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Review

Review of solar-biomass pyrolysis systems: Focus on the configuration of thermal-solar systems and reactor orientation

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ABSTRACT

Solar energy and biomass produce energy, which is sustainable and does not harm our environment. This characteristic of the two-energy feedstock is harnessed using the pyrolysis method to produce liquid and gaseous fuel that is transportable while bio-char regarded as a by-product has found usefulness in soil amendments. Solar-biomass pyrolysis technology combines these two low-density energy feedstock to produce high energy density fuel. The effectiveness of this process depends not only on the feedstock or reaction dynamics but also on the solar-thermal systems and reactor configuration. This review addressed the benefits of solar-biomass pyrolysis, available optical concentrating device, conceptual heating modes, the existing configuration of solar-thermal and reactor orientations, and some basic model equations applied in solar biomass pyrolysis.

Contents

1. Introduction

The world population has continued to increase which demands increased energy consumption. Researchers have postulated that by 2050, the global population will hit 9.3 billion people (Crossette, 2011). This awesome population will require a lot of

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Nomenclature

A,	Surface area of the reactor or Arrhenius pre-exponential factor
Aα	Pre-exponential factor of given α
c	Circumference (m) or char
a_j and b_j	Concentrations of the reactant and product of the j elementary step, usually expressed using reaction extent, as (1- a) and a
Ea, E	Activation energy, J/mol
C	Cartesian coordinates
C_P	specific heat capacity
v_g	gas superficial velocity
m_o,	Initial mass
m_t	Mass at any time t
m_f	Final residue mass
k_{eff}	Effective thermal conductivity
g	Gas mixture phase,
h	Enthalpy W/m^2 ∘C
i	i-th heating rate, or ith component of the phase
M	Molecular weight, kg/mol,
P	Pressure, N/m2,
Pg	Pressure in the gas mixture phase, N/m^2,
q_0	Concentrated radiation, W/m^2
R_0 or R	Universal gas constant J/(mol K),
s	Solid phase, boundary surface
SD	Dry solid biomass,
Ta,i	Temperature corresponding to given a of i-th heating rate
T_{fis}	Final
T	Absolute Temperature (K)
Δhi	Heat of pyrolysis, J/kg

Symbols

$\alpha_{reactor}$	Absorbance of the reactor fraction
$\alpha_{biomass}$	Absorbance of the biomass, fraction
$\tau_{reactor}$	Transmittance of the reactor, fraction
η_{optic}	Optical efficiency
η_{focus}	Focus efficiency
φ	Distribution of the irradiation (W/m^2)
ρ	Density of phase, kg/m^3
ϵ	Volume fraction,
α	The feed stock conversion or normalized mass
η	Interpolation factor
W_i	Rrate of consumption or production of products
β	Temperature increase at a given time
f,(α)	suitable reaction model
*β*i	Differential α versus temperature T

energy resources to sustain the daily energy demand. Again, climate change is a big global issue and the demand for clean energy is now necessary all over the world. Although the global reserves for fossil fuel are fast diminishing, however, the focus is an entire shift away from it due to its environmental challenges that aggravate climate change. Emphasis is on the tapping of renewable energy resources mostly from solar and biomass conversion to produce solar energy and biofuel. These two processes are sustainable and can solve global energy needs. Another advantage of this is that they can convert waste generated in the agricultural process and other agro-allied and similar industries to wealth. This will solve the problem of waste dumping which sometimes poses human health hazards. The processes involved also generates not the only biofuel but additionally, it produces biogas, bio-oil, and biochar (McKendry, 2002; Lehmann and Joseph, 2009; Brown, 2009; Deal et al., 2012; Lehmann et al., 2006; Verheijen et al., 2009; Yao et al., 2011; Vamvuka, 2011). Sharma et al. (2015) defined biomass as any mixture of hydrocarbon material comprising of carbon, hydrogen, and oxygen with trace elements of sulfur and nitrogen. The content of these organic and inorganic constituents can vary from 1 to 50 % depending on the biomass type (Fitz et al., 1996; Zabaniotou, 1999; Yaman, 2004). One of the major methods involved in the biomass conversion is the thermal reduction of these biopolymers available in the biomass in the absence of oxygen known as pyrolysis (Ringer et al., 2006; Morales et al., 2014; Papari and Hawboldt, 2015).

Generally, polymeric materials, extractives, and minerals are components of biomass (Yaman, 2004; Sharma et al., 2015). The distribution of these elements during pyrolysis contributes to the product yields. The yield of liquid biofuels in pyrolysis is majorly due to hemicellulose and cellulose decomposition while Lignin degenerates to liquid, gas and solid bio-char products (Grønli, 2003). Ash is retained in the biochar as minerals while the extractives contribute to gas and liquid by-products by decomposition or volatilization (Brownsort, 2009).

According to Sharma et al. (2015), initially, pyrolysis studies focused on the decomposition of coal (Shen et al., 2000; Yip et al., 2007). Tyler (1979) studied flash pyrolysis of coals in a small fluidized-bed reactor. Wiktorsson and Wanzl (2000) studied Kinetic parameters for coal pyrolysis at low and high heating rates. Baumann et al. (1988) studied Pyrolysis of coal in hydrogen and helium plasmas while Bittner et al. (1985) studied the relationship between coal properties and acetylene yield in plasma pyrolysis. Das (2001) studied the evolution features of gases during the pyrolysis of the maceral concentrates of Russian coking coals. Casal et al. (2005) studied low-temperature pyrolysis of coals with diverse coking pressure features. Zhou et al. (2005) studied the effect of the atmosphere on the development of sulfur-containing gases in coal pyrolysis. Although biomass and coal are carbonaceous feedstock, they differ in density, cellulose content, lignin content, and structural matrix that influence residence time in the pyrolysis process during thermal reduction.

