SOLAR THERMAL GASIFICATION OF BIOMASS

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Abstract. *Solar thermal steam-gasification of carbonaceous materials uses concentrated solar energy as source of the high-temperature process heat. The main advantage compared to autothermal processes is an upgrade of the feedstock's calorific value by up to 33 % instead of a 30 % energy penalty due to consumption of the feedstock for the generation of the process heat. This process represents thus an efficient way of converting intermittent solar energy into an easily storable and dispatchable chemical form. Three innovative reactor designs based on packed beds and entrained flows have been developed and experimentally demonstrated for the combined pyrolysis and gasification of biomass, charcoal, petcoke, coal, and carbonaceous waste feedstocks: indirectly-irradiated packed-bed reactor, directly-irradiated vortex-flow reactor, and indirectly-irradiated entrained-flow reactor. They are compared by their main performance parameters, solar-to-fuel energy conversion efficiency and energetic upgrade factor. The performance of a 10 MW commercial-scale indirectly-irradiated entrained-flow reactor is predicted by numerical simulation.*

Keywords: *Solar thermochemistry, Biomass, Solar fuels*

1. INTRODUCTION

Thermal steam-gasification of solid carbonaceous feedstocks is used to obtain an energy-rich mixture of H_2 and CO, called synthesis gas (syngas), according to the simplified overall reaction

$$\mathrm{CH}_x\mathrm{O}_y(\mathrm{s}) + (1-y)\,\mathrm{H_2O} \longrightarrow \mathrm{CO} + \left(1+\frac{x}{2}-y\right)\mathrm{H_2} \qquad (1)$$

Possible uses of syngas have been thoroughly described by Wender (1996). Syngas can be directly used as combustion fuel in industrial burners, for combined-cycle (Wright and Gibbons, 2006) or fuel cell power generation (Song, 2002). Alternatively, it can be processed into conventional fuels (Höök and Aleklett, 2010) or into hydrogen (Steinfeld, 2005) to be used in the transportation sector. Finally, it can serve as source material for the production of commodities (Spath and Dayton, 2003).
The necessary process heat to drive the endothermic reaction (1) can be delivered autothermally, i.e. by combusting part of the feedstock or of the produced syngas. This can result in a reduction of the feedstock's original energy content by over 30 % (Lédé, 1999).

Using concentrated solar energy as the source of high-temperature process heat (Meier and Steinfeld, 2010; Romero and Steinfeld, 2012) eliminates this drawback. Additionally, solar steam-gasification offers the following benefits compared to the autothermal process:

- The calorific value of the produced syngas can be increased by up to 33 % compared to the original feedstock, thanks to the solar energy input (Piatkowski and Steinfeld, 2011).
- Higher gasification temperatures can be obtained (1500 K), which result in faster kinetics and allow for low tar content of the product as well as for a broad range of exploitable feedstocks.
- Steam being the only gasifying agent, no upstream air separation is required.
- It is an efficient means of storing – naturally intermittent – solar energy in chemical form for simple transportability and dispatchability.

Tested materials for solar steam-gasification include petrochemical (Z'Graggen *et al.*, 2007) and water treatment waste (Piatkowski *et al.*, 2009); coal, active carbon, or coke (Gregg *et al.*, 1980, von Zedtwitz and Steinfeld, 2005); and cellulose (Murray and Fletcher, 1994; Lichty *et al.*, 2010), and biochar (Melchior *et al.*, 2009; Piatkowski *et al.*, 2009). If biomass is used as feedstock, the process can be considered CO_2-neutral.

The solar-to-fuel energy conversion efficiency, is defined as

$$\eta = \frac{m_{\text{syngas}} \cdot LHV_{\text{syngas}}}{Q_{\text{solar}} + m_{\text{feedstock}} \cdot LHV_{\text{feedstock}}} \tag{2}$$

where Q_{solar} is the total solar energy delivered through the reactor's aperture and $m_{\text{feedstock}}$ and m_{syngas} are the gasified feedstock and evolved syngas mass, respectively, integrated over the duration of the experimental run. The energetic upgrade factor is defined as the ratio of the heating value of the syngas produced to that of the feedstock processed,

$$U = \frac{m_{\text{syngas}} \cdot LHV_{\text{syngas}}}{m_{\text{feedstock}} \cdot LHV_{\text{feedstock}}} \tag{3}$$

For the stoichiometric system C+H_2O, the equilibrium composition at 1300 K consists of an equimolar mixture of H_2 and CO, for which U = 1.33 (Piatkowski *et al.*, 2011) .

