Renewable Energy 74 (2015) 671–680

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Biomass gasification using low-temperature solar-driven steam supply

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ARTICLE INFO

Article history:
Received 9 January 2014
Accepted 14 July 2014
Available online 18 September 2014

Keywords:
Concentrating solar
Biomass gasification
Thermal energy storage
Process simulation

ABSTRACT

A numerical modeling study on the low-temperature steam gasification process is presented to outline the possibility to drive the process with an integrated Concentrated Solar Power (CSP) plant, which provides low-temperature steam, with the aim of preserving a comparable efficiency of the new plant with traditional high-temperature biomass gasification processes. To meet this, the effective parameters and operating conditions are assessed and determined for low-temperature biomass gasification by means of sensitivity analysis, in order to find out the optimal design of the new gasifier. Crucial parameters comprise the residence time of the solid fuel and of the gas phase (leading to efficient gas–solid interactions), as well as the amount of injected oxygen and steam. Moreover, several operative parameters such as content of moisture in the biomass feedstock, size of the solid particles, equivalence ratio and structural components amount in the biomass feedstock are taken into account to optimize the operation. The molar ratio of H_2/CO has been selected as a benchmark of efficiency in the process because the produced syngas would be applied in the methanol synthesis process, which needs a molar ratio of H_2/CO close to the value of two. The percentage of the solid residue (weight % of the solid feedstock) has been evaluated along with the molar ratio of H_2/CO in the low-temperature process to guide the redesign of the solar driven gasifier, in terms of reactor volume and amount of required oxygen and steam, which are necessary to sustain the process. The modeling and simulation to design the process have been accomplished by a comprehensive modeling package (GASDS), which includes kinetics of biomass devolatilization and pyrolysis, gasification, and secondary gas phase kinetic schemes. The gasifier, owing to its intrinsic multi-scale nature, is simulated describing both the particle and the reactor scales.

1. Introduction

Owing to oil price fluctuations, environmental protocols, and the significant growth in applying energy produced from non-fossil fuel sources, it is encouraging for the energy sector to focus the attention on the power generation from renewable-based power plants. On the other hand, saving energy and reducing fossil fuels consumption for high-consuming processes, such as coal-powered gasification processes, drives the attention to apply alternative sources for generating steam and energy with a strong insight on mechanistic physical and chemical aspects, in order to optimize power and chemical plants operation.

Biomass gasification could provide a suitable way to produce syngas in a greener fashion, preserving a comparable efficiency with respect to traditional coal supplied gasifiers. Therefore, the focus on biomass is going to be concentrated intensively as a renewable source more than coal, and interests are driven towards sustainable bio-products for future, such as bio-methanol.

Several modeling and experimental studies focus the attention on biomass gasification to assess and evaluate the sensitivity of operating parameters on the efficiency of the process. [18] reported a lab-scale fixed bed reactor of steam biomass gasification considering the effect of particle size at different temperature above 700 °C. Results show that the efficiency of the gasification as well as the yield of hydrogen are increased by decreasing the particle size, consequently the content of char and tar decreases [18]. In the other interesting experimental study, [19] have reported the effect of air-steam gasification in a fluidized bed. They considered a series of operating parameters such as the ratio of steam to biomass (SBR),

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http://dx.doi.org/10.1016/j.renene.2014.07.021
0960-1481/

equivalent ratio (ER), among the others, in different reactor temperatures, and they showed the direct effect of higher temperatures on higher hydrogen yield and the inverse effect on LHV [19]. [8,21] presented a very comprehensive work on the characteristic effect of the different biomass types on combustion [21]. Perez et al. studied the effect of operating and design parameters, especially the geometry of the reactor, on the performance of the gasification/combustion of biomass in downdraft reactors [23]. The effect of air inlet temperature and oxygen concentration is analyzed by Ref. [30] as the gasifying agent in the updraft reactor [30].

The main objective of this work is to investigate the effect of different operating conditions and to design a new configuration of reactor for low-temperature gasification to achieve a comparable efficiency with respect to high-temperature gasification, looking for optimizing the molar ratio of H_2/CO in produced gas. The advantageous of this route relies on the possibility to use low-temperature steam derived from a renewable source of energy (CSP plant), and simultaneously, preserving the calorific value of the process by manipulating the different effective operating parameters. Concentrated Solar Power plants are proposed in this work as an appropriate alternative to replace fossil fuels in providing low-temperature steam, fulfilling environmental and economic issues. According to the authors' knowledge, studies taking into account this aspect of study for low-temperature steam driven solar power plant biomass gasification for 2nd generation biofuels have not been published in the literature so far.

