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Insights into the influence of biomass feedstock type, particle size and feeding rate on thermochemical performances of a continuous solar gasification reactor

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ABSTRACT

The solar-driven steam gasification of different lignocellulosic biomass feedstocks was experimentally investigated with a 1.5 kW_{th} continuously particle-fed solar reactor at high temperature using real high-flux solar radiation provided by a parabolic dish concentrator. Experiments were carried out with five carbonaceous materials under different biomass feeding rates in the range of 0.8–2.7 g/min at 1300 °C in order to optimize the synthesis gas production and composition. Increasing biomass feeding rate (at constant slightly over-stoichiometric steam/biomass ratio) noticeably promoted the syngas yields that reached up to 83.2 $mmol/g_{biomass}$. The syngas yield (especially H_2) was more affected by the biomass feedstock (chemical composition) than by the particle size in the considered range (0.3–4 mm). The calorific value of the biomass was solar upgraded up to 24% through the syngas produced with a carbon conversion above 90%, thereby accomplishing efficient solar energy storage into the produced syngas. Increasing the biomass feeding rate inherently shortened the solar processing duration (for a given biomass amount). Thus, the solar energy input and the heat losses were reduced while the overall syngas production capacity was increased, which in turn drastically enhanced both the thermochemical reactor efficiency and the solar-to-fuel energy conversion efficiency with maximum values typically beyond 25%.

1. Introduction

Among the renewable energy sources available on Earth, both biomass and solar energy are sustainable carbon-neutral energy sources with growing interest. While biomass represents an environmentally clean and widely available resource that can be converted into fuels through gasification, solar energy is an inexhaustible abundant and free energy source that can be converted to heat through concentrating solar power technologies for supporting endothermic reactions [1]. However, solar irradiation is diluted, intermittent and non-equally distributed over the world, and thus conversion of solar energy into chemical energy carriers, i.e. solar fuels, which can be stored-transported, is essential. Thus, the combination of biomass and solar energy in a solar-driven thermochemical gasification process is of particular interest to convert solid carbonaceous materials to gaseous carbon neutral solar fuels [2], consisting primarily of CO and H_2 commonly called “synthesis gas” [3], thereby offering an efficient means of storing intermittent solar energy.

The ideal stoichiometric steam-based gasification reaction of solid carbonaceous materials to syngas can be written by the simplified overall reaction as:

$$C_xH_yO_z + (x-z)H_2O \rightarrow \left(\frac{y}{2} + x - z\right)H_2 + xCO \quad (1)$$

In the conventional autothermal gasification process, a part of biomass feedstock in the range of approximately 35–40% [4,5] is internally combusted with oxygen in order to supply high-temperature process heat for endothermic reaction, thereby directly reducing the complete use of biomass feedstock and adversely leading to the contamination of syngas product. Hence, to avoid wasting biomass resources for process heat and to achieve

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full utilization of the feedstock for fuel production, the utilization of concentrated solar power as an external process heat source for carbonaceous materials gasification has been investigated [2,3,6].

Regarding gas products applications, syngas can be used as a primary feedstock for a multitude of chemical synthesis processes. Moreover, it can be burned directly in gas engines, furnaces, boilers and stoves, utilized to produce methanol and hydrogen, or further converted into synthetic liquid fuel via the Fisher-Tropsch method [7].

Gasification performance mainly depends on solar thermochemical reactor designs [8], operational conditions [9] and starting carbonaceous materials [10]. Regarding carbonaceous materials, several researches related to both the pyrolysis and gasification processes have been performed on charcoal [11], petroleum coke [12–16], cellulose [17] and waste materials [18–23] to produce syngas. Moreover, some studies have addressed the bio-oil production through the pyrolysis process from a wide variety of sustainable carbonaceous feedstocks such as rice husk [24], or palm oil waste [25]. Wieckert et al. [21] operated a 150 kW_{th} packed-bed solar reactor with six different carbonaceous waste feedstocks. They reported that different values of syngas yields as well as reactor performances regarding the solar-to-fuel energy conversion efficiency and energetic upgrade factor were obtained because of different physical properties of the feedstock such as particle size, porosity and specific surface area, and various initial contents of moisture, volatile and fixed carbon. The influence of particle properties such as size, shape and density on particle flow and flame propagation was studied in a traditional gasification process [26,27]. Size reduction improved the conversion processes because of the creation of larger reactive surface areas, thus resulting in enhanced heat transfer conditions. Moreover, Z'Graggen et al. [12] indicated that small particle sizes show a positive influence on thermochemical reaction rates. However, sufficient grinding is energy demanding and carbonaceous materials with low bulk density are possibly subjected to feeding problems [28].

