2020). Control algorithms applied to active solar tracking systems: A review. In Solar Energy (Vol. 212, pp. 203–219). Elsevier Ltd. https://doi.org/10.1016/j.solener.2020.10.071
7. Rahman, M. A., Parvej, A. M., & Aziz, M. A. (2021). Concentrating technologies with reactor integration and effect of process variables on solar assisted pyrolysis: A critical review. Thermal Science and Engineering Progress, 25. https://doi.org/10.1016/j.tsep.2021.100957
8. Ayala-Cortés, A., Arcelus-Arrillaga, P., Pacheco-Catalán, D. E., Arancibia-Bulnes, C. A., & Villafán-Vidales, H. I. (2022). Solar hydrothermal liquefaction: Effect of the operational parameters on the fuels. MRS Advances, 7(2–3), 24–27. https://doi.org/10.1557/s43580-021-00204-z
9. Ayala-Cortés, A., Arcelus-Arrillaga, P., Millan, M., Okoye, P. U., Arancibia-Bulnes, C. A., Pacheco-Catalán, D. E., & Villafán-Vidales, H. I. (2022). Solar hydrothermal processing of agave bagasse: Insights on the effect of operational parameters. Renewable Energy, 192, 14–23. https://doi.org/10.1016/j.renene.2022.04.059
10. Ermanoski, I., Siegel, N. P., & Stechel, E. B. (2013). A new reactor concept for efficient solar-thermochemical fuel production. Journal of Solar Energy Engineering, Transactions of the ASME, 135(3). https://doi.org/10.1115/1.4023356
11. Koepf, E., Villasmil, W., & Meier, A. (2016). Pilot-scale solar reactor operation and characterization for fuel production via the Zn/ZnO thermochemical cycle. Applied Energy, 165, 1004–1023. https://doi.org/10.1016/j.apenergy.2015.12.106
12. Tregambi, C., Padula, S., Galbusieri, M., Coppola, G., Montagnaro, F., Salatino, P., Troiano, M., & Solimene, R. (2020). Directly irradiated fluidized bed reactor for thermochemical energy storage and solar fuels production. Powder Technology, 366, 460–469. https://doi.org/10.1016/j.powtec.2020.02.045
13. AEEICB 2. 2016 Chennai, Beulah Devamalar, P. M., Thulasi Bai, V., Moorthi, M., Institute of Electrical and Electronics Engineers, International Conference on Advances in Electrical & Electronics, I., IEEE International Conference on Advances in Electrical, E., & AEEICB 2 2016.02.27-28 Chennai. (2016) 2nd International Conference on Advances in Electrical & Electronics, Information, Communication & Bio-Informatics AEEICB - 2016, 27th & 28th February.
14. Natarajan, S. K., Thampi, V., Shaw, R., Kumar, V. S., Nandu, R. S., Jayan, V., Rajagopalan, N., & Kandasamy, R. K. (2019). Experimental analysis of a two-axis tracking system for solar parabolic dish collector. International Journal of Energy Research, 43(2), 1012–1018. https://doi.org/10.1002/er.4300
15. Parthipan, J., Nagalingeswara Raju, B., & Senthilkumar, S. (2016). Design of one axis three position solar tracking system for paraboloidal dish solar collector. Materials Today: Proceedings, 3(6), 2493–2500. https://doi.org/10.1016/j.matpr.2016.04.167

16. Foulaadvand, M. E., Aghamohammadi, A., Karimi, P., & Borzouei, H. (2021). Flux profile at focal area of concentrating solar dishes. Scientific Reports, 11(1). https://doi.org/10.1038/s41598-021-03768-w
17. Sahu, S. K., Arjun Singh, K., & Natarajan, S. K. (2021). Design and development of a low-cost solar parabolic dish concentrator system with manual dual-axis tracking. International Journal of Energy Research, 45(4), 6446–6456. https://doi.org/10.1002/er.6164
18. Yeh, P. Y., Yen, P. C., Yen, J. Y., Wu, T. T., Liu, P. L., Wu, C. L., & Peng, C. Y. (2011). Focal point tracking system for concentration solar power collection. In Renewable and Sustainable Energy Reviews (Vol. 15, Issue 6, pp. 3029–3033). Elsevier Ltd. https://doi.org/10.1016/j.rser.2011.03.011
19. Xie, W. T., Dai, Y. J., & Wang, R. Z. (2011). Numerical and experimental analysis of a point focus solar collector using high concentration imaging PMMA Fresnel lens. Energy Conversion and Management, 52(6), 2417–2426. https://doi.org/10.1016/j.enconman.2010.12.048
20. Natraj, Rao, B. N., & Reddy, K. S. (2021). Wind load and structural analysis for standalone solar parabolic trough collector. Renewable Energy, 173, 688–703. https://doi.org/10.1016/j.renene.2021.04.007
21. Hijazi, H., Mokhiamar, O., & Elsamni, O. (2016). Mechanical design of a low cost parabolic solar dish concentrator. Alexandria Engineering Journal, 55(1), 1–11. https://doi.org/10.1016/j.aej.2016.01.028
22. Ho, C. K. (2014). Computational fluid dynamics for concentrating solar power systems. Wiley Interdisciplinary Reviews: Energy and Environment, 3(3), 290–300. https://doi.org/10.1002/wene.90
23. Kim, K., Moujaes, S. F., & Kolb, G. J. (2010). Experimental and simulation study on wind affecting particle flow in a solar receiver. Solar Energy, 84(2), 263–270. https://doi.org/10.1016/j.solener.2009.11.005
24. Butler, C., & Grimes, R. (2014). The effect of wind on the optimal design and performance of a modular air-cooled condenser for a concentrated solar power plant. Energy, 68, 886–895. https://doi.org/10.1016/j.energy.2014.01.086
25. Renno, C. (2022). Energy and economic comparison of three optical systems adopted in a point-focus CPV system. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 44(3). https://doi.org/10.1007/s40430-022-03408-y