C. R. Chimie xxx (2016) 1–8

Contents lists available at ScienceDirect

Comptes Rendus Chimie

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Biomass conversion to hydrogen-rich synthesis fuels using water steam plasma

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ARTICLE INFO

Article history:
Received 27 May 2015
Accepted 1 December 2015
Available online xxxx

Keywords:
Biomass
Conversion
Hydrogen
Synthesis fuels
Thermochemical
Water steam
Arc plasma

ABSTRACT

In this study, an experimental plasma-chemical reactor equipped with an arc discharge water steam plasma torch was used for biomass conversion to hydrogen-rich synthesis fuels. Glycerol and crushed wood were used as biomass sources. The effects of different conversion parameters including the water steam flow rate, treated material flow rate, and plasma torch power were studied. The experimentally obtained results were compared with the model based on the thermodynamic equilibrium. Additionally, the quantification of the plasma conversion system in terms of energy efficiency and specific energy requirement was performed. It has been found that the synthesis gas can be effectively produced from the biomass using water steam plasma.

1. Introduction

Global energy consumption continuously grows due to the increasing population and industrial development. In the context of fossil fuel abatement, environmental issues and rising waste volumes, sustainable strategies for waste management and diversifying energy production are required. The production of biodiesel from biomass is expected to increase in the European Union in order to meet the goal of replacing 20% and 30% of petroleum-based fuels with biofuels by 2020 and 2030, respectively [1, 2]. In the past few years, biomass and waste have become attractive as renewable sources that could play a major role in renewable energy [3]. Waste treatment aims to reduce landfill disposal and to minimize the environmental impact, whereas biomass seeks to diminish the dependence on fossil fuels. Various thermal processes, such as incineration [4, 5], pyrolysis [6, 7] or gasification [8, 9], have been developed for biomass/waste treatment to recover energy from the organic fraction. The thermochemical conversion of biomass/waste to energy allows generation of a combustible gas, called synthesis gas, which is mainly composed of hydrogen (H_2) and carbon monoxide (CO). This synthesis gas can be used as a feedstock for liquid fuel production via the Fisher–Tropsch synthesis [10, 11], gas turbine or fuel cell for energy production [12, 13] or chemical products as ammonia, methanol and hydrogen [14]. However, the conventional methods have some limitations, such as a low energy balance, pollution, catalyst requirement and its deactivation, process control, flexibility, the compactness and size of equipment, etc., which might be overcome using plasma [15].

Thermal plasma seems to be one of the most attractive and environmentally friendly technologies for the biomass/waste treatment. High gas temperatures in plasma,

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http://dx.doi.org/10.1016/j.crci.2015.12.002
1631-0748/

reaching up to 15000 K [16], offer a possibility to advantageously contribute to the pyrolysis/gasification of organic materials by accelerating the reaction kinetics. The easiest enthalpy control by adjusting the electric power and flow rate of the plasma-forming gas allows controlling the parameters of the conversion process *in situ*. The production of reactive species by the plasma, such as atomic oxygen, hydrogen and hydroxyl radicals, is an additional advantage of using plasma [17]. However, the maturity of thermal plasma in terms of economic feasibility has not been proved yet because of the use of expensive electrical energy to run plasma torches.

The oxidation environment in the waste treatment process is also an important feature. Knoef [18] shows the differences obtained between two different oxidation agents used (pure oxygen and air). Pure oxygen provides a gas with a calorific value of 10.1 MJ/m^3, while the use of air gives only 4.2 MJ/m^3 due to the dilution of the synthesis gas with nitrogen introduced with the airflow. Water steam is generally preferred, because it produces the desired reactions including the steam reforming reaction and increases the H_2 ratio in the synthesis gas. However, the steam reforming reaction is highly endothermic and needs a high temperature (1100–1700 K) [19].