The thermal reduction in pyrolysis takes place in the reactor. These reactors can be fixed bed reactors, fluidized beds, ablative systems, kilns and drums, plasma type, auger type, microwave reactor and free-fall type of different configurations and operating mode. However, the fluidized bed and the auger reactors are the most common type of reactors because of the rapid temperature rise of the feedstock due to good heat and mass transfer (Meier and Faix, 1999). The flow processes of some of these reactors in conventional pyrolysis can be fast (fast pyrolysis) or slow (slow pyrolysis) with operating temperature in the range of 673–973 °K (Sharma et al., 2015) depending on the product. Maschio et al. (1992) further classified this process into Torrefaction, flash, fast, and slow pyrolysis at different operating temperatures. Elsewhere, published literature exists on several reviews work on the biomass pyrolysis technology using fossil fuel, microwave, or plasma as a heat source (Macquarrie et al., 2012; Chaouki, 2013; Motasemi and Afzal, 2013; Papari and Hawbodlt, 2015). Researchers have reviewed the feedstock, product yield, kinetics and models for different biomass materials (Atkinson et al., 2010; Sohi et al., 2010; Bridgwater, 2012; Chen et al., 2014; Qian et al., 2015; Sharma et al., 2015). However, review focusing on solar-biomass pyrolysis is still scarce (Morales et al., 2014; Herron et al., 2015, Tuller, 2017) especially the concentrator and reactor design arrangements for optimum results.

Pyrolysis takes place at elevated temperatures in the absence of oxygen. Therefore, to attain the desired temperature requires heat energy (Basu, 2010). Most times this heat energy is generated using fossil fuel, which generates greenhouse gases that negatively affect the environment. To solve this problem, researchers have focused or used optical devices to concentrate solar energy to a tubular reactor or directly to the material (Bashir et al., 2017). This can be achieved by focusing the solar radiation heat on a small area through the walls of the reactor or direct irradiation of the feedstock, which raises the temperature of the feedstock while the reactor, is at a lower temperature (Nzihou et al., 2012; Morales et al., 2014). Application of optical devices like concentrators redirects solar radiation energy from a large area and concentrates them on a smaller area producing a temperature as high as 1000 °C depending on the capacity of the concentrator. Therefore, researchers have used different arrangements of the thermo-solar-reactor systems installations made up of the collector, concentrator, the reactor and the support architectures to achieve a different level of efficiency (Sobek and Werle, 2019). Focusing the radiation at various angles while the reactors are positioned either vertically or horizontally. The target of this review is to collate and analyze these thermo-solar-reactor systems set up/arrangements and the results obtained. Understanding the solar thermal reactor design for biomass pyrolysis is key in capturing adequate solar irradiance to attain the desired pyrolysis temperature and efficient liquid collection. This has become necessary due to the global pursuit to eliminate non-renewable energy applications in the energy demand chain.

2. Solar-biomass pyrolysis potential

Solar and biomass generate sustainable energy that is harmless to our environment (Almasoud et al., 2015, Okonkwo et al., 2018). This characteristic of the two-energy feedstock is harnessed using the pyrolysis method to produce liquid and gaseous fuel that is transportable. However, tar regarded as a by-product is used in soil amendments. Solar –biomass pyrolysis technology combines these two low-density energy feedstocks (solar energy and biomass) to produce high energy density fuel (Piatkowski et al., 2009; Chueh et al., 2010) and eradicate keen interest in the storage of solar energy. Therefore the process allows solar energy to be stored as bio-fuel or tar, thereby converting solar energy to chemical compounds (Chueh et al., 2010). These byproducts produced do not suffer contamination from external combustion fuel (Weldekidana et al., 2019). The utilization of high powered dish receiver, or concentrators, helps to attain the initial pyrolysis temperature at a shorter time (high heat flux) compared to fossil fuel heating, and the rate of heating can be controlled (Zeng et al. (2015a). Besides, it boasts reactivity because of a more functional site that decreases the residence time of the tar vapour in pores and shortens the condensation reaction. Therefore, more oxygen and hydrogen in the chair retained, due to low carbon content caused by the increased heating rate for solar-biomass pyrolysis (Zeng et al., 2015b; Laurendeau, 2009). Accordingly, solar biomass pyrolysis generates more gas with high heating values per unit of feedstock and cleaner than those generated by other heating methods produced (Puig-Arnavat et al., 2013; Weldekidana et al., 2019). Transportation of biomass feedstock consumes a lot of fossil fuel that increases the running cost of the pyrolysis plant, adopting the same fossil fuel or electricity for heating will encroach into the profits of companies. Therefore, the adoption of solar thermal heating will help to overcome the above challenges ((Puig-Arnavat et al., 2013). Also, it produces no nitrogen gas and at the same time, no toxin released to the environments. The major problem of solar biomass pyrolysis involves the individual negative attributes of solar energy and biomass processing. Ordinarily, biomass has some undesirable fuel features, which include, being bulky, low energy density and high initial moisture content; therefore, biomass might require a pre-processing operation before they can be used which will add to the initial running cost. Additionally, a biomass-based process produces fouling and corroding contaminants formed from chemical elements, which is part of the by-products (Nzihou, 2010). The absorbing optical properties of biomass are low due to high reflectivity, therefore producing more chars than bio-oil (Lédé, 1998; Bashir et al., 2017). This will be a disadvantage if the interest is biofuel but can be an advantage if the interest is for producing biochar for soil enrichment. Also, solar insolation apart from being intermittent (which will interfere in the rapid transient response of the solar system) in heat supply, has low energy density and requires concentrators or supplementary heat support for the pyrolysis (Adinberg et al., 2004).

