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Syngas Production by Thermochemical Gasification of Carbonaceous Waste Materials in a 150 kW_{th} Packed-Bed Solar Reactor

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ABSTRACT: The solar thermochemical steam-based gasification of carbonaceous materials is investigated using concentrated solar energy as the source of the high-temperature process heat. Vis-à-vis conventional autothermal gasification, the solar-driven process delivers a higher syngas output of higher quality and lower CO_2 intensity because no portion of the feedstock is combusted and its energy content is solar upgraded. The operation of a solar gasification pilot plant for a 150 kW_{th} solar-radiative power input was experimentally demonstrated using a packed-bed solar reactor operated in batch mode. The experimentation was carried out in a solar tower. Six different carbonaceous waste feedstocks have been successfully processed: industrial sludge, fluff, tire chips, dried sewage sludge, low-rank coal, and sugar cane bagasse. The calorific value of the produced syngas was upgraded by a factor of up to 1.3. The solar-to-fuel energy-conversion efficiency, defined as the ratio of the heating value of the fuel produced to the solar and feedstock energy inputs, varied between 22 and 35%.

1. INTRODUCTION

The steam-based thermochemical gasification of solid carbonaceous feedstock to syngas can be described by the simplified overall reaction

$$CH_x O_y(s) + (1-y)H_2 O \rightarrow \left(1 + \frac{x}{2} - y\right)H_2 + CO$$
(1)

In conventional autothermal gasification, about 35% of the injected feedstock mass is combusted internally with pure O₂ to supply high-temperature process heat for endothermic reaction 1, which inherently decreases the feedstock utilization and contaminates the product gases. Alternatively, concentrated solar energy can be used as the source of the required process heat.¹ The advantages of solar-driven vis-à-vis autothermal gasification are fourfold: (1) It delivers higher syngas output per unit of feedstock because no portion of the feedstock is combusted for process heat. (2) It avoids the contamination of syngas with combustion byproducts and consequently reduces costly downstream gas cleaning and separation requirements. (3) It allows for higher gasification temperatures (>1100 $^{\circ}$ C) without the need for an oxygen-blown furnace, resulting in faster reaction kinetics and a higher quality of the syngas produced with low (or without) tar content that further enables the processing of virtually any type of carbonaceous feedstock, resulting in a higher exploitation of the available resources. (4) It eliminates the need for an upstream air separation unit because steam is the only gasifying agent, which further facilitates economic competitiveness. Ultimately, solar gasification offers an efficient means of storing intermittent solar energy in a transportable and dispatchable chemical form. Because no portion of the feedstock is combusted for process heat, the energy content of the feedstock is upgraded by up to 33% through the solar energy input that is equal to the enthalpy change in reaction 1.1 The syngas product can be used as a

combustion fuel (e.g., for cement kilns or in IGCC plants for power generation) or further processed to H_2 or liquid hydrocarbon fuels.^{2–5} Depending on the intended application, different degrees of purity and adjustment of the H_2/CO ratio are required.⁶ Purification is simpler in allothermal solar gasification than in traditional autothermal gasification because of the absence of combustion byproducts. Specifically, the production of H_2 via solar-driven gasification has been proposed as a midterm approach toward solar H_2 from H_2O .^{7,8}

The thermodynamics and kinetics of reaction 1 have been previously examined (see ref 1 and the literature cited therein). The carbonaceous feedstocks experimentally investigated included $\operatorname{coal}_{,}^{9-11}$ petcoke,^{12,13} cellulose,^{14,15} biochar,^{11,16} and waste materials such as scrap tire chips and powders, dried sewage sludge, industrial sludges, and fluff.¹¹ If biomass is used as feedstock, then the process can be considered CO₂ neutral. System analysis of a solar-hybrid gasification process for the production of liquid fuels indicated that the energetic output can be more than 20% above that of a conventional, autothermal pressurized gasification plant^{17,18}

