Energy 128 (2017) 509–518

Contents lists available at ScienceDirect

Energy

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

Gasification characteristics of sawdust char at a high-temperature steam atmosphere

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ARTICLE INFO

Article history:
Received 21 November 2016
Received in revised form
12 April 2017
Accepted 14 April 2017

Keywords:
Sawdust char
High-temperature steam gasification
Carbon conversion rate
Pore structure
Kinetic analysis

ABSTRACT

Gasification characteristics of sawdust char at a high-temperature steam atmosphere were experimentally studied in a fixed bed reactor. The char was prepared at 600–1400 °C. The effects of temperature, steam flow rate, reaction time and char preparation temperature on conversion rate, the composition of product gas, the pore structure of char and ash, as well as kinetics were analyzed. Gas chromatography, scanning electron microscopy, and a specific surface area analyzer were utilized to measure the composition of the gas, the surface morphology, and the specific surface area of the char and ash. Results show that the carbon conversion rate increases with temperature, steam flow rate, and reaction time. At 800–1200 °C, H_2 content in product gas increases from 53.08% to 60.01%, and CO increases from 15.35% to 21.87%, while both CH_4 and CO_2 decrease. At 0.94–2.61 g/min, H_2 in the product gas rapidly increases, but since CO decreases, H_2 and CO slightly decrease. The specific surface area of sawdust ash increases to 948.84 m^2/g and 987.61 m^2/g at 800 °C and 1000 °C, respectively, on account of the fact that new micropores are generated, but it reduces to 520.76 m^2/g at 1200 °C as a result of the decrease of micropores and mesopores. The surface reaction controlled shrinking core model can describe high-temperature steam gasification reaction of sawdust char.

1. Introduction

Biomass char is a solid product enriched in fixed carbon by pyrolysis. The volatile and oxygen contents of biomass char are significantly reduced compared to biomass, and it is high-quality raw material for gasification due to its high reaction activity. As one of the primary methods of biomass conversion, gasification has attracted much attention with its advantages of the high efficiency of utilization and high heating value of the product gas [1–4]. Biomass char pore structure, kinetics and operational parameters of gasification play an important role in biomass char conversion [5–8]. Therefore, it is significant to study the characteristics of biomass char gasification for revealing the mechanism of gasification and the design and operation of a gasifier [9–11].

In literature, there have been many studies on biomass gasification. Zhou et al. [12] studied steam gasification of CaO additive and municipal solid waste (MSW) in a batch fixed bed at 700–900 °C. Hydrogen concentrations were found to increase, and CaO was found to have a catalytic effect. Kumar et al. [13] investigated the effects of temperature in a gasifier on carbon conversion rate and composition of the product gas. The temperature had significant effects on carbon conversion rate, and H_2 and CH_4 content increased with temperature. Li et al. [14] found that the effects of high temperature on producing hydrogen-rich gas through steam gasification of biomass were remarkable. Zhao et al. [15] studied the characteristics of air gasification of sawdust in a cyclone gasifier. The results showed that the optimal equivalence ratio was 0.29. Natarajan et al. [16] studied the gasification characteristics of peanut shell at 550–900 °C in a fluidized bed gasifier. They obtained the highest cold gas efficiency of 73.5% and carbon conversion efficiency of 82.5%. Fu et al. [17] observed the variation of the pore structure of biomass during pyrolysis and found the pore structure and morphology of biomass char were significantly affected by temperature. Aho et al. [18] investigated the effects of alkali metal on pine pyrolysis and gasification and found that alkali metal catalyzed pyrolysis and gasification. Fatehi et al. [19] established a gasification model considering pore structure with carbon conversion rate of biomass char. The results showed that as the char conversion proceeded, the pore enlargement increased the contribution of micropores as well as the effective surface area,

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http://dx.doi.org/10.1016/j.energy.2017.04.083

Nomenclature

A	Ash content of sawdust (%)
c	Constant related to the adsorption heat
E_a	Apparent activation energy of the gasification reaction (kJ/mol)
k_0	Pre-exponential factor (s^{-1})
k_G	Reaction rate constant of shrinking core model (s^{-1})
k_v	Reaction rate constant of homogeneous reaction model (s^{-1})
m	Mass (g)
N_A	Avogadro constant (6.02×10^{23})
n	Number of adsorption layers
P	Pressure (Pa)
R	Gas constant value (8.314 J/molK)
r	Kelvin critical radius (m)
S	Specific surface area (m^2/g)
T	Temperature (K)
t	Thickness of adsorption layer (m)
V	Volume (m^3)
V_m	Saturated absorption capacity (m^3)
x	Carbon conversion rate (%)
X	Ash content of the char (%)

Greek symbols

γ	Surface tension (N)
η	: Char yield (%)
θ	Angle (°)
v	Molar volume (m^3/mol)
σ	Absorption section constant
τ	Thickness of monolayer adsorption (m)

which led to an increased reactivity of char during the entire conversion process. Pattanotai et al. [20] investigated the gasification characteristics of sawdust char and found that pores in sawdust char aligned in the axial direction. Lech et al. [21] found the shrinking core model for the reaction-controlled regime was the best for predicting the rate of sewage sludge char gasification in CO_2 and O_2.