3. Conceptual heating modes in solar-biomass pyrolysis

The method of heat transfer to the biomass is a major design consideration in the solar-assisted pyrolysis system assembly. Solar assisted pyrolysis is mostly fast pyrolysis and an endothermic process that demands a lot of energy. Therefore, various adopted heating concepts exist depending on available resources. The application of solar heating in solar-biomass pyrolysis can be in a hybrid model where the heating process is partially assisted with other supplementary heat sources (Joardder et al., 2014). Most medium range concentrator can only produce temperature range of 100 to 500 °C (World Energy Council, 2013) which will not be enough for the pyrolysis process to undergo both the primary and secondary reaction process (at 400–900 °C), therefor additional heat energy is required to raise the biomass temperature further. Another reason is the non-continuous nature of solar insolation that makes solar applications characterized by both sunshine and off—sunshine periods (Ndukwu et al., 2018; Ndukwu and Bennamoun, 2018; Simo-Tagne et al., 2019; Ndukwu et al., 2020a, 2020b). However, in a situation of no sunlight or low solar insolation, artificial light simulator (Tungsten lamp; Xenon arc lamps; carbon arc lamps; Halogen lamps, Super Lasers, etc.) with similar visible spectra wavelength (400 to 700 nm) and emissive power as solar radiation were adopted (Esen et al., 2017; Weldekidan et al., 2018). Therefore, solar pyrolysis can also be categorized based on the natural and artificial sources of rays (Sobek and Werle, 2019). Another heating mode is to continuously heat or irradiate the biomass feedstock with only solar heat. Three methods of heat transfer to the biomass are available which are direct, indirect (heat absorbed first by a black body that formed the reactor wall and transferred to the biomass by conduction) or through an intermediate transfer fluid (supercritical water, molten salt or gas–solid suspension) (Adinberg et al., 2004; Kodama et al., 2010). In an intermediate fluid heat carrier, the fluid is heated up first, before transferring to the reaction bed and the process is continuously recycled. The concentration of the solar heat is by the use of high-powered concentrators with receivers that collates and focuses the radiation on or through the reactor wall (Weldekidana et al., 2019). Another method reported is using solar energy to produce electrical power to create a plasma condition from the gaseous fluid. This method scale up the energy efficiency of solar energy and high temperature will be generated (Nzihou et al., 2012). Generally, the method of continuous heating with only solar radiation provides a significant environmentally friendly heating process, unlike hybrid heating. Nevertheless, the pyrolysis of biomass produces a significant amount of CO_2 that can be mitigated with the help of catalysts by some researchers (Liu et al., 2014). Keeping the reactor surface free of dust envelops and overcoming the temperature range drawback presented by the black body (if indirect irradiance is adopted) is important for efficient operation (Adinberg et al., 2004; Kodama et al., 2010).

4. Solar receivers and concentrators

Powering solar radiation to achieve the desired temperature requires a support system to boost the solar flux density. World Energy Council (2013) reported that on the surface of the earth the average horizontal surface irradiance is 170 to 300 W/m^2 which can produce ambient temperature conditions of less than 50 °C. This value cannot power a pyrolysis process. Therefore over the years, researchers have used optical devices to boast this solar radiation density in several energy systems. These applications range from the use of flat plate collectors in solar drying or water heating (Ndukwu et al., 2017) to a high-energy industrial application like power generations using central dish receivers. The choice of an optical device is a function of the temperature range desired. Available concentrating and non– concentrating optics includes flat plate collectors (non-concentrating and temperature range less than 100 °C), parabolic, mirror trough or dish (100 to 500 °C), linear mirrors (about 9 kW thermal power), linear Fresnel and central dish receivers ($\geq$1000 °C) (Grassmann et al., 2015; Morales, 2014). Fig. 1 shows different optical concentrating devices (Citossi and Cobal, 2018). Additionally, in solar –biomass pyrolysis using light simulators, researchers have utilized elliptical reflectors, or mirrors (non-imaging optical tool), deep-dish parabolic mirror and lamp reflector to direct the radiation beam through the reactor window (Pozzobon et al., 2014; Weldekidana et al., 2019). Research shows that to achieve the desired temperature (often in the range of 300–900 °C); these concentrators can be increased in number for a singular process as shown by Pozzobon et al. (2014). However, no matter the type of concentrating device adopted proper installation arrangement is crucial to achieving thermal decomposition of biomass and proper liquid collection.

5. Thermal-solar systems and reactor orientations

To achieve efficient utilization of solar-driven biomass pyrolysis process, apart from other considerations like the type of feedstock type, choice of concentrating optics, process thermodynamics, and the product yields, appropriate installation orientation of solar-thermal systems and the reactor must be designed (Weldekidana et al., 2019). Reactor design/configuration and orientation are at the heart of a pyrolysis process and constitute about 10–15% of the overall capital cost of the entire system (Bridgwater, 2012). Reactor configuration influences the liquid collection method. There has been a lot of innovation in reactor design for pyrolysis systems. These designs ranged from bubbling fluid beds, entrained flow, circulating fluid beds, free-fall reactor, vacuum pyrolysis, rotating cone, fix-bed, ablative, screw, and augur kilns, etc. However solar biomass pyrolysis is dominated with fixed bed reactors probably due to its simplicity (Bridgwater, 2012; Heidari et al., 2014) and most research is still at the laboratory scale. Though solar-biomass pyrolysis is mostly a fast pyrolysis process conducted in a laboratory, it has been argued that it will be difficult to see a fixed bed fast pyrolysis that will satisfy all the needed requirements for industrial application (Bridgwater, 2012). Again many reactors will be required to scale up to commercial configuration. According to Bridgwater (2012), fixed bed reactors are most likely to give a phase separating liquid which is desirable in applications that require fractionating but it will likely produce less liquid yield. Reactor orientation in solar thermal systems can be vertical while radiated through the concentrator and heliostat assembly that directs the radiation to the reactor (Zhang et al., 2017) or placed horizontally and the radiation beam on it with the help of the concentrators (Morales et al., 2014).

5.1. Vertically oriented continuous heated reactors (with a natural light source)

Many solar pyrolysis designs have adopted vertical orientation of the reactor probably to allow the easy collection /sweeping of the liquid aided by gravity. Ayala-Cortés et al. (2018) adopted a vertical placed spherical-shape borosilicate fixed reactor in solar-biomass pyrolysis of tomato waste and agave leave in Mexico. The reactor – thermal system orientation is shown in Fig. 2. The heliostat directs the received radiation towards the horizontally placed solar concentrator furnace (25 kW, temperature range 450–1550 °C) placed 3.68 m from the reactor assembly with a concentration area of 8 cm in diameters. The orientation of the installation enabled direct irradiation of the biomass. Argon gas was used to clean the reactor walls and provide inert conditions inside the reactor. The objective of the design is to produce more of bio-char and physiochemically characterize them at various heating rates and residence time of 1–2 h.

