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Solar receiver/reactor for hydrogen production with biomass gasification in supercritical water

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ABSTRACT

A novel receiver/reactor driven by concentrating solar energy for hydrogen production by supercritical water gasification (SCWG) of biomass was designed, constructed and tested. Model compound (glucose) and real biomass (corncob) were successfully gasified under SCW conditions to generate hydrogen-rich fuel gas in the apparatus. It is found that the receiver/reactor temperature increased with the increment of the direct normal solar irradiation (DNI). Effects of the DNI, the flow rates and concentration of the feedstocks as well as alkali catalysts addition were investigated. The results showed that DNI and flow rates of reactants have prominent effects on the temperature of reactor wall and gasification results. Higher DNI and lower feed concentrations favor the biomass gasification for hydrogen production. The encouraging results indicate a promising approach for hydrogen production with biomass gasification in supercritical water using concentrated solar energy.

1. Introduction

With the rapid increase of world energy consumption and serious environmental pollutions caused by the utilization of fossil fuels, sustainable energy systems based on hydrogen as energy carrier coupled with renewable energy resources such as solar, biomass etc., are considered as an effective way to resolve issues of concern today including greenhouse gas emissions, national energy security, air pollution, and energy efficiency [1–3]. Solar energy with the characteristics such as clean and inexhaustible, is one of the most promising energy resources on Earth and in space, but it also have drawbacks such as dilution, intermission and unequal distribution, which limit its large-scale high-efficiency utilization. Concentrating solar power (CSP) has the potential to make major contributions to solar thermal utilization, which can be used to supply heat for endothermic chemical reactions [4,5]. As we know, one of the drawbacks of biomass gasification systems is that the energy to power these reactors is typically drawn from a portion of the feedstock combustion with an oxidizing agent causing the gaseous products contamination [6]. However, solar energy heating can offer a truly carbon-neutral, environmentally friendly alternative to conventional heating practices [7]. Solar-driven gasification, in which concentrated solar radiation is supplied as the energy source of high-temperature process heat to the endothermic reactions, is one of the most attractive candidates for the conversion process of solar high-temperature heat to chemical fuels [8–10].

Solar hydrogen production from biomass gasification in supercritical water (SCW) is one of the promising clean and renewable approaches for utilizing solar energy and high

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moisture content biomass [11], because the combination of SCWG of biomass with CSP technology to concentrate solar thermal as the energy source for high-temperature process heat offers several important advantages as follows [12–17]: (1) Concentrated solar thermal can be used to supply necessary energy, and low-grade solar heat and the calorific value of feedstock are upgraded to high-grade chemical energy for further utilization by solar-driven process [18]. (2) Compared to other conventional biomass gasification technologies, such as air gasification or steam gasification, SCWG not only can directly deal with the wet biomass with a natural water content of 80 wt% or more without energy-intensive drying process, but also has high gasification efficiency in lower temperatures (<700 °C), higher molar fraction of hydrogen and lower CO content in the gas products, and little tar and char are produced [19,20]. (3) The required retention time for SCWG of biomass is in the order of a few seconds to 1 min. This means that the required reactor size is relatively small. (4) Energy recovery from SCWG process can occur directly by a compact and efficient high-pressure heat exchanger from the exit flow of reactor which has a strong effect on the thermal efficiency of the process [21]. (5) CO_2 has high solubility in high pressurized water at room temperature, so it can be easily separated from H_2 and off gas treatment can be neglected, in addition, high-pressure products are easy for future transportation and usage.

So far, most of the solar thermochemical hydrogen production has focused on the utilization of solar thermal energy concentrated above 1000 °C [22]. Based on above considerations for clean and efficient hydrogen production, in this paper, to lower the extremely high operating temperatures required and to eliminate the need for high-temperature gas separation in conventional gasification, a novel receiver/reactor driven by concentrating solar energy for hydrogen production by SCWG of biomass was designed, fabricated and tested. A concentrated solar heat of around 500–750 °C was utilized as process heat to drive SCWG of biomass. Model compound (glucose) and real biomass (corncob) were successfully gasified under SCW conditions to generate hydrogen-rich fuel gas with the solar receiver/reactor. The results of the solar-driven hydrogen production by SCWG of biomass are reported, and the thermal performance of the receiver/reactor is determined.