The solar-reactor concepts applied to solar gasification included a directly irradiated fluidized bed,^{19,20} molten-salt pool,²¹ and vortex-flow^{12,13} as well as indirectly irradiated particle-flow¹⁶ and packed bed.¹¹ Sundrop Fuels (USA) has constructed a solar tower pilot plant with an indirectly irradiated particle-flow solar gasifier.²² Alternatively, the packed-bed reactor concept is characterized by its robustness, simplicity of operation, and an ability to accept bulk moist carbonaceous feedstock of any shape and size without prior processing.¹¹ The operation of a respective 5 kW_{th} solar-reactor prototype was experimentally demonstrated in a solar furnace

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for gasifying a wide variety of carbonaceous waste feedstock.¹¹ A heat and mass transfer model has been formulated and applied for scaling up the reactor design.²³ A similar solar-reactor concept has already been applied in the solar carbothermal reduction of ZnO^{24-27} and the treatment of electric-arc-furnace dust.²⁸

The present Article describes the experimental testing of a 150 kW_{th} packed-bed solar-gasification pilot plant in a solar tower. In contrast to conventional gasifiers, the scaling up of the solar-reactor technology involves the design of the cavity-receiver for the efficient absorption of concentrated solar radiation coming from a sun-tracking heliostat field, and the operation of the solar reactor and peripheral components under transient solar-radiation conditions. Several heat and mass transfer aspects of the solar reactor design as well as its dynamic behavior during batch operation are examined for various carbonaceous feedstocks. Therefore, the main goal of this work is to investigate the performance of the solar gasification system in a scaled-up version, encompassing the solar concentrating optics, solar reactor, and off-gas handling unit.

As will be shown in the analysis that follows, the experimental results demonstrate the robustness of the solar-reactor technology to accommodate diverse carbonaceous waste feedstocks of varying composition and size as well as the technical viability of solar-driven thermochemical gasification for high-quality syngas generation on an industrial scale.

2. EXPERIMENTAL SECTION

A packed-bed solar-gasification pilot plant has been built for a 150 kW_{th} solar-radiative power input. The solar reactor and its peripheral components are shown schematically in Figure 1. It consists of two cavities in series, with the upper one functioning as the solar absorber and the lower one functioning as the reaction chamber. The upper cavity has a 525 mm diameter circular aperture covered by a 12 mm thick quartz window for the access of concentrated solar radiation. The window reduces convective and IR-radiative losses, but it does so at the expense of reflection losses (\sim 7% of incident solar energy). A faceted SiC-coated graphite plate, denoted as the emitter plate, separates the two cavities. The emitter plate is directly irradiated and acts as a solar absorber and radiant emitter to the lower cavity. With this arrangement, the deposition of particles or condensable gases on the quartz window is prevented, ensuring a clean window during operation. The lower cavity is a $1100 \times 1100 \times 800 \text{ mm}^3$ box that is thermally insulated and lined with SiC plates and contains a packed bed of the carbonaceous feedstock. Four height-adjustable steaminjection lances are inserted from the bottom into the packed bed. The temperature distribution is measured by thermocouples located in a vertical tube positioned at the center of the lower cavity, 5, 10, 15, and 20 cm from the bottom. The product gases exit the lower cavity through an outlet port located above the packed bed close to the emitter plate, where the high temperature favors the thermal decomposition of volatiles. To avoid tar formation during the heating phase, the product gases exiting the solar reactor flow through an electrically heated tubular furnace for tar cracking, which was operated at 1100 °C during the entire test. Thereafter, the product gases are scrubbed and analyzed by gas chromatography and IR detection. Finally, the gases are vented to a torch.