Solar Reactor Technology – Solar gasification reactors may be classified as: 1) directly-irradiated reactors, where the solid carbonaceous reactants are directly exposed to the concentrated solar irradiation; and 2) indirectly-irradiated reactors, where heat is transferred to the reaction site through an opaque wall. Directly-irradiated reactors provide efficient heat transfer directly to the reaction site, but they require a transparent window for the access of concentrated solar radiation, which becomes a critical component under high-pressures, severe gas environments, and particularly at large scales. Indirectly-irradiated reactors eliminate the need for a window at the expense of having less efficient heat transfer – by conduction – through the walls of an opaque absorber. Thus, the disadvantages are linked to the limitations imposed by the materials of the absorber, with regards to maximum operating temperature, inertness to the chemical reaction, thermal conductivity, and resistance to thermal shocks. Three innovative reactor designs based on packed beds and entrained flows have been developed and experimentally demonstrated for the combined pyrolysis and gasification of biomass, charcoal, petcoke, coal, and carbonaceous waste feedstocks. Their configurations are shown in Fig. 1 for the a) indirectly-irradiated packed-bed reactor; b) directly-irradiated vortex-flow reactor; and c) indirectly-irradiated entrained-flow reactor.

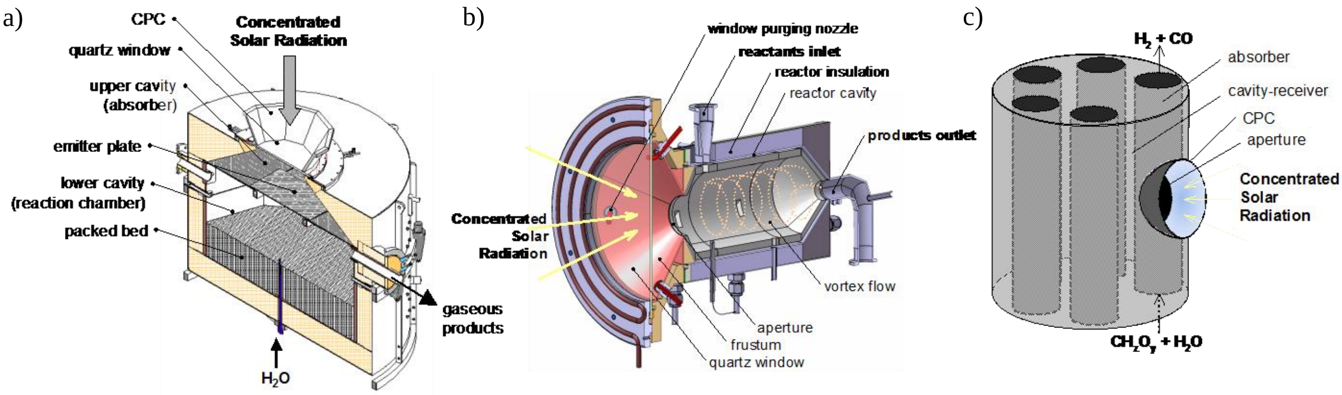

Fig. 1. Solar reactor configurations for the steam-based thermochemical gasification of carbonaceous feedstocks: a) indirectly-irradiated packed-bed reactor; b) directly-irradiated vortex-flow reactor; and c) indirectly-irradiated entrained-flow reactor.

The indirectly-irradiated packed-bed reactor, Fig. 1a, is specifically designed for beam-down incident solar radiation as obtained through a Cassegrain optical configuration that makes use of a hyperbolic reflector at the top of a solar tower to redirect sunlight collected by a heliostat field to a receiver located at ground level. It consists of two cavities in series: the upper one functions as the solar absorber and the lower one functions as the reaction chamber and contains the packed bed on top of the steam injector. An emitter plate separates the two cavities to eliminate contact between the quartz window and the reactants/products, preventing deposition of particles or condensable gases. The reactor is operated in batch mode, with the packed bed shrinking as the gasification progresses. An 8 kW reactor prototype was fabricated and applied to the gasification of charcoal, bituminous coal, and carbonaceous wastes such as scrap tire chips and powders, industrial and sewage sludge, and fluff (Piatkowski *et al.*, 2009). These carbonaceous wastes were characterized by volatile contents up to 80 wt%, ash contents up to 40 wt% and high heterogeneity. For beach charcoal, η = 29% and U = 1.3 (Eqs. 2-3) were experimentally obtained (Piatkowski *et al.*, 2009).

