INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 20968–20978

Available online at www.sciencedirect.com

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

Experimental study on biomass steam gasification for hydrogen-rich gas in double-bed reactor

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ARTICLE INFO

Article history:
Received 12 July 2014
Received in revised form
9 October 2014
Accepted 20 October 2014
Available online 7 November 2014

Keywords:
Biomass steam gasification
Response surface methodology
Double-bed reactor
Catalyst

ABSTRACT

Based on Response Surface Methodology, the experiments of biomass catalytic gasification designed by Design-Expert software were carried out in steam atmosphere and double-bed reactor. The response surface was set up with three parameters (gasification temperature, the content of K-based catalyst in gasification bed and the content of Ni-based catalyst in reforming bed) for biomass gasification performance of carbon conversion efficiency and hydrogen yield to make analysis and optimization about the reaction characteristics and gasification conditions. Results showed that gasification temperature and the content of K-based catalyst in gasification bed had significant influence on carbon conversion efficiency and hydrogen yield, whilst the content of Ni-based catalyst in reforming bed affected the gasification reactions to a large extent. Furthermore, appropriate conditions of biomass steam gasification were 800 °C for gasification temperature, 82% for the content of K-based catalyst in gasification bed and 74% for the content of Ni-based catalyst in reforming bed by the optimization model. In these conditions, the steam gasification experiments using wheat straw showed that carbon conversion efficiency was 96.9% while hydrogen yield reached 64.5 mol/kg, which was in good agreement with the model prediction. The role of the reforming bed was also analyzed and evaluated, which provided important insight that the employment of reforming bed made carbon conversion efficiency raised by 4.8%, while hydrogen yield achieved a relative growth of 50.5%.

Introduction

With the gradual depletion of fossil fuels and growing threaten from global warming, an increasing number of attention has been paid to renewable energies, biomass included. The key of biomass utilization is the transformation of energy grade from low to high, and biomass steam gasification, with the highest hydrogen yield and minimal environment impact [1], is one of the most promising technologies [2]. However, there are still some main obstacles, such as low carbon conversion efficiency and high proportion of tar, etc. especially at lower gasification temperatures. To improve the conversion effects, choices of gasification temperatures and catalysts are crucial approaches.

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http://dx.doi.org/10.1016/j.ijhydene.2014.10.083

Alteration of temperature makes strong promotion or inhibition to some reactions during the process of biomass steam gasification, affecting the overall effects greatly. Generally, rise in temperature increases the heating rate among biomass particles, which results in effective destruction of the particles and proceeds for complete gasification reactions [3]. He et al. [4] confirmed that temperature rise led to better decomposition of char and tar through thermal cracking reactions. Luo et al. [5] reported that higher heating rates produced more light gases as well as less char and condensate. Kumar et al. [6] through their work have substantiated that the enhancement in hydrogen content can be attributed to the increase in temperature to a large extent. The study results of biomass gasification at lower temperatures, however, are far from satisfactory, and ways to enhance the reaction performance have attracted a large amount of attention. Results obtained by Xiao et al. [7,8] revealed that with animal waste employed as feedstock the hydrogen yield reached 20 mol/kg and carbon conversion efficiency was 40% while nearly 26 mol/kg of hydrogen yield could be achieved using red pine chips around 600 °C, which were relatively low. Similarly, Li et al. [9] through their gasification experiments using Japanese cypress confirmed that the hydrogen yield was only about 20 mol/kg at 550 °C with Ni-based catalyst. Biomass gasification at lower temperatures, with energy-saving consideration and its possibility to comprise CO_2 capture employing CaO, is of dramatic attractivity. Nevertheless, shortcomings such as large proportion of tar, low conversion efficiency of carbon and poor selectivity of hydrogen [10] cannot be ignored. Numerous parameters have been investigated to improve the performance of biomass gasification at lower temperatures, where biomass type, steam to biomass ratio, particle size and catalyst are included, in this study, moreover, appropriate contents of different catalysts are expected to be obtained for better performance of biomass gasification at relatively low temperatures (below 800 °C).