The experimentation was carried out at the CESA-1 solar tower of CIEMAT's Plataforma Solar de Almeria in Spain. The solar reactor was positioned 46 m high on the solar tower. A field of sun-tracking heliostats focused the sunrays toward a refrigerated mirror positioned above the window that directed the concentrated solar beam through the aperture. For an industrial-scale (MW_{th}) solar reactor, a Cassegrain optical configuration would be implemented that makes use of a hyperbolic reflector at the top of a solar tower to redirect the sunlight



Figure 1. Schematic of the solar reactor and peripheral components installed at the solar tower of the Plataforma Solar de Almeria.

collected by the heliostat field to the solar reactor located on the ground level.²⁹ Such an optical arrangement facilitates the feeding of solid reactants and the handling of product gases.

Six carbonaceous feedstocks were tested: low-rank coal, tire chips, fluff, dried sewage sludge, industrial sludge, and sugar cane bagasse. These materials were characterized by their wide-ranging sizes (Figure 2), dissimilar morphologies, and heterogeneous compositions. Their ultimate and proximate analyses are shown in Table 1. Prior to the experiment, the reaction chamber was filled with the feedstock, resulting in typical initial bed heights of ca. 200 mm, depending on the amount of material and its density. The solar reactor was operated in batch mode, with the packed bed shrinking as the gasification progresses. Figures 3-8 show the volumetric flow rates of the steam injected $(\dot{V}_{\rm steam,in})$ and of the product gases $(\dot{V}_{\rm H_2,out}, \dot{V}_{\rm CO,out})$ and $\dot{V}_{
m CO_2,out}$) as well as the emitter plate and bed temperatures at various heights (5, 10, 15, and 20 cm from the bottom) as a function of the time of day during which each of the six experimental runs with lowrank coal, tire chips, fluff, dried sewage sludge, industrial sludge, and sugar cane bagasse were performed, respectively. The mean solar concentration ratio, defined as the solar radiative flux over the aperture normalized to the DNI, ranged between 601 and 768, resulting in solar-radiative power inputs in the range of 108-145 kW. The temperature of the directly irradiated emitter plate responded rapidly, whereas the typically poor thermal conductivity of the packed bed impeded the temperature rise at the bottom of the bed. Thus, heat transfer across the porous bed proved to be the rate controlling mechanism, which was already observed with the 5 kW_{th} reactor prototype.^{11,23} Within the initial heating phase, pyrolysis took place for about 2 h until the top of the bed exceeded the 1300 K temperature favorable for gasification. At above 1300 K, the predominant heattransfer mode in the bed was radiation. In fact, a 7-fold increase in the effective thermal conductivity was shown for beech charcoal.²³ Toward the end of each run, the temperatures rose slowly and syngas production decreased steadily resulting from the depletion of the



Figure 2. Photos of the feedstock processed. (a) Low-rank coal (the right photo was taken after loading in the solar reactor), (b) tire chips (the right photo was taken after loading in the solar reactor), (c) fluff, (d) dried sewage sludge, (e) industrial sludge, and (f) bagasse. The unit scale on the ruler is 1 cm.

| Lable 1. Olimate and 1 Ioannate maryses of the 1 ceustock ese | Table 1 | . Ultim | nate and | d Proximate | Analyses | of the | Feedstock | Used |
|---|---------|---------|----------|-------------|----------|--------|-----------|------|
|---|---------|---------|----------|-------------|----------|--------|-----------|------|

| | | no. 1 low-rank coal | no. 2 tire chips | no. 3 fluff | no. 4 dried sewage sludge | no. 5 industrial sludge | no. 6 sugar cane bagasse | | |
|-----------------------------|---------------------|---------------------|------------------|-------------|---------------------------|-------------------------|--------------------------|--|--|
| Ultimate Analysis (as Fed) | | | | | | | | | |
| С | wt % | 44.4 | 71.0 | 56.3 | 36.5 | 82.6 | 22.8 | | |
| Н | wt % | 2.9 | 7.6 | 9.0 | 5 | 3.1 | 2.8 | | |
| 0 | wt % | 12.6 | 0.3 | 3.7 | 17 | 1.2 | 19.2 | | |
| Proximate Analysis (as Fed) | | | | | | | | | |
| ash | wt % | 4.2 | 18.5 | 1.5 | 26.5 | 7.0 | 4.5 | | |
| volatiles | wt % | 32.1 | 54.6 | 65.0 | 61.1 | 22.2 | 39.1 | | |
| moisture | wt % | 35.0 | 0.5 | 29.0 | 7.7 | 5.4 | 50.5 | | |
| fixed C | wt % | 28.7 | 26.4 | 4.5 | 4.7 | 65.4 | 5.9 | | |
| LHV | MJ kg ⁻¹ | 15.7 | 30.0 | 27.0 | 16.0 | 31.0 | 7.5 | | |