2. Steam and power generation

Steam is a critical energy vector and it is essential for all industrial processes for heating utilities, driving the equipment and powering the processes. Moreover, the dependency of the chemical industries from steam is inevitable and, therefore, it is promising to provide alternative clean productions of it. All conventional processes such as gas turbine combined cycle (CC), integrated gasification combined cycle (IGCC), pressurized fluidized bed combustion (PFBC) are fuel-based steam/power generation processes (see also [9,14]).

Nowadays, coal and natural gas are the main fuels to produce steam and power. Environmentally speaking, reducing the carbon footprint from the chemical plants requires the extensive attempts in reducing the energy requirement, and reducing the carbon emissions associated with the remaining energy is required [7,15,16]. In addition, changing the processes to one involving less energy-intensive chemistry route or less energy-intensive unit operations is the approach to reduce the consumption of energy by chemical industries. Moreover, changing the process to alter the relative requirements for thermal energy is the other approach for energy reducing purposes [32]. Following these approaches, replacing fuel-based power plants to renewable and clean source of energy could bring the beneficial challenging in comparison with the traditional ways of steam generation processes. In this work, it has been utilized the steam generated from a pre-designated concentrated solar power plant [33]. The process is accomplished based on storing the heated working fluid via solar collector field (Thermal Energy Storage, TES), and therefore, generating power. More details on solar plants and a comprehensive review on CSP technologies could be found in the work of [31].

3. Low-temperature biomass gasification

Biomass gasification is the thermo-chemical conversion of organic waste feedstock in a reduced oxygen medium (partial oxidization); while the combustion takes place completely in the presence of stoichiometric oxygen. The common operating temperature for gasification is rather high, commonly varies from 750 °C to 1000 °C, depending on the type of feedstock and operating conditions. The resulting product is syngas, mainly composed by carbon monoxide, carbon dioxide, hydrogen, methane, and solid residues are the by-products (ashes and unconverted biomass). A relevant interest towards biomass gasification produced a huge number of scientific works and perspectives, which are nicely reviewed in the publication by Ref. [27]. Although the gasification is conceptually a high-temperature process, it might be operate at lower temperatures with adapting the effective parameters, operation conditions and alternative design options in the configuration of the reactor. The main concern of this activity is to investigate and apply the low-temperature steam (~410 °C) generated from the pre-designed solar power plant, which is integrated to the biomass gasification process and drives it efficiently (Fig. 1). According to the authors' knowledge, studies taking into account this aspect of study for low-temperature steam driven solar power plant biomass gasification for 2nd biofuels have not been published in the literature so far. [6] assess a solar-based electricity generation in Chile by CSP, achieved by a Solar Power Tower plant (SPT) using molten salt as heat carrier and store. [12] proposed a study on the gasification process for 3rd generation biofuels. In his work, the design is based on steam gasification of biomass with the heat directly provided by a solar concentrating tower, which provides temperatures over 1000 °C. However, in our work the low-temperature steam (~ 410 °C) is generated by the concentrated solar power plant and it provides the oxidizing agent for the gasification process.

In order to provide the consistent and effective operation, the process is controlled by thermochemical heat of reaction along with related key parameters. Due to the applications of the product syngas, which could be used as a fuel, or to produce chemicals, it is crucial to keep high the yield of hydrogen and carbon monoxide, thus reducing the amount of unconverted solid residue. In addition, when the final goal is the synthesis of chemicals, such as methanol or dimethyl ether, it would be appropriate to keep controlled the molar ratio of H_2/CO (close to the value of two for methanol synthesis). In order to demonstrate the process feasibility of low-temperature steam biomass gasification, it is necessary to understand and unveil the chemistry involved in the process, in order to design an effective solar-powered gasifier. Fig. 2 shows the schematic of the gasifier, underlining the multi-scale nature of the process. The process is modeled starting from the description of the chemical evolution of biomass particles, which are discretized into concentric shells. Solid particles interact with the surrounding gas phase, which is considered as perfectly mixed. Several gas–solid elemental layers could be then interconnected in a cascade to reproduce the updraft gasifier at the reactor scale.

In the detailed chemical description, the process occurs in the three main stages. Drying happens around 100 °C, releasing water vapor from the surface and inner pores of the solid fuels. In this stage, some organic and inorganic compounds of fuel are released. Pyrolysis, which is observed by increasing the temperature, is a transient step to promote the destructuring of the solid fuel, originating new chemical species. Three main products derives from this stage and are usually classified in light gases, tars and char. The gasification and combustion stage, which includes the main gas–solid reactions, occurs between the solid fuel (char) and the chemical species in the surrounding atmosphere. The gaseous species include these released during drying and pyrolysis. Moreover, hot ashes and unconverted char are responsible for the heating of the oxidizing gas fed from the bottom. In comparison, combustion process requires the use of stoichiometric oxygen, which might produce H_2O, CO_2, related to the fuel compositions.