Li et al. (2016) showed a solar-biomass (forestry products) pyrolysis orientation where the fix-bed Pyrex balloon reactor (swept with argon gas for cleaning and provision of the oxygen-free environment) is vertically placed at the focus of a vertical axis solar furnace. The sunrays are tracked and concentrated with the help of a parabolic mirror (2 m in diameter) heliostat tracker and beamed down directly on the reactor. The biomass pellet was placed in a graphite crucible enclosed in a graphite foam layer to minimize the temperature gradient. The sample was steadied to the solar radiation focus with the help of a water-cooled clamp. Radiation heat loss was minimized by another layer of graphite foam. The orientation of the solar furnace is in contrast to the solar furnace orientation presented by Ayala-Cortés et al. (2018). However, the two orientation was positioned to enable direct radiation of the reactor. The results of the effect of heating rate, final temperature and lignocellulose composition of the product distribution of forestry product showed that high heating rate and final temperature favour the syngas production and the tar decomposition. They achieved a gas yield of 63.5 wt% from pine sawdust at 50 °C/s and 1200 °C. This same reactor set up orientation presented by Li et al. (2016) was also adopted by Zeng et al. (2015a, 2015b, 2014) in the pyrolysis of beech wood with various research objectives. The solar rays tracking sensor incorporated in the solar-thermal system tracks the sun position and automatically focuses the heliostats to beam the illumination onto the parabolic mirror facing down on the reactor. Zeng et al. (2015a, 2015b, 2014)) achieved a gas yield of 62% at a lower heating value of 10 376 ± 218 (kJ/kg of wood) and temperature, heating rate, pressure, and argon flow rates of 1200 °C, 50 °C/s, 0.85 bar and 12 NL/min. respectively. Biomass energy upgrading ranged from 38 to 53%. However, Joardder et al. (2014) presented a schematic presentation of a hybrid sola-biomass pyrolysis (Fig. 3) of the date palm with a vertically placed steel reactor (the inert atmosphere was presented with nitrogen gas) that was partially heated with biomass heater. The thermal system consists of a double parabolic dish that receives the sunrays and focuses it on the walls to raise the steel reactor temperature to about 162 °C.

The result of the experiment showed 50 wt the percentage found for liquid oil at 500 °C operating temperature and gas flow rate of 6 L/min and 120 min residence time and 32.4% of CO_2 can be prevented from entering the environment. Adinberg et al. (2004) presented a conceptual indirect solar-assisted pyrolysis of

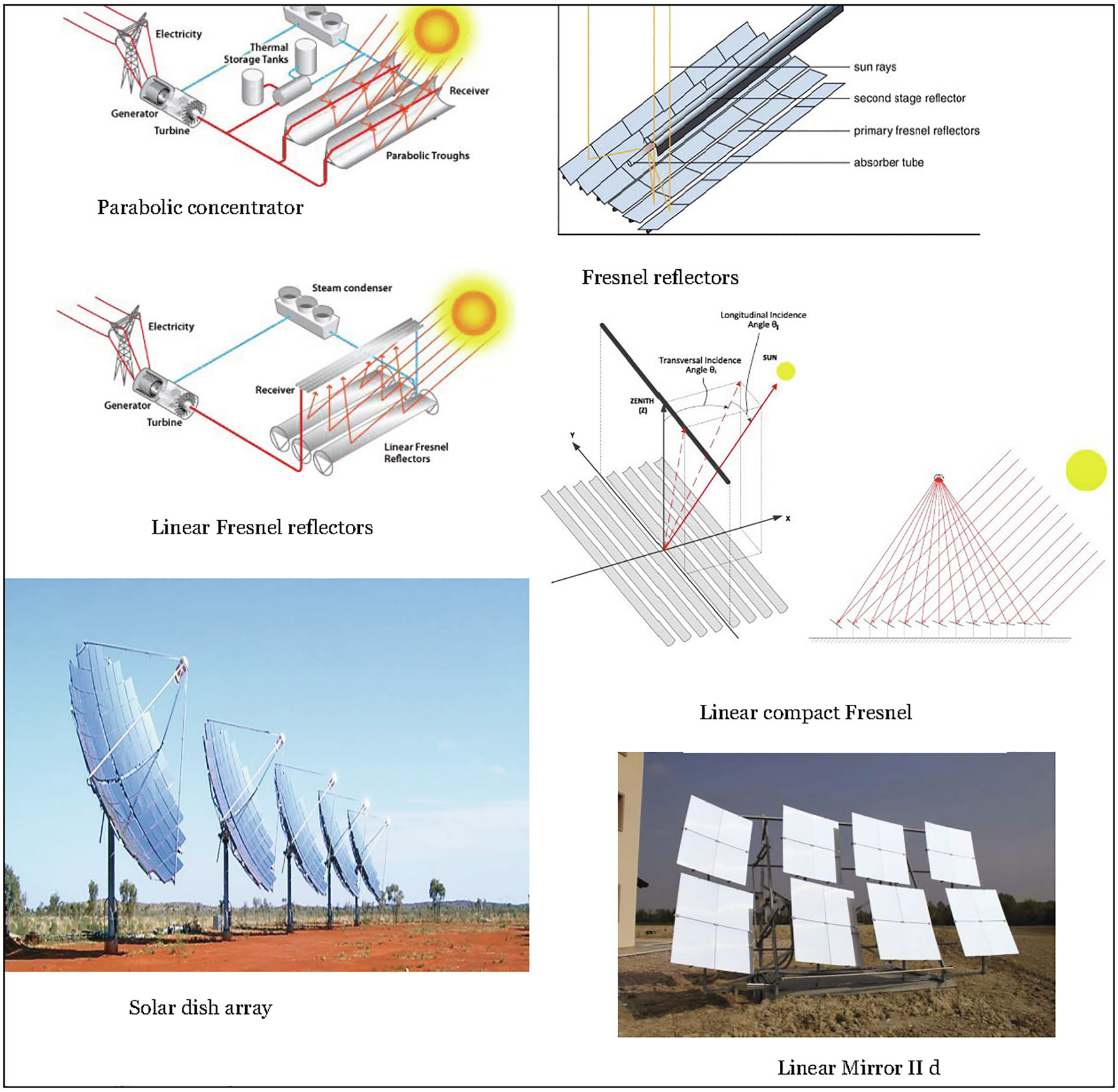

Fig. 1. Different optical concentrating devices ()). Source: Citossi and Cobal (2018