feedstock and a reduction in the endothermic heat sink. Maximum bed temperatures of 1450 and 1300 K were measured at 20 and 5 cm of bed height, respectively.

The extent of the reaction or carbon conversion is defined as

$$X_{\rm C} = 1 - \frac{N_{\rm C, feedstock, f}}{N_{\rm C, feedstock, 0}}$$
(2)

calculated on the basis of the microelementary analysis (LECO CHN-900) of samples collected after each experiment. The carbon content was additionally verified by thermogravimetric analysis of the collected samples. To close the carbon mass balance, the carbon yield in the syngas is calculated by

$$Y_{\rm C} = \frac{N_{\rm out, CO} + N_{\rm out, CO_2} + N_{\rm out, CH_4} + N_{\rm out, C_2H_4}}{N_{\rm C, fs, 0}}$$
(3)

where the total molar outlet flow is $N_{\text{out},i} = \int_{t_0}^{t_f} \dot{N}_{\text{out},i}(t^*) dt^*$. The difference between X_{C} and Y_{C} is due to soot production. The tar content in the gas product was negligible because tars that evolved underwent in situ decomposition at the top of the bed and (during heating phase) in the tar cracker.

The principal performance indicators of the solar reactor are the solar-to-fuel energy-conversion efficiency and the energetic upgrade factor. The solar-to-fuel energy-conversion efficiency is defined as the low heating value (LHV) of the syngas produced divided by the sum of the LHV of the feedstock (attributable to the syngas) and the input solar energy:

$$\eta = \frac{Q_{\text{syngas,out}}}{Q_{\text{fs,converted}} + Q_{\text{solar}}}$$
$$= \frac{\sum_{i} m_{\text{out,i}} \text{LHV}_{i}}{(m_{\text{fs,0}} \text{LHV}_{\text{fs}} - m_{\text{C,res}} \text{LHV}_{\text{C}} - m_{\text{C,soot}} \text{LHV}_{\text{C}}) + Q_{\text{solar}}}$$
(4)

The energetic upgrade factor is defined as the ratio of the LHV of the syngas produced to that of the feedstock (attributable to the syngas)

$$U = \frac{Q_{\text{syngas,out}}}{Q_{\text{fs,converted}}} = \frac{\sum_{i} m_{\text{out,i}} \text{LHV}_{i}}{(m_{\text{fs,0}} \text{LHV}_{\text{fs}} - m_{\text{C,res}} \text{LHV}_{\text{C}} - m_{\text{C,soot}} \text{LHV}_{\text{C}})}$$
(5)

where the total outlet mass flow is $m_{out,i} = \int_{t_0}^{t_f} \dot{m}_{out,i}(t^*) dt^*$ for each relevant species $i = \{H_2, CO, CH_4, C_2H_4\}$. Note that the LHV of the feedstock attributable to the syngas is obtained by subtracting the LHV of the carbon in the residue and that of the soot collected downstream. The error introduced by considering only the carbon in the residue is negligible, as confirmed by thermogravimetric analysis, because most of the material left in the reaction chamber undergoes pyrolysis. This definition of η does not account for the sensible heat of the hot product gases exiting the reactor, which could be recovered and used, for example, for generating steam. Compared to $Q_{\text{syngas,out}}$ the sensible heat amounts to about 10% at 500 °C (allowing the use of a fan for venting the gas) and to about 20% at 1000 °C. Note that η does not include the optical efficiency of the solar-concentrating system, which is typically 60–70% for solar towers.^{30,31} η has a direct impact on the

