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Process simulation of staging pyrolysis and steam gasification for pine sawdust

*Ming Zhai**, *Li Guo, Yanan Wang, Yu Zhang, Peng Dong, Huan Jin*

School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, Heilongjiang, China

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ABSTRACT

A two-stage biomass pyrolysis and gasification scheme for pine sawdust are proposed. The process makes use of the gas produced by biomass pyrolysis and gasification. Part of product gas combusts in a burner outside of the gasifier and then produces the flue gas and heat required for pyrolysis and steam gasification. Aspen Plus software is used to simulate the process of staging pyrolysis and steam gasification for pine sawdust. By taking heat recovery, utilization and recycling of the product gas into consideration, the influence of temperature and the amount of steam on yield, carbon conversion rate, and lower heating value of the product gas are investigated. The results show that heat self-support is realized by combustion of 15–21% of the total product gas. As the gasification temperature increases, so do the content of H_2 and CO in the product gas, and the carbon conversion rate also increases. The lower heating value of the product gas reaches a minimum at 700 °C. With the increase of the steam amount, the yield of H_2 and CO increases, which lead to the increase of carbon conversion rate and the decrease of the lower heating value of product gas. The yield of CO decreases as the amount of steam increases. Meanwhile, the carbon conversion rate is almost 100% at 900–1000 °C, $w(H_2O)/w(B) > 0.24$. The lower heating value of product gas decreases with the rise of the steam amount.

Introduction

Biomass gasification refers to converting biomass to CO, H_2 and other combustible gases consisting of smaller molecular hydrocarbons through thermo-chemical reactions [1]. In the conversion process, biomass feedstock with lower heating density is converted to high-quality heat sources, which are convenient to store and transport. Thus, the conversion effectively enhances the utilization efficiency of biomass energy. Biomass gasification is mainly classified into air gasification, oxygen gasification, steam gasification, hydrogen gasification, and compound gasification according to gasification agent used in the process. When steam is adopted as gasification agent, there are not only reduction reactions between steam and carbon but also reforming reactions between steam and the product gas such as CH_4 and unsaturated hydrocarbons. In the process, the product gas mainly consists of H_2 and CO. As the content of H_2 and alkane gases is high in the product gas, the heating value of product gas is also relatively high [2–6]. However, the high tar content in biomass gasification gas has been a major problem existing in biomass gasification technology. How to effectively remove or reduce the tar content has become the key to biomass gasification technology research and development. One of the potential ways to effectively eliminate or reduce the tar content

* *Corresponding author.*
E-mail address: zhaiming@hit.edu.cn (M. Zhai).
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Nomenclature

Letter symbols

a	conversion factor, L/mol
B	biomass
C	mass fraction of carbon, %
G_v	gas yield at normal condition, m^3/kg
H	lower heating value of component gas, kJ/m^3
LHV	lower heating value of the product gas, kJ/m^3
M	molecular weight, kg/mol
w	mass weight, kg

Greek symbols

φ	volume fraction, %
η_C	carbon conversion rate, %

Subscripts

C	carbon
ν	cas

is to increase the reaction temperature. As the reactions between biomass and steam are heat absorbing, the temperature in the device is hard to maintain during the process of steam gasification. In this regard, according to the physical and chemical properties of biomass and its characteristics in the gasification process, we propose a two-stage biomass cyclone pyrolysis and gasification scheme that separates pyrolysis zone from gasification zone using the cyclone furnace combustion principle. The scheme is to burn part of product gas in a high-speed burner to produce low oxygen content flue gas injecting into the cyclone pyrolysis chamber for biomass pyrolysis. At the same time, the content of tar in the product gas is reduced. After that, steam is injected into cyclone gasification chamber to react with char and tar produced in the pyrolysis process, so that gasification efficiency of biomass, the heating value of product gas and utilization of energy are all improved [7]. Heat self-support is realized in the whole process. Unfortunately, reactions of pyrolysis and gasification are complicated, and the experiments require high investment and high operational costs. Therefore, it is economical to carry out process simulation for experiment and process design.

Computational models in combination with experimental data can be used to evaluate gasifier's operation, solve operational issues, develop new designs and provide performance for scale-up of the gasifier [8]. Aspen Plus is a process simulation software that is widely applied in fields of solid fuel combustion, pyrolysis and gasification [9–13]. Chen [14] used Aspen Plus to establish a biomass-air gasification model according to Gibbs free energy minimization method and verified the model according to actual operating data from a fluidized gasifier. Qiu xiao [15] simulated the gasification process of two different biomasses in a fluidized gasifier. Mehrdokht [16,17] compared data from the simulated model with those from the pine gasification experiment. The data from the simulation coincided with those from the experiment. Naveed [18] analyzed gasification characteristics of three biomasses including food residuals, solid wastes and dejection of domestic animals and fowls. He also analyzed the influence of temperature, equivalence ratio and water content in biomass in the product gas. At present, there are reports of using Aspen Plus to carry out an investigation on gasification of biomass and other fuels with steam in literature. However, most of them were focused on the fundamental process of pyrolysis and gasification, optimization of gasification still requires further study.

As the primary difference from previous studies is that there is an interest to confirm the feasibility of the proposed two-stage biomass cyclone pyrolysis and gasification process scheme and the parameters of the product gas are linked to the operational parameters. The objective of this paper is to establish a proper model based on Aspen Plus software for pine sawdust staging pyrolysis and gasification with steam that takes recovery and utilization of heat, recycle of product gas into consideration. The influences of temperature and steam amount on gasification characteristics will be analyzed so as to provide a reference to experiments on staging gasification of biomass and to industrial design.

Methods

Basic assumptions

Since zero-dimensional thermodynamic equilibrium models are used in the Aspen Plus software, it is necessary to realize some assumptions that are as follows. 1) The model is a steady-state model. 2) The particles of the biomass are uniform, and the temperatures in the particles are uniform without gradient. 3) The gas phase and the solid phase are mixed well and reach equilibrium instantaneously. 4) The pressure drop in the gasification furnace is neglected. 5) The ash is regarded as inert material, and there is only carbon and ash after pyrolysis. 6) The model takes into account the combustion reaction of part of the combustible gas in the product gas and the reactions of the pyrolysis product (gas and solid) and the gasification agent are heterogeneous and homogeneous.

Parameters setup

Definition of the components

Conventional materials: C, S, H_2, O_2, N_2, H_2O, CO, CO_2, H_2S, CH_4, C_2H_4 and benzene, where H_2O refers to steam and benzene stands for tar. Neeft et al. [19] defined tar as “all organic contaminants with a molecular weight larger than 78, which is the molecular weight of benzene.” The International Energy Agency (IEA) Bioenergy Agreement and the U.S. Department of Energy (DOE) agreed to identify all components of the product gas having a molecular weight higher than benzene as tar [20]. Due to the specificity of each biomass source and difficulty in appraising tar content and their individual effects on the final conversion, benzene is considered as the tar, a representative heavy hydrocarbon compound. Under given pressure and temperature, the data bank of the software judges its effective phase according to fixed conditions.

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