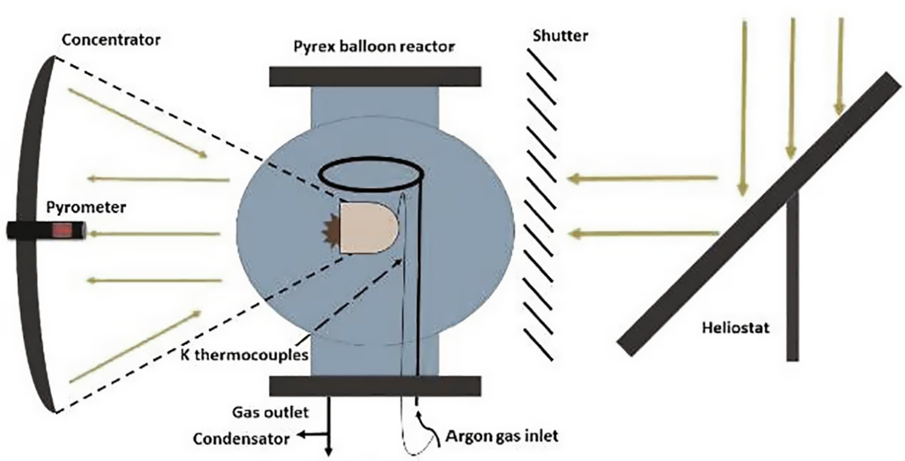

Fig. 2. Solar biomass pyrolysis orientation ()). Source: Ayala-Cortés et al. (2018

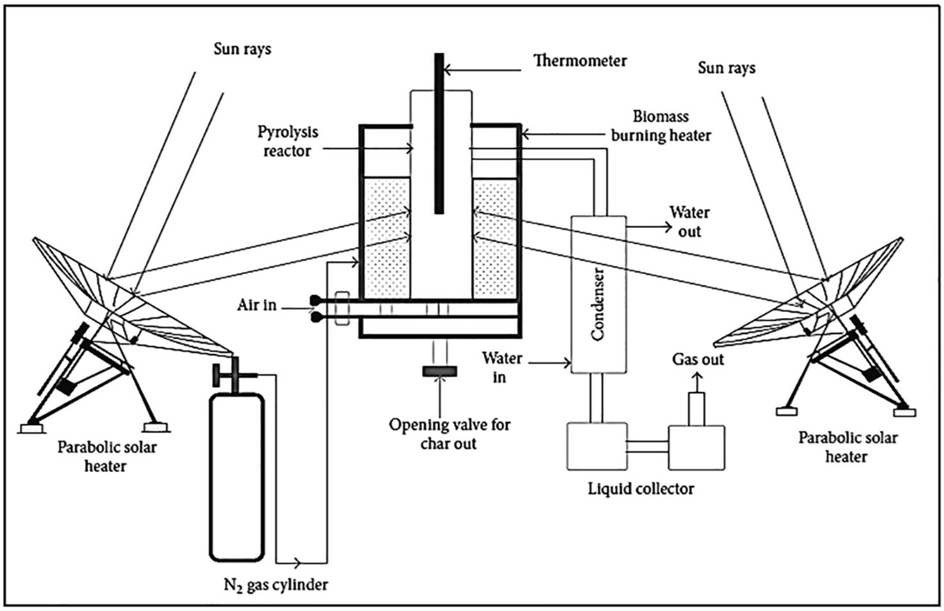

Fig. 3. Solar biomass pyrolysis orientation (Source: Joardder et al. (2014).

biomass. The reactor (cylindrical or vertical) oriented vertically was surrounded by tubes of molten Sodium and Potassium carbonate that serves as thermal storage. The set up was enclosed with an insulated dome that has an opening to let in solar radiation. The thermal-solar system was installed on top of a tower and consists of concentrated parabolic trough and heliostat to focus the beam. Heat transfer to the biomass is by conduction from the molten salt (1123 K) after being heated up by a solar concentrator.

5.2. Vertically oriented continuous heated reactors (with light simulators)

Solar –biomass pyrolysis has been performed with solar radiation simulators using different reactors and solar simulator orientations. The earlier researcher started the application of solar-assisted decomposition of carbonaceous material by using artificial light similar to sun rays and this method is still receiving attention today due to the non-continuous nature of natural sunlight. A vertically oriented fix bed reactor was published by Sobek and Werle (2019) for a solar-biomass pyrolysis with the solar radiation simulated and powered by Xenon arc lamp (heat flux density, 2.2 MWm^{-2}) with elliptical reflector. The insulated copper reactor was adopted as the reactor due to high thermal conductivity. A black body made of absorbing coating was implemented on the walls of the reactor. The rays were beamed directly on the walls of the reactor and the heat transfer to the biomass by conduction (indirect heating). This installation was designed with sliding support for the lamp to control the focal distance of the lamp and the temperature of heating. The geometry of the installation was such that the number of pellet in the reactor was as a function of the temperature gradient and irradiated area distant on the reactor. The same Xenon arc lamp equipped with a deep-dish parabolic concentrator was used to simulate solar biomass pyrolysis of Pine sawdust, using a modified cinema projector to serve as a simulator (wavelengths 850 to 1050 nm) by Rony et al. (2018). The reactor is a double wall (29 mm and 58 mm in diameter) fixed bed (the reactor can also operate as a fluidized bed) vertically positioned quartz reactor. The inner wall of the cylindrical reactor tapper to grip a fritz for holding the biomass at the focus of the solar simulator. Nitrogen gas was used to create an inert atmosphere inside the reactor and for sweeping the gas. The space between the walls compensated for heat loss. The simulator utilizes adaptable screw devices to vary the locus of the focal point. This varies the solar flux (varying the input power to regulate the temperature) with distance. The orientation of the solar –thermal system set up enabled direct irradiation of the biomass. Hopkins et al. (1984) simulated solar biomass pyrolysis of biomass with Xenon bulbs (5 kW) equipped with parabolic mirrors (1.5 m in diameter and flat glass mirrors (24 in numbers). The reactor is a vertically sprout cylindrical Amersil quartz tube (1.5 mm thick) that tapered at the base to form a cone of 20° slant angle. The biomass fed from the top is pyrolyzed as they repeatedly pass through the focus in a trapped stream of a circulating flow of sprouted bed. The solar simulator delivers about 150 W of energy to the focal zone at a flux range of 200 W/cm^2. The bio-oil yield from the cellulose biomass obtained was about 63%. Boutin et al. (1999) also adopted this same simulator in a direct measurement of the optical properties of biomass components of solar flash pyrolysis of biomass. A converging lens concentrates the parallel beam of light from a xenon lamp before it enters the integrated sphere that contains the pellets. Sobek and Werle (2019) presented simulated solar-assisted pyrolysis of waste biomass using vertically oriented opaque copper tube and Xenon arc lamp (1.6 kW, heat flux density 2.2MWm^{-2}) integrated with an elliptical reflector as a solar simulator. The utilization of opaque copper material as a reactor is to enable indirect heating of the biomass through conduction. Grønli (2000) presented a simulation of solar-biomass pyrolysis of birch, pine, and spruce biomass using Xenon lamp also. The pyrolysis took place in a bell-shaped Pyrex reactor with one face made with a fused silica window that allows maximum transmission of radiant heat. The xenon lamp was directly focused on the biomass through the window for 5–10 mins. Close to the window are three ports of purge gas of nitrogen gas to keep it free from smoke. The gas swept to a cold trap through the outlet port at the top. The heat flux generated by the lamp is in the range of 80 and 130 kW/m^2. Bio-char, tar and gas yield for the two flux densities were 26.2–28.7, 27.9–38 and 35.9–45.2 wt% respectively. Beagle (2012) presented simulated solar pyrolysis of woody biomass with xenon bulb (5 kW) equipped with a concentrator. The reactor is a vertically oriented quartz tube preheated with nitrogen gas. Separation of products is in 4-stages using four tubes consisting of heated ethylene glycol bath, heated water bath, room temperature water bath, and water/ice bath at 120, 70, 22, and 0 °C respectively. Tables 1 and 2 presents the summary of solar-assisted and solar simulated pyrolysis of biomass respectively.