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economics of the process. Higher η values imply a smaller solarconcentrating system for the same syngas output, which directly translates to lower specific syngas fuel cost, because (analogous to solar thermal electricity (CSP) plants) the major cost component derives from the investment of the solar collecting and concentrating infrastructure.^{32,33} The values experimentally obtained ranged from η = 21.8% for sewage sludge to η = 35.3% for low-rank coal. A heattransfer model²³ indicated that the principal mode of heat loss is by radiative transfer through the aperture and by the sensible heat consumed during the transient heating of the insulated reactor. Values of U greater than 1 indicate the successful storage of solar energy in chemical form and the upgrading of the calorific value of the converted fuel achieved with the solar-gasification process. The lowest U value of 1.06 was obtained for fluff, whereas the highest U value of 1.32 was obtained for sugar cane bagasse. Note that typically U = 0.7 for the conventional autothermal gasification because of the significant portion of the feedstock combusted for process heat.¹ The different values of η and U obtained for the various feedstocks are due to their heterogeneous morphological properties (particle size, porosity, and specific surface area) and their different initial content of moisture, volatiles, and fixed carbon (Table 1). These differences strongly affect heat-transfer rates, reaction kinetics, and enthalpy changes, which in turn results in different reaction extents and syngas compositions. In addition, the operational conditions (e.g., the solar radiative flux \dot{q}_{solar} and the mass flow rate of steam) were somewhat dissimilar among the different experimental runs. These aspects are elaborated on in the following experimental observations for each of the six feedstocks.

3. EXPERIMENTAL RESULTS

The experimental runs with each of the 6 feedstocks is presented and discussed.



Figure 3. Volumetric flow rates of the steam injected ($\dot{V}_{\text{steam,in}}$) and the product gases ($\dot{V}_{H_2,\text{out}}$, $\dot{V}_{CO,\text{out}}$ and $\dot{V}_{CO_2,\text{out}}$) as well as the emitter plate and bed temperatures at various heights (5, 10, 15, and 20 cm from the bottom) as a function of the time of day during experiment no. 1 with low-rank coal. The subscript N denotes normal conditions. Mass flow rates were calculated at 273 K and 101 325 Pa.

Experiment No. 1: Low-Rank Coal. Low-rank coals are wet coals with a high volatile content and hence relatively low carbon and energy contents, such as sub-bituminous coals. Low-rank coal (180 kg) from Indonesia was loaded in the lower cavity chamber. The progression of the experimental run can be seen in Figure 3. The steam injection at 14.5 kg/h was started after the heating of the bed top and was reduced to 10.5 kg/h after 4.5 h. The heating of the porous bed was slow because of



Figure 4. Volumetric flow rates of the steam injected ($\dot{V}_{\text{steam,in}}$) and the product gases ($\dot{V}_{\text{H}_2,\text{out}}$, $\dot{V}_{\text{CO},\text{out}}$, and $\dot{V}_{\text{CO}_2,\text{out}}$) as well as the emitter plate and bed temperatures at various heights (5, 10, 15, and 20 cm from the bottom) as a function of the time of day during experiment no. 2 with tire chips.



Figure 5. Volumetric flow rates of the steam injected ($\dot{V}_{\text{steam,in}}$) and the product gases ($\dot{V}_{\text{H}_2\text{out}}$, $\dot{V}_{\text{CO},\text{out}}$, and $\dot{V}_{\text{CO}_2\text{out}}$) as well as the emitter plate and bed temperatures at various heights (5, 10, 15, and 20 cm from the bottom) as a function of the time of day during experiment no. 3 with fluff.

its poor effective thermal conductivity, with the lowest part not exceeding 900 °C. This resulted in a low $X_{\rm C}$ of 57% after 8 h of operation. Nevertheless, on the basis of the material gasified, $\eta = 35.3\%$.