The directly-irradiated vortex-flow reactor, Fig. 1b, consists of a continuous flow of steam laden with carbonaceous particles confined to a cavity receiver and directly exposed to concentrated solar radiation. Slurry of carbonaceous particles and water is injected through an inlet port on the cavity top at a controlled rate. Inside the cavity, the slurry forms a vortex flow that progresses towards the rear along a helical path. With this arrangement, the particles are directly exposed to the high-flux solar irradiation, providing efficient heat transfer directly to the reaction site. Energy absorbed by the reactants is used to evaporate and superheat the water, raise the reactants temperature to above 1300 K, and drive the steam-based gasification reaction. A 5 kW solar reactor prototype was fabricated and tested at PSI's solar furnace for the steam-based gasification of a water-petcoke slurry (Z'Graggen *et al.*, 2007). For a nominal reactor temperature of 1500 K, a water-petcoke molar ratio of 4.8, and a residence time of 2.4 s, the degree of petcoke conversion was 87%. Typical syngas composition produced was 62% H_2, 25% CO, 12% CO_2, and 1% CH_4. The reactor performance indicators (Eqs. 2-3) were η = 26% and U = 1.2 (Z'Graggen *et al.*, 2007).

The indirectly-irradiated entrained-flow reactor, Fig. 1c, consists of a cylindrical cavity-receiver with a windowless aperture containing an array of tubular absorbers, through which a continuous two-phase flow of water vapor laden with carbonaceous particles reacts to form syngas. A compound parabolic concentrator (CPC) is incorporated at the aperture to further augment the incident solar flux intensity, obtain a more uniform radiative distribution inside the cavity, and minimize re-radiation losses through a smaller aperture. A 3 kW solar reactor prototype containing a single SiC concentric tubular absorber was fabricated and tested for the steam-based gasification of beech charcoal particles. Main product gases were H_2, CO and CO_2 with H_2:CO ratios of 3 and CO_2:CO ratios of 1 due to the overstoichiometric water supply (Melchior *et al.*, 2009; Lichty *et al.*, 2010).

Of the three solar reactor concepts, the one based on the packed bed is the most flexible in handling and processing heterogeneous feedstocks with varying compositions and particle sizes (typically 0.1-10 mm). Because of long residence times, it can also tolerate lower reactivity feedstocks. However, its energy conversion efficiency is constrained by the rate of heat and mass transfer. In contrast, the solar reactors based on the entrained flow exhibit more efficient transport properties, but at the expense of being sensitive to particle sizes (typically < 10 μm). Because of the short residence times, they are most suited to high reactivity feedstocks. The directly-irradiated concept bypasses the limitations imposed by conductive heat transfer through ceramic walls and, consequently, promises high energy conversion efficiencies; however, it introduces a critical quartz window. The indirect-irradiated concept is a more technically feasible approach, but with an associated energy penalty. Recently, pilot-scale solar gasification plants have been commissioned in solar towers. Ultimately, successful market entry of solar gasification technology will depend on the dominant market price of solid feedstocks and fossil fuels, as well as credits for pollution abatement and CO_2 mitigation.

2. PERFORMANCE PREDICTION OF COMMERCIAL-SCALE REACTOR

Piatkowski and Steinfeld (2011) modeled and numerically predicted the performance of a 200 kW indirectly-irradiated packed-bed reactor. With an inlet solar flux of 0.84 $MW \cdot m^{-2}$, a peak η = 89.4 % was predicted for industrial sludge.

A 10 MW commercial-scale system on a solar tower was modeled, consisting of a series of cavity-receiver reactors having a total size (W x H x D) of 10 x 4 x 2 m and containing totally 66 absorber tubes, each having an inner diameter of 8 cm and a length of 4 m. The model couples radiative heat transfer within the cavity-receiver with radiation/convection/conduction heat transfer for a reacting flow inside the absorber tubes (Maag and Steinfeld, 2010), as schematically shown in Fig. 1c. Experimental validation of the model was carried out with a 3 kW solar reactor prototype tested by Melchior et al. (2009). For a desired outlet temperature of 1500 K, and an inlet solar flux of 1.5 $MW \cdot m^{-2}$, X_C of 67 % and η = 67.1 % are predicted, assuming a solar upgrade of 1.30, and using biochar as feedstock. An estimation of the improvement potential for the solar-to-chemical energy conversion efficiency shows values for η up to 79.9 % for an inlet solar flux of 1.5 $MW \cdot m^{-2}$ to be achievable through optimization of the cavity and absorber tube sizes in order to completely react the feedstock. Such a setup could convert 1,094 $kg \cdot h^{-1}$ of biochar into syngas.

3. SUMMARY

A comparison of three innovative reactor designs based on packed beds and entrained flows have been developed and experimentally demonstrated for the combined pyrolysis and gasification of biomass, charcoal, petcoke, coal, and carbonaceous waste feedstocks. The comparison parameters are the solar-to-fuel energy conversion efficiency η and the energetic upgrade U. For the indirectly-irradiated packed-bed reactor, the maximum values are η = 29 % and U = 1.3. For the directly-irradiated vortex-flow reactor, maximum η = 26 % and U = 1.2 were obtained. The indirectly-irradiated packed-bed reactor, proved to be the most versatile in terms of accepted types of feedstock. Numerical simulation of the indirectly-irradiated entrained flow reactor, a maximum η = 79.9 % is predicted.

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