5.3. Horizontally-oriented continuous heated reactors

Research adopting horizontal reactor orientation found in literature is very few. Morales et al. (2014) presented a solar- pyrolysis system for an orange peel with horizontal fix-bed rector orientation (Fig. 4). The system consists of a borosilicate glass tube reactor, the hub, the parabolic concentrator (1.3 m wide), and multiple condensation tubes. The hub serves as the supporting structure and rotates in a single axis to focus the entire system. The inert condition was provided with helium gas. The system was designed to enable direct irradiation of the biomass thus making the feedstock the hottest part of the system. The light enters the reactor from under while the gaseous fluid is collected by the condensation trained placed adjacently. The gas produced was collected in a cooling tube dipped in liquid nitrogen at −200 °C. The maximum concentrated solar level obtained was 27,088 W/m^2 with an average flux of 12,553 W/m^2. They obtained yield from the orange peel were 1.4, 21 and 77.6 (wt. %) for gas, char and oil respectively. Bashir et al. (2017) proposed an inclined conceptual fluidized bed horizontal reactor. A preheated nitrogen introduced from one end to move the biomass towards the other end fluidized the biomass. The pyrolysis reaction was sustained with the help of a parabolic concentrator that is focused directly on the reactor wall. The gas and solid phase was separated with a conical flow deflector that allows the gas-free solid to pass through an inserted pipe. This applied separation technique provides for better control of the gas residence time while limiting the time spent between the char and the gas after formation. This is to limit the thermal and catalytic cracking of the gas to improve the bio-oil yield. A solar thermal horizontal reactor for pyrolysis of biomass located at C.N.R.S laboratory in Odeillo France was presented by Beattie et al. (1983). The concentrating device was parabolic trough mirror located at the overhang section of a building while the heliostat was at the southern location of the building. The system was oriented to allow direct irradiation of the feedstock. The results showed that the spectra distribution of sunlight did not affect gas yield but varied with the position of the sample relative to the focal point of the furnace. Additionally, they stated that adopting two-step pyrolysis of devolitization of the biomass and gas-phase pyrolysis of vapour will increase yield. A horizontally oriented fix bed reactor (silica glass tube) was presented by Weldekidana et al. (2019) for a solar –biomass pyrolysis of chicken-litter waste. This same reactor (Fig. 5) has been used by Weldekidan et al. (2018) in solar- pyrolysis of rice husk. The biomass was packed at the centre of the tube with the help of quartz wool. One end of the fix bed reactor was connected to an argon carrier gas which provided the inert situation while the other end connected to the ice chamber to track the by-product. The solar radiation was powered by a parabolic dish concentrator (1.8 m in diameter) with the surface laminated with 88% reflective aluminium polyethene terephthalate. Grassmann et al. (2015) presented a rotary horizontal stainless reactor (cylindrical retort

Table 1
Summary of continuous (complete) solar-heated biomass pyrolysis.

S/No	Biomass	Reactor	Reactor configuration	Concentrator	Power	Max. Flux density	Outcomes	Source
1	Beechwood	Transparent Pyrex balloon	Vertical furnace	Down facing the parabolic mirror	1.5 kW	15,000 kW/m^2	the gas yield of 62% at a lower heating value of 10 376 ± 218 (kJ/kg of wood) at temperature, heating rate, pressure, and argon flow rates of 1200 °C, 50 °C/s, 0.85 bar and 12 NL/min. respectively. Biomass energy upgrading ranged from 38 to 53 %.	Zeng et al. (2015a, 2015b, 2014)
2	Wheat straw	rotary stainless cylindrical kiln	Horizontal retort	linear mirror II	–	–	solar carbon of 16.9 MJ/kg energy density	Grassmann et al. (2015)
3	tomato waste and agave leave	spherical-shape borosilicate	vertical	parabolic trough	25 kW, temperature range 450–1550 °C		biochar produced at a low temperature of less than 900 °C had good surface area and capacitance compared to a higher temperature	Ayala-Cortés et al (2018)
4	Orange peel	borosilicate glass tube	horizontal	parabolic trough covered with a silver mirror coating placed according to the angle of sunlight	–	27,088 W/m2,	1.4, 21 and 77.6 (wt. %) for gas, char, and oil respectively	Morales et al (2014)
5	peach pit, grape stalk and grape marc in powder	Transparent Pyrex balloon	vertical	Down facing the parabolic mirror	1.5 kW	15000 kW/m^2	The maximum gas yield of 63.5% was obtained from pine sawdust at final temperature 2000 °C,	Li et al. (2016)
6	Date palm	Steel reactor (partial heating)	vertical	Double parabolic dish	–	–	50 wt the percentage found for liquid oil at 500 °C operating temperature and gas flow rate of 6 L/min and 120 min residence time and 32.4% of $CO_{2\ abetted}$	Joardder et al. (2014)
	–	stainless steel dish	Flat	parabolic trough mirror	–	–	–	Beattie et al. (1983)
8	Dry biomass	Spherical or cylindrical reservoir with molten salt surrounded by 22 cylindrical tubes	vertical	Compound parabolic concentrator	3000 kW	–	–	Adinberg et al (2004)
9	Rice straw	Cylindrical silica glass tube	Horizontal	Dish concentrator	–	–	–	Weldekidan et al., 2018