Experiment No. 2: Tire Chips. Tire chips are obtained by cutting scrap tires into pieces of about 100-150 mm in length and width. The experimental run is shown in Figure 4. Steam at a mass flow rate of 10.5 kg/h was injected after the heating of the bed and continued for the entire duration of the experiment. A very high H₂/CO and a low CO/CO₂ ratio was registered, indicative of a water-gas shift reaction that was presumably happening in the outlet because of excess water in the system. Toward the end of the experiment, product gas flow rates dropped as a result of volatiles depletion.



Figure 6. Volumetric flow rates of the steam injected ($\dot{V}_{\text{steam,in}}$) and the product gases ($\dot{V}_{\text{H}_{2},\text{out}}$, $\dot{V}_{\text{CO},\text{out}}$, and $\dot{V}_{\text{CO}_{2},\text{out}}$) as well as the emitter plate and bed temperatures at various heights (5, 10, 15, and 20 cm from the bottom) as a function of the time of day during experiment no. 4 with dried sewage sludge.



Figure 7. Volumetric flow rates of the steam injected ($\dot{V}_{\text{steam,in}}$) and the product gases ($\dot{V}_{H_2,\text{out}}$, $\dot{V}_{\text{CO},\text{out}}$, and $\dot{V}_{\text{CO}_2,\text{out}}$) as well as the emitter plate and bed temperatures at various heights (5, 10, 15, and 20 cm from the bottom) as a function of the time of day during experiment no. 5 with industrial sludge.

Experiment No. 3: Fluff. The fluff consists of fine fraction of recycled plastics. The progression of the experimental run is shown in Figure 5. In spite of the solar-power input being comparable to the other cases, the heating of the bed was significantly slower because of the lower conductivity of the fluff. As the fixed carbon content was small, the decomposition of volatiles was dominant for the syngas production. This, together with the steam injection and the original moisture of the feedstock (29%), leads to a high H₂ concentration and a low CO/CO₂ ratio at the outlet.

Experiment No. 4: Dried Sewage Sludge. Sewage sludge is the solid-waste residual derived from the treatment of municipal waste water. The experimental run is shown in Figure 6. After bed heating, the steam was injected at varying mass flow rates of up to 22 kg/h. The bed heating was relatively



Figure 8. Volumetric flow rates of the steam injected ($\dot{V}_{\text{steam,in}}$) and the product gases ($\dot{V}_{H_2,\text{out}}$, $\dot{V}_{\text{CO},\text{out}}$ and $\dot{V}_{\text{CO}_2,\text{out}}$) as well as the emitter plate and bed temperatures at various heights (5, 10, 15, and 20 cm from the bottom) as a function of the time of day during experiment no. 6 with sugar cane bagasse.



Figure 9. Syngas composition (H_2/CO , CO_2/CO , and CH_4/CO molar ratios) measured downstream of the scrubber for the six solar experimental runs.

slow because of the low thermal conductivity of the feedstock. After 2 h of steam feeding, the product production rates drop because of feedstock depletion, resulting in a $X_{\rm C}$ of 100%.

Experiment No. 5: Industrial Sludge. Industrial sludge is the solid-waste residual derived from the treatment of industrial waste water. The main operational parameters of the experiment are shown in Figure 7. As the feedstock has very low moisture content (5.4%), steam injection at a mass flow rate varying between 7.2 and 14.5 kg/h was started after the bed heating and continued for the entire duration of the experiment. Despite the increasing temperature at the bottom of the bed, the product outlet flow rate started dropping steadily after 4 h into the run because of the depletion of volatiles and the slower conversion of fixed carbon that also requires a significantly higher amount of energy. Indeed, the fixed C content of industrial sludge is the highest among the



Figure 10. Energetic upgrade factor, *U*, solar-to-fuel energy efficiency, η , and averaged upper- and lower-cavity temperatures, T_{uc} and T_{lc} , for all six experimental runs.

considered feeds tocks, which results in a relatively poor $X_{\rm C}$ of 36% after 9 h.