Considering the slagging characteristics of biomass ash, the existing gasifiers for treating biomass operate below 900 °C. For low-temperature gasification, the heating value of the product gas is low, and the content of tar in the product gas is high. Therefore, a two-stage high-temperature cyclone pyrolysis and gasification process scheme of biomass were proposed [22,23]. It would achieve high-temperature pyrolysis and gasification by a cyclone gasifier or furnace where the slagging ash can be collected and controlled, and hydrocarbons and tar could be converted into H_2 and CO by reforming of steam [23]. However, the gasification characteristics of biomass char at high-temperature steam atmosphere are not clear.

The aim of the study is to reveal the gasification characteristics of sawdust char at high-temperature (~1200 °C) steam atmosphere in a fixed bed reactor, considering the effects of gasification and char preparation temperature, steam flow rate, reaction time and pore structure on the conversion rate, and composition of product gas. Through kinetic analysis, the kinetic parameters of sawdust char steam gasification at high temperature will be obtained for the design and operation of biomass staged high-temperature gasification.

2. Material and methods

Sawdust, the typical biomass found in Heilongjiang province, was chosen as the raw material. The proximate and ultimate analyses of sawdust are shown in Table 1. The high-temperature steam gasification of sawdust char was carried out in a fixed bed gasifier. The experimental setup is shown in Fig. 1. It mainly consists of a steam generator (accuracy: ±0.01 g/min), a fixed bed reactor (length = 800 mm, inside diameter = 50 mm, outside diameter = 60 mm, temperature accuracy: ±5 °C), a condenser, and absorption devices. The sawdust with similar size (1 mm) was put into a sealed crucible, heated in an elevator furnace to 600 °C, 800 °C, 1000 °C, 1200 °C and 1400 °C at a heating rate of 20 °C/min and stagnation time of 40 min at each final temperature to prepare the char. The sawdust char was then dried at the temperature of 105–110 °C for 3 h. The fixed bed reactor was heated with steam fed into the reactor at a flow rate of 1.69 g/min to 1200 °C. The reaction boat, filled with 2 g of sawdust char, was pushed into the reaction zone, and the end of the corundum tube was sealed. Condensable gas was concentrated in the collecting bottle while incondensable gas was dried in the drying bottle. After 6 min, the reaction boat with residues was moved out of the reaction zone for 3 h to cool and dry. The mass of the residues was weighed and measured by the electronic balance (precision: 0.1 mg) for calculation and analysis. Each operational condition and results of the experiments were repeated three times for an average value, with the error being controlled within 2%.

Table 1
Proximate and ultimate analysis of sawdust.

M^1_{ad}%	V_{ad} %	A_{ad} %	FC_{ad} %	C^2_{daf}%	H_{daf} %	O_{daf} %	N_{daf} %	S_{daf} %
15.0	62.7	6.9	15.5	52.1	5.9	41.4	0.5	0.1

1 ad: air-dry basis. 2 daf: dry, ash free basis. M: Moisture. V: Volatile. A: Ash. FC: Fixed Carbon.

Char yield η, carbon conversion rate x, and ash content of the char X are calculated by the following equations.

$$\eta = \frac{m3 - m2}{m1} \tag{1}$$

$$x = \frac{m3 - m2 - m4}{(1 - A/\eta)(m3 - m2)} \tag{2}$$

$$X = \frac{A}{\eta - (\eta - A)x} \tag{3}$$

where, m_1 is the mass of sawdust before pyrolysis; m_2 is the mass of the crucible; m_3 is the mass of sawdust char and crucible at room temperature; m_4 is the mass of the residue after gasification; A is the ash content of sawdust.

7890A gas chromatograph (accuracy: ±1% RSD), produced by American Agilent, was adopted to detect the gas samples collected. Wherein, a flame ionization detector (FID) was used to detect CO, CH_4, and CO_2, and a thermal conductivity detector (TCD) was employed for the detection of H_2.

EVO18 scanning electron microscopy, produced by German ZEISS was used to observe surface morphology of sawdust char and ash. Scanning electron microscope (SEM) is the main means to study the surface morphology of objects. An electron beam emitted