Table 2
Summary of solar simulated biomass pyrolysis.

S/No	Biomass	Reactor	Reactor configuration	Concentrator	Power and max flux	Light source	Outcomes	Source
1	Kraft paper	cylindrical Amersil quartz tube that tapered at the bottom	Vertical, Spouted bed	parabolic mirrors and 24 flat glass mirrors	150 W, 200 W/cm^2	5 kW arc Xenon bulbs	syrup yield of 63%	s et al. (1984)
2	Mixed biomass components similar to wood	Integrated sphere	vertical	converging lenses	–	a xenon lamp	Reflection of 44–86% of pellets was observed	Boutin et al. (1999)
3	Norwegian birch, pine, and spruce	bell-shaped Pyrex, with one face made with fused silica window	horizontal	Direct concentration through a glass tube	80–130 kW/m^2	a xenon arc lamp	Bio-char, tar and gas yield for the two flux densities were 26.2–28.7, 27.9–38 and 35.9–45.2 wt% respectively.	Grønli (2000)
4	wood	quartz tube	vertical	Direct concentration		5 kW arc xenon bulb	Heavy tar and light bio-oil	Beagle (2012)
5	Waste biomass	copper, Indirect (conduction)	vertical	Elliptical reflector	2.2MWm^{-2}	1.6 kW Xenon arc lamp	–	Sobek and Werle (2019)
6	chicken-litter	Copper, Indirect (conduction)	vertical	Elliptical reflector	2.2MWm^{-2}	0.6 kW Xenon arc lamp	The maximum CO and H_2 yields were 63 wt% and 15 wt%, were obtained at the 50% CaO in-situ loading at 800 °C	Sobek and Werle (2019)
7	Pine sawdust	Cylindrical quartz reactor	vertical	Deep-dish parabolic concentrator	–	5 kW Xenon arc lamps	–	Rony et al (2018)

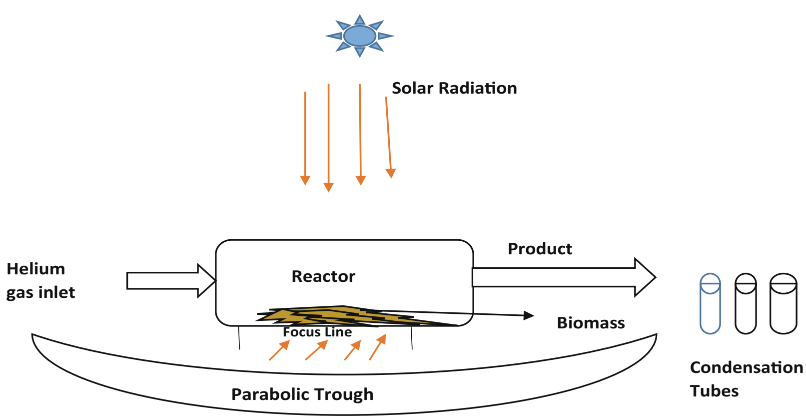

Fig. 4. Fix bed horizontal oriented solar biomass pyrolysis reactor (). adapted from Morales et al., 2014

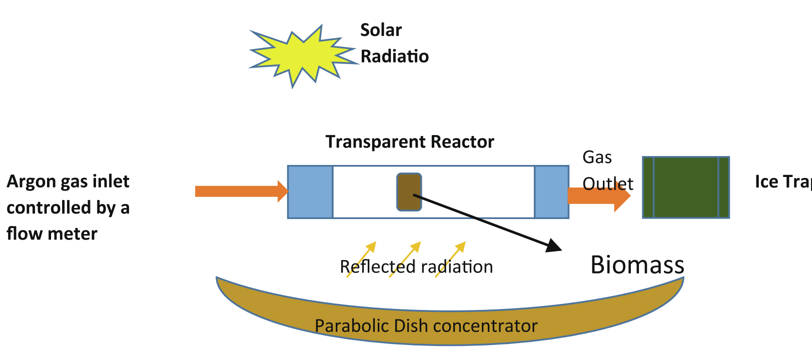

Fig. 5. Fix bed horizontal oriented solar biomass pyrolysis reactor (). adapted from Weldekidan et al., 2018

kiln) powered by a slow revolving motor. The concentrator was an array of four linear mirrors placed in two rows with an inclination of about 2° that tracks the sun. The concentrated solar irradiance was deflected to the reactor by the aid of a deflector placed at the focal axis of the mirrors. Solar carbon produced from the set up was 16.9 MJ/kg energy density.

6. Model equations used in solar-biomass pyrolysis

The orientation of the reactor and the methods of heating are considered in process analysis and simulations of the pyrolysis process. Despite the similarity of the optimum condition of operations of biomass pyrolysis, there is variation contributed by the nature of biomass and reactor orientations, which might offer different, transport resistance and feedstock impact (Papari and Hawboldt, 2015). A reactor process model in a complete pyrolysis system involves the heat and mass transfer models, the kinetic reaction models coupled with the transport models or a generated empirical relationship (Papari and Hawboldt, 2015). Model equations are required to understand and optimize the pyrolysis reactor. Due to the complexity of the heat transfer to the reactor and kinetic reactions contributed by various compositions of the biomass at different temperature and heating rate. Simplification of intrinsic processes has been applied to understand the reactor heating and reaction kinetics.