Experiment No. 6: Sugar Cane Bagasse. Sugar cane bagasse is an agricultural by-product derived from sugar-cane processing for sugar or ethanol production. Its moisture content is relatively high (typically 50%), which makes it unattractive for incineration but particularly suitable for gasification.³⁴ Interestingly, variations in the steam flow rate did not affect the reaction rate because the moist bagasse contained excess water for the gasification. Steam feeding at a mass flow rate of 14 kg/h was applied intermittently for short periods of time during the experiment, as shown in Figure 8, resulting in the expected rise in both H₂ and CO₂ resulting from the water-gas-shift reaction. Because no beneficial effect on the gasification was observed, steam injection was not applied for most of the run. This experiment yielded the highest energetic upgrade of the feedstock, U = 1.3.

A comparison of the average syngas molar ratios downstream the scrubber, defined as

$$\frac{V_{\rm i}}{V_{\rm j}} = \frac{\int_0^{t_{\rm f}} \dot{V}_{\rm i,out}(t^*) \, \mathrm{d}t^*}{\int_0^{t_{\rm f}} \dot{V}_{\rm j,out}(t^*) \, \mathrm{d}t^*} \tag{6}$$

is shown in Figure 9. The H_2/CO ratios ranged between 2.0 (expt. no. 6) and 5.2 (expt. no. 3), CO/CO₂ ratios ranged between 1.1 (expt. no. 3) and 2.0 (expt. nos. 1 and 5), and CO/ CH₄ ratios ranged between 1.6 (expt. no. 3) and 10.8 (expt. no. 5). These ratios can be strongly influenced by excess steam in the system because of the water-gas-shift reaction occurring downstream of the reactor. A comparison of the energetic performance of the different runs is presented in Figure 10. The energetic upgrade factor, U, ranged between 1.03 (expt. no. 3) and 1.30 (expt. no. 6), and the solar-to-fuel energy efficiencies ranged between 22 (expt. no. 4) and 35% (expt. no. 1). The temperatures shown are recorded on the upper side of the absorber plate (T_{uc}) and at a 45 cm height of the thermocouple tube positioned in the lower cavity (T_{lc}) that is always above the bed. They are averaged over the period of the respective test with $T_{\rm uc} > 1000$ °C.

An overview of the main operational parameters and results for all six experimental runs is shown in Table 2. Overall, the 150 kW_{th} pilot plant operation confirmed the experimental results obtained with the lab-scale 5 kW_{th} solar reactor.¹¹ As predicted by dynamic modeling,²³ the reaction rate was limited by heat transfer across the packed bed characterized by a transient ablation regime in which the rate of heat transfer (predominantly by radiation) to the top layer of the packed bed undergoing endothermic gasification proceeded faster than the rate of heat transfer (predominantly by effective conduction) to the depth of the packed bed. The solar pilot plant demonstration was accomplished under realistic operating conditions relevant to large-scale industrial implementation. The results provide compelling evidence for the viability of solar thermochemical gasification and clarified the efforts still required to further scale up the solar-reactor technology for MW_{th} solar-radiative input in a solar-tower configuration.