Numerous investigations have been carried out employing thermal plasma (DC – direct current, AC – alternating current, RF – radio frequency, and MW – microwave) with a different type of plasma-forming gas for biomass/waste conversion to energy. References [20, 21] investigated the pyrolysis/gasification of biomass and waste for synthetic fuel production using a hybrid argon–water stabilized DC plasma torch. It was found that the synthesis gas with a high caloric value, a high content of hydrogen and CO, and a low concentration of CO_2 was produced. An AC plasma torch stabilized with an air stream was used for wood gasification in [22]. The authors claim that 1 kg of wood with a moisture content of ~20% can generate ~13.5 MJ/kg of chemical energy with an energy consumption of ~2.16 MJ/kg. The MW plasma gasification of glycerol was performed in [23]. It was found that, at a zero O_2/fuel ratio, it is possible to produce the syngas with a high H_2 and CO content of 57% and 35%, respectively. Additionally, when the steam/fuel ratio increased, the H_2 content in the syngas increased, whereas the syngas heating value and gasification efficiency decreased. The pyrolysis of waste tire powder in a capacitively coupled RF plasma reactor under reduced pressure was studied in [24]. The results suggested that the pyrolysis of polymeric waste may be a feasible technique for recycling polymer waste. The gaseous product contains a large amount of H_2 and CO and a small amount of methane and other light hydrocarbons. The gasification of municipal solid waste using the pilot-scale Plasma Gasification Melting (PGM) process is reported in [25]. The syngas lower heating value (LHV) varied from 6 to 7 MJ/Nm^3. The production of a high-purity H_2 (>99.99%) from the thermal plasma gasification of paper mill waste is shown in [26].

In this study, a thermal DC arc discharge water steam plasma was used to pyrolyze/gasify organic materials to synthesis gas. Glycerol and crushed wood were used as a source of biomass. The effects of different conversion parameters including the water steam flow rate, the treated material flow rate and the plasma torch power were studied. The modeling of chemical processes, based on a classical thermodynamic equilibrium reactor model (TER), was also proposed. Furthermore, the quantification of the plasma conversion system in terms of energy efficiency and a specific energy requirement was performed. It was found that the synthesis gas with a high content of H_2 and CO could be effectively produced from glycerol and wood by the thermal water steam plasma pyrolysis/gasification process.

2. Experimental setup and methods

2.1. Design of the biomass conversion system

In this study, the conversion of glycerol and wood to synthesis gas was carried out using an entrained bed plasma-chemical reactor (PCHR). The experimental system is shown in Fig. 1.

It consists of an atmospheric pressure DC arc plasma torch, a power supply system, a steam generator, a superheater, a gas supply system, a chemical reactor, an organic material supply, a condenser with silica gel (to remove moisture from the gas produced), and a gas chromatograph. The entrained bed plasma-chemical reactor used in this study was 1 m long with 0.4 m inner diameter. At the bottom of the reactor, there is a section for the removal of char and condensed water, and in the middle an outlet chamber for the produced gaseous products is installed. The residence time varied from 0.5 to 1 s, which depended on the flow rates of steam and the treated organic material, and the size of the PCHR.

Pure glycerol (99.5%) was used as a substitute for crude glycerol, which is considered a by-product of biodiesel production after the transesterification process. Glycerol was supplied to the chemical reactor at a constant rate of 2 g/s through the special spray nozzles. The optimal operating pressure of a spray nozzle is 10 bar. Therefore, the pressure in the glycerol feeding line was kept at 10 bar and regulated by nitrogen gas from a cylinder. To improve the fluidity and spray stability of glycerol, it was preheated to 343 K with a heater before supplying to the reactor.

Wood was chosen as a solid organic material because of the known chemical composition: C – 50.25%, H – 6.09%, O – 43.35%, N – 0.2%, and S – 0.1% [22]. It was supplied to the reactor by a special feeder at the flow rate of 1.2 g/s.

An atmospheric pressure DC arc plasma torch was used to generate active plasma radicals (O, H, and OH) from the water steam. The power of the plasma torch depends on the current intensity, voltage, and the flow rate of the plasma-forming gas. Argon was used as a shielding gas in order to protect the tungsten cathode of the plasma torch from erosion. During the experiments, the plasma torch power was changed from 48 kW to 56 kW (current 200 A, voltage 240–280 V, steam flow rate (at 500 K) 2.63–4.48 g/s). The mean temperature in the plasma-chemical reactor was simply calculated from the heat balance equation corresponding to the plasma enthalpy. The methodology is concisely defined in [27]. During the experiments, the

Please cite this article in press as: A. Tamošiūnas, et al., Biomass conversion to hydrogen-rich synthesis fuels using water steam plasma, Comptes Rendus Chimie (2016), http://dx.doi.org/10.1016/j.crci.2015.12.002