For solar-assisted pyrolysis with a transparent reactor that is directly irradiated without thermal storage, the heat flux involves the heat absorbed by the endothermic reaction, heat absorbed by the biomass, and heat absorbed by the reactor. Also, the heat lost includes the heat lost to the environment, the reactor reflects heat, heat absorbed by the concentrator and the focusing inefficiency of the concentrator (Morales et al., 2014). Considering the direct irradiated system presented by Morales et al. (2014) and other similar systems, the heat balance for the solar biomass system considering the entire heat produced from the solar energy as follows

$$dQ_{absorbed}^{solar} = dqo(\alpha_{reactor} + \tau_{reactor}\alpha_{biomass}) \tag{1}$$

The irradiation on the surface of the reactor (dqo) is expressed as follows

$$dq_0 = \varphi \eta_{optic} \eta_{focus} dAdt \tag{2}$$

The distribution of the irradiation along the circumference depends on the solar insolation deduced experimentally and given as Eq. (3) as follows

$$\varphi = I\left(2\times10^{7}c^{4} + 2\times10^{-3}c^{3} - 44828c^{2} - 3\times10^{-13}c + 33\right) \tag{3}$$

The heat lost to the environment is expressed as follows

$$dQ_{environment}^{loss} = h(T_f - T_\infty)dAdT \tag{4}$$

Grønli (2000) in modelling a solar biomass pyrolysis system emphasized the coupling of drying and pyrolysis process assuming all phases are at equal temperature and equilibrium pressure equal to the partial vapour pressure. They developed three critical Eqs. (5)–(7) for energy conservation, the relationship between the gas mixture and specific heat capacity of the gas mixture respectively as follows

$$\left(\langle\rho_s\rangle C_{p,s} + \epsilon_g\langle\rho_g\rangle^g C_{p,g}\right)\frac{\partial\langle T\rangle}{\partial t} + \left(\langle\rho_g\rangle^g\langle v_g\rangle C_{p,g}\right)\frac{\partial\langle T\rangle}{\partial x} = \frac{\partial}{\partial x}\left(k_{eff}\frac{\partial\langle T\rangle}{\partial x}\right) - \sum_i\langle\dot{w}_i\rangle\Delta h_i \tag{5}$$

$$\left(\rho_g\right)^g = \sum_i(\rho_i)^g,\ (P_g)^g = \frac{\left(\rho_g\right)^g R_o T}{M_g},\ M_g = \left(\sum_i\frac{(\rho_i)^g}{\left(\rho_g\right)^g M_g}\right)^{-1} \tag{6}$$

$$C_{p,g} = \sum_i C_{p,i}\frac{(\rho_i)^g}{\left(\rho_g\right)^g},\ C_{p,s} = \eta C_{p,SD+(1-\eta)}C_{p,c} \tag{7}$$

In biomass pyrolysis thermogravimetric analysis is carried out and the behaviour of the process is evaluated at different temperatures and heating rates. Researchers currently have focused on the thermal decomposition determined by the weight evolution as the temperature increases (conversion model). The kinetic principle is mostly based on the condensed phase or solid-phase used to establish the conversion rate. The most important thing in the kinetic model is to preserve the physical characteristics of the process. In a solid phase, the feedstock is heated constantly as the temperature rises over time. The rate of conversion is expressed as an Arrhenius equation as follows

$$\frac{d\alpha}{dT} = \beta^{-1}Aexp\left(\frac{-E}{RT}\right)f,(\alpha) \tag{8}$$

$$\alpha = \frac{m_o - m_t}{m_o - m_f} \tag{9}$$

Isoconversion models have also been presented for kinetic modelling of solar biomass pyrolysis which allows the calculation of the pre-exponential parameter and the activation energy without the knowledge of the reaction equations (Sobek and Werle, 2020). These models are still based on the conversion model earlier stated and listed in Eqs. (10)–(11) as follows

$$ln\left[\beta_i\left(\frac{d\alpha}{dT}\right)_\alpha\right] = ln[A_\alpha f,(\alpha)]\frac{-E_\alpha}{RT_{d,i}} \tag{10}$$

$$\frac{d\langle\alpha\rangle}{dT} = \frac{A}{\beta}exp\left(\frac{-E}{RT}\right)f,(\alpha) \tag{11}$$

Model-based kinetics which uses the reaction step has been presented where the mass loss is evaluated as the sum of the integrated part of the conversion rate expressed below.

$$\left(\frac{d\alpha}{dt}\right)_j = \left(\left(\frac{d(a_j\rightarrow b_j)}{dt}\right)\right)_j = A_j exp\left(\frac{-E_j}{RT}\right)f_j,(a_jb_j) \tag{12}$$

In the case of kinetic models, the choice of the best model is still subject to debate.

7. Conclusion

This paper addressed the benefits of solar-biomass pyrolysis, available optical concentrating device, conceptual heating modes, the existing configuration of solar-thermal and reactor orientations, and some basic model equations applied in solar biomass pyrolysis. To achieve efficient utilization of solar-driven biomass pyrolysis process, apart from other considerations like the type of feedstock type, choice of concentrating optics, process thermodynamics, and the product yields, appropriate installation orientation of solar-thermal systems and the reactor must be properly designed. Reactor design/configuration and orientation are at the heart of a pyrolysis process. Reactor configuration influences the liquid collection method and writing of the heat balance equations in model development. There has been a lot of innovation on reactor design for pyrolysis systems but fix-bed vertically oriented reactors dominated solar biomass pyrolysis and most of the research is at the laboratory scale. This will limit commercialization, as multiple reactors will be required to scale up the quantity of process biomass to achieve commercial status. The available literature reviewed, therefore, showed that the current design of reactors is not enough to move solar pyrolysis towards commercialization. Improved design that will scale up the quantity of biomass processed is required. This kind of reactor should operate at a dynamic thermal condition rather than isothermal and the modelling process should reflect the dynamic conditions. The integration of nanoscale particles in reactor and concentrator construction might have a promising outlook on solar thermal system efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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