Addition of catalysts cannot only promote pyrolysis of biomass, gasification of char and cracking of tar, reducing the reaction activation energy required, but also has significant influence on the reforming of tar and light hydrocarbons, achieving higher gasification efficiency at lower temperatures [11]. Ni et al. [12] reported that dolomite, Ni-based catalysts and alkali metal oxide catalysts were preferable to gasification reactions. Balat [13] found that use of catalyst was not only affecting gas yield but strongly controlled gas composition. Corte et al. [14] employed Ni-based catalysts in their studies and found that nickel catalysts were suitable for production of light hydrocarbons. Ma et al. [15] demonstrated the characteristics of biomass gasification for hydrogen-rich gas production in a series of experiments with alkali metal catalysts. According to the research of Du et al. [16], K-based and Ni-based catalysts with the concentration of 30%, supported by γ-Al_2O_3, have great promotion to the gasification of biomass and the reforming of large organic molecules in steam atmosphere, furthermore, this study points out that mechanical mixtures of the two catalysts in a fluidized bed tend to achieve preferable gasification performance compared to runs in the same experimental conditions with only K-based catalyst involved. Hence, the catalytic effect of the mixture of K-based catalyst and Ni-based catalyst, as well as the influence of their contents, during biomass gasification is investigated in this paper.

For further study about the synergistic effect of gasification temperature and the ratios of K-based catalyst to Ni-based catalyst in double-bed reactor, a fluidized bed fitted with a fixed bed is employed in this paper. By changing gasification temperature and catalyst ratios in the two beds, appropriate conditions for biomass steam gasification are expected to be obtained.

Experimental

Materials

Wheat straw is used as biomass feedstock in this study, and catalysts involved for the experiments consist of K-based catalyst and Ni-based catalyst. The size of wheat straw particles is 0.3–0.6 mm, and the catalysts, with the same size as wheat straw particles, are supported by γ-Al_2O_3. K-based catalyst, with the K_2CO_3 concentration of 30% by weight, is prepared as follows: K_2CO_3 aqueous solution, where 7.5 g K_2CO_3 are dissolved in a certain amount of deionized water, is impregnated slowly into 17.5 g γ-Al_2O_3 for 20 h soaking, the mixture is dried in an oven at 105 °C then, and the semi-finished product is calcined in a muffle furnace at 800 °C for 5 h eventually to obtain the K-based catalyst, which is denoted as KAl below. Ni-based catalyst, using $Ni(NO_3)_2$ aqueous solution to achieve the NiO concentration of 30% by weight, is prepared by the same steps as KAl but calcined at 850 °C, which is denoted as NiAl below.

The amount of biomass feedstock employed for each experiment is 2.5 g, whose proximate and ultimate analyses are shown in Table 1. And catalysts used in this paper are all mechanical mixtures of KAl and NiAl with the total mass of 2.5 g for each reactor.

Experimental system

Experimental set-up is shown in Fig. 1. The whole system consists of gasification bed (31 mm internal diameter, 600 mm height), reforming bed (20 mm internal diameter, 400 mm height), steam generating unit, cooling and collecting devices, electric heating control system. The experimental steps are as follows: Firstly, the double-bed reactors are heated to required temperatures, and the whole system is purged by nitrogen during the heating process, ensuring the inert atmosphere. Then, 2.5 g mixtures of KAl and NiAl are fed into gasification and reforming beds from upper charging openings respectively. When the whole system reaches stable state, the gasification bed is charged with 2.5 g wheat straw particles, and steam is passed continuously in at the same time. This is

Table 1 – Proximate and ultimate analyses of wheat straw.

Proximate analysis (wt%, ad)				Ultimate analysis (wt%, ad)			
V	FC	A	M	C	H	O	N
66.91	15.73	7.75	9.61	36.57	4.91	40.59	0.57