Table 2. Overview of the Main Operational Parameters and Results for All Six Experimental Runs

| | | no. 1 low-rank coal | no. 2 tire chips | no. 3 fluff | no. 4 dried sewage sludge | no. 5 industrial sludge | no. 6 sugar cane bagasse | | |
|-----------------------------|--------------------|---------------------|------------------|-------------|---------------------------|-------------------------|--------------------------|--|--|
| Mass Balance | | | | | | | | | |
| $m_{\rm feedstock,0}$ | kg | 180.0 | 63.4 | 51.0 | 55.0 | 83.3 | 138.0 | | |
| $m_{\rm feedstock,f}$ | kg | 42.0 | 25.4 | 1.2 | 14.6 | 50.2 | 8.8 | | |
| $X_{\rm C}$ | | 0.57 | 0.70 | 0.99 | 1.00 | 0.36 | 0.92 | | |
| $Y_{\rm C}$ | | 0.44 | 0.32 | 0.48 | 0.73 | 0.27 | 0.72 | | |
| Average Syngas Composition | | | | | | | | | |
| H_2/CO | | 2.2 | 4.4 | 5.2 | 2.7 | 2.6 | 2.0 | | |
| CO/CO_2 | | 2.0 | 1.4 | 1.1 | 1.6 | 2.0 | 1.6 | | |
| $\rm CO/CH_4$ | | 7.4 | 2.0 | 1.6 | 4.9 | 10.8 | 9.4 | | |
| | | | | | | | | | |
| $\dot{q}_{ m solar,\ peak}$ | kW m ⁻² | 620 | 498 | 576 | 670 | 583 | 644 | | |
| C _{mean, peak} | | 724 | 609 | 601 | 768 | 609 | 741 | | |
| Q _{solar, peak} | kW | 134 | 108 | 125 | 145 | 126 | 140 | | |
| $\dot{Q}_{ m solar, avg^*}$ | kW | 113 | 88 | 102 | 113 | 104 | 111 | | |
| $T_{ m uc, \ avg^*}$ | K | 1410 | 1372 | 1438 | 1426 | 1456 | 1446 | | |
| $T_{ m lc, avg^*}$ | K | 1301 | 1295 | 1334 | 1331 | 1262 | 1381 | | |
| η | | 0.35 | 0.27 | 0.25 | 0.22 | 0.25 | 0.27 | | |
| U | | 1.26 | 1.07 | 1.03 | 1.05 | 1.14 | 1.30 | | |
| | | | | | | | | | |

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4. CONCLUSIONS

The technical feasibility of the solar thermochemical gasification of six different types of carbonaceous waste materials (industrial sludge, fluff, tire chips, dried sewage sludge, low-rank coal, and sugar cane bagasse) was demonstrated with a 150 kW_{th} packed-bed pilot plant operated at a solar tower of the Plataforma Solar de Almeria. The various heterogeneous feedstocks proved to be suitable for the production of high-quality syngas, with the best energy efficiency observed for low-rank coal ($\eta = 35\%$) and the best energetic upgrade for sugar cane bagasse (U = 1.3). The solar-reactor concept is scalable to an industrial application (MW_{th}) and can, in general, accept bulk carbonaceous feedstock of any shape and size without prior processing.

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Notes

The authors declare no competing financial interest.

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NOMENCLATURE

- $A = \text{area, } m^2$
- DNI = direct normal irradiation, $W m^{-2}$
- LHV = lower heating value, J kg⁻
- m = mass, kg
- \dot{m} = mass flow rate, kg s⁻¹
- N = amount of substance, mol
- \dot{N} = molar flow rate, mol s⁻¹
- Q = energy, J
- \dot{Q} = power, W
- \dot{q} = power flux, W/m²
- T =temperature, K
- t = time, s
- U = energy upgrade
- \dot{V} = volume flow rate, $m_N^3 h^{-1}$
- $X_{\rm C}$ = carbon conversion
- $Y_{\rm C}$ = carbon yield in syngas

Greek Letters

 η = energy conversion efficiency

Subscripts

0 = initial conditions

- avg = averaged over entire test
- avg^* = averaged over period with $T_{uc} > 1000$ °C
- f = final conditions
- fs = feedstock
- lc = lower cavity

N = at normal conditions (T = 273.15 K, p = 101325 Pa)

- mean = averaged over aperture area
- res = residue
- out = outlet
- uc = upper cavity

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