2. Experimental sections

2.1. *Solar receiver/reactor configuration*

Solar reactors for concentrated solar systems usually feature a cavity-receiver type configuration, i.e. a well-insulated enclosure with a small aperture to let in concentrated solar radiation [23]. A cylindrical cavity-type solar receiver/reactor for SCWG of biomass constructed of spiral tube was developed, as shown in Fig. 1. The solar receiver/reactor consists of two cavities separated by insulation materials, with the upper one serving as the solar receiver/reactor and the lower one containing a deionized water pre-heater heated by crawler-type electric heaters as a backup when there are clouds in the sky. The receiver/reactor was constructed in 316 stainless steel spiral tubes (5 mm i.d. and 18 m length) and heated using solar radiation concentrated by a 10 kW multi-dishes concentrator designed by IEE, CAS. The cavity-type geometry approaching a blackbody absorber was designed to effectively capture the incident solar radiation by a 25 cm diameter aperture equipped with a quartz window, through which the concentrated solar radiation irradiates the inner wall of the receiver/reactor. In order to achieve homogeneous temperature distribution and enhancement of heat and mass transfer, spiral tube was used as reactor simultaneously serving as the receiver for accepting and converting the concentrated solar energy to the reaction tube to drive the thermochemical reaction. To improve thermal efficiencies, the sensible heat of hot products exiting the reactor can be recovered by a countercurrent high-pressure coaxial spiral heat exchanger to preheat the preheating water. Type K-thermocouples were inserted into the center of the stainless steel tube to measure the fluid temperature, which were installed respectively in the outlet of feedstock pre-heater, outlet of water pre-heater, inlet and outlet of reactor, inlet and outlet of high-pressure spiral tube heat exchanger.

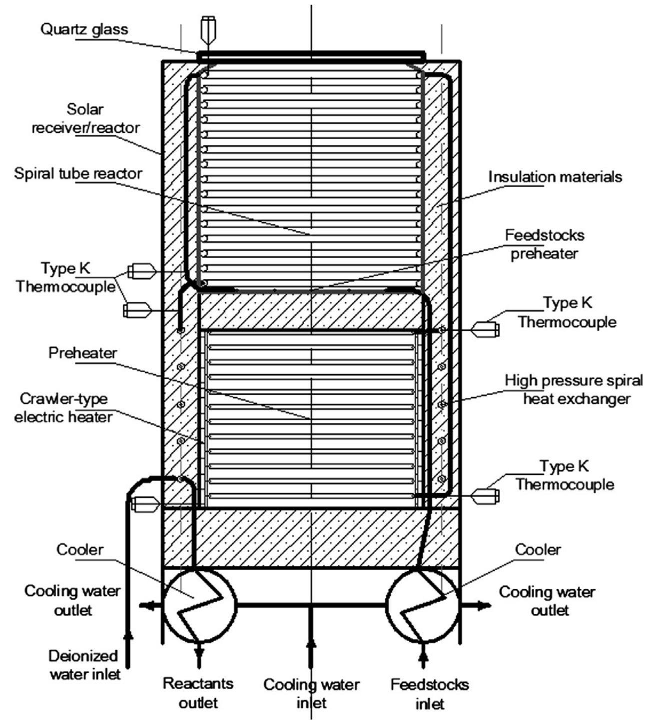

Fig. 1 – Schematic diagram of the solar receiver/reactor for SCWG of biomass.

2.2. *Experimental apparatus and procedures*

The schematic diagram of SCWG of biomass driven by solar–thermal system is shown in Fig. 2. The biomass loading stream and deionized water were pressurized in two different lines by two high-pressure metering pumps and then separately preheated. To improve the heat ratio of reaction, feedstocks were preheated to 200–250 °C depending on the