The performance assessments of solar gasification reactors are usually reported in terms of the solar-to-fuel energy conversion efficiency, energy upgrade factor, carbon conversion and thermochemical reactor efficiency. The solar-to-fuel energy conversion efficiency (η_{solar}) is defined as the ratio of the chemical energy of the syngas produced to the total energy input, which is the summation of the solar input and the lower heating value of the feedstock:

$$\eta_{solar} = \frac{(LHV_{syngas} \cdot \dot{m}_{syngas})}{\dot{Q}_{solar} + \left(LHV_{feedstock} \cdot \dot{m}_{feedstock}\right)} \quad (2)$$

Where LHV_{syngas} and $LHV_{feedstock}$ are the lower heating values (J/kg) of syngas products and biomass feedstock, $\dot{m}_{syngas}$ and $\dot{m}_{feedstock}$ are the mass flow rates (kg/s) of syngas products and biomass feedstock, respectively, and $\dot{Q}_{solar}$ is the solar power input (W).

The energy upgrade factor (U) is given by the ratio of the energy content of the chemical products to that of the biomass feedstock processed:

$$U = \frac{LHV_{syngas} \cdot \dot{m}_{syngas}}{LHV_{feedstock} \cdot \dot{m}_{feedstock}} \quad (3)$$

The carbon conversion (X_C) is defined as the ratio of the carbon yield in the syngas to the initial amount of carbon in the biomass feedstock (F_i represents the molar flow rate of species i, mol/s):

$$X_C = \frac{\int_0^t F_{CO}(t)dt + \int_0^t F_{CO_2}(t)dt + \int_0^t F_{CH_4}(t)dt + \int_0^t 2F_{C_2H_m}(t)dt}{\int_0^t xF_{C_xH_yO_z}(t)dt} \quad (4)$$

The thermochemical reactor efficiency represents the ratio of solar energy absorbed by the reactor that is used for driving the chemical reaction and for heating the steam, inert gas and solid reactant:

$$\eta_{reactor} = \frac{\dot{Q}_{heating} + \dot{Q}_{reaction}}{\dot{Q}_{solar}} \quad (5)$$

In this study, the development and performance assessment of an innovative 1.5 kW_{th} solar thermochemical reactor design based on the principle of conical spouted bed reactor for continuous wood biomass gasification was conducted using real solar radiation concentrated by a parabolic dish solar concentrator. The feasibility and reliability of this type of reactor for solar biomass gasification with various types of biomass in a continuous process needs to be demonstrated. In addition, based on the experimental investigations of biomass gasification, several studies were focused on the effect of operating parameters, especially biomass feeding rate, on the reactor performance in conventional autothermal gasification [29–31]. However, no prior work has been devoted to the biomass feeding rate influence in allothermal solar gasification processes. Indeed, this quantifiable operating parameter is a relevant metric that directly affects the reactor capacity for a given solar power input absorbed by the reactor, and thus the solar-to-chemical energy conversion efficiency. Therefore, the impact of biomass feeding rate on reactor performances must be assessed. It must be closely related to the rate of the gasification reaction, in order to avoid solid accumulation inside the reactor (due to incomplete biomass gasification) and low syngas quality, if the feeding rate is too high with respect to the reactor capacity, which in turn may downgrade the reactor performance. Inversely, insufficient feedstock flow rates with respect to nominal conditions may yield complete feedstock conversion but limited syngas production, thus resulting in the underutilization of the reactor capacity and available solar power input. Therefore, the identification of suitable feeding rates as nominal processing conditions is required to optimize both the syngas production capacity and the thermochemical reactor efficiency of the continuous process.

The present study describes the experimental investigation of solar-driven biomass gasification using the continuously-fed solar reactor with a large variety of biomass feedstocks to optimize the reactor performance as well as syngas production capacity by focusing on the biomass feeding rate adjustment.

2. Experimental

2.1. Biomass feedstock

Five variants of carbonaceous materials from different lignocellulosic biomass sources consisting of beech wood (Type A and B) or a mix of pine and spruce wood (Type C, D and E) were utilized for solar-driven experiments in order to investigate the influence of biomass variant on the syngas production yield and reactor performance. These biomass feedstocks were shredded into different sizes, according to Fig. 1, for assessing the impact of their initial particle size on the gasification performance as well as on the biomass injection in a continuous feeding mode [28]. Their characteristics, ultimate and proximate analyses are presented in