Energy 161 (2018) 202–213

Contents lists available at ScienceDirect

Energy

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

Hydrogen-rich syngas produced from co-gasification of wet sewage sludge and torrefied biomass in self-generated steam agent

Y.W. Huang [a], [b], M.Q. Chen [a], [b], *, Q.H. Li [c], **, W. Xing [d]

[a] Institute of Thermal Engineering, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
[b] Beijing Key Laboratory of Flow and Heat Transfer of Phase Changing in Micro and Small Scale, Beijing 100044, China
[c] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China
[d] Datang International Beijing Gaojing Thermal Power Plant, Beijing 100041, China

ARTICLE INFO

Article history:
Received 22 April 2018
Received in revised form
9 June 2018
Accepted 15 July 2018
Available online 19 July 2018

Keywords:
Hydrogen-rich syngas
Co-gasification
Wet sewage sludge
Torrefied biomass
Thermodynamic equilibrium model

ABSTRACT

A synergistic scheme of co-gasification of wet sewage sludge and torrefied biomass was proposed in order to get the hydrogen-rich syngas, which could avoid the dual energy input for drying of wet sewage sludge and steam generation. Co-gasification behavior of wet sewage sludge and torrefied biomass was evaluated by using a general non-stoichiometric thermodynamic equilibrium model developed based upon the Gibbs free energy minimization. The tenary plot of C–H–O system was used to evaluate the theoretical carbon formation performance at thermodynamic equilibrium state. The effects of mixing ratio and torrefaction severity on carbon conversion ratio, compositions of dry syngas, and H_2 yield were also addressed. High mixing ratio of wet sewage sludge and high gasification temperature were required for the high carbon conversion ratio. The gasification temperature of 1100 K was a favorable level for the H_2 yield and energy input. The optimal mixing ratio range of wet sewage sludge for low and middle temperatures torrefied biomass samples was between 30% and 40%, while that for high temperature ones was approximately 55%. This work could provide a feasible technical route and basic data for the resource and energy utilization of sewage sludge and biomass.

1. Introduction

Organic solid wastes (sewage sludge, biomass, food waste, and plastic waste, etc.) must be disposed properly with the requirement of environment protection. Currently, the energy and resource utilization of organic solid waste is considered as a promising disposal way, which can reduce largely the volume of waste and produce some valuable products [1]. Thermochemical and biochemical methods are usually used to convert the organic solid waste into biofuels or chemical materials. Compared with the biochemical methods, the thermochemical methods have some advantages including higher conversion efficiency, shorter reaction time, and better adaptability for diversity of feedstock. Gasification, as an advanced thermochemical technique, can produce syngas that mainly consists of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) [2]. Syngas composition can be adjusted by changing gasification agent and reaction condition to satisfy subsequent applications. At present, hydrogen-rich syngas is acting as a pollution-free fuel and a versatile chemical feedstock, which can be generated from steam gasification of organic solid waste [3–5].

Biomass and sewage sludge among organic solid wastes are two good candidates for producing hydrogen-rich syngas via steam gasification due to their large production and low-cost [6,7]. The two wastes need to be pretreated before being gasificated due to their high moisture content and low energy density. The quality of biomass can be improved through drying and torrefaction [8,9]. The torrefied biomass has high energy density, homogeneous property, and low oxygen content, which would lead to the high-quality syngas formed [10] and high-efficiency performance [11]. The

---

* Corresponding author. Institute of Thermal Engineering, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China.
** Corresponding author. Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China.
E-mail addresses: mqchen@bjtu.edu.cn (M.Q. Chen), liqh@tsinghua.edu.cn (Q.H. Li).

https://doi.org/10.1016/j.energy.2018.07.097
0360-5442/

torrefied biomass is a kind of fuel product, which can be bought from torrefaction plants or imported from other areas or countries. The steam gasification of torrefied biomass is only considered, ignoring the torrefaction process of biomass. Scenario A in Fig. 1 is the whole process of producing H_2-rich syngas from steam gasification of biomass, which includes drying, torrefaction, and steam gasification. The steam gasification of torrefied biomass requires the input energy for the reaction process and steam generation. The drying and steam gasification of sewage sludge is described in scenario B. As the high moisture content of sewage sludge after mechanical dewater is unacceptable for steam gasification, a large amount of energy is consumed to remove the water in the sewage sludge [12]. After that, the dried sludge is fed into steam gasifier, into which the steam and energy are injected to maintain the gasification reaction. Actually, the steam gasification processes of torrefied biomass and dried sludge both require the inputs of energy and steam, and the drying of wet sewage sludge also requires a large amount of energy. Co-gasification of torrefied biomass and wet sewage sludge was proposed, as shown in scenario New. The new scenario has double benefits that the water in the wet sewage sludge can provide steam for co-gasification process, and the drying of wet sewage sludge is also avoided.

Some investigation about co-gasification of sewage sludge and biomass/other organic solid wastes have been reported. Peng et al. [13] examined the co-gasification behavior of wet sewage sludge and forest waste in steam agent, and concluded that the gas yield decreases with increasing the wet sewage sludge content, and the concentrations of H_2 and CO was maximum at the wet sewage sludge content of 50%. Hu et al. [14] addressed the catalytic co-gasification characteristics of wet sewage sludge and pine sawdust, and noticed that the maximum dry gas yield, H_2 yield and carbon conversion efficiency are obtained at 900 °C in presence of catalyst with 40% pine sawdust. Ong et al. [15] carried out the co-gasification of woody biomass and sewage sludge, and noted that less than 33% dried sewage sludge is suitable for syngas generation by considering the formation of agglomerated ash caused by high ash content in sewage sludge. Rong et al. [16] evaluated the toxicity of bottom ash from co-gasification of sewage sludge and woody biomass. Chiang [17] examined the feasibility of co-gasification of sewage sludge and paper-mill sludge, and pointed out that sewage sludge has a higher thermal reaction activity. To date, no literature about co-gasification of wet sewage sludge and torrefied biomass has been found.

The optimization for operation condition is very important for high-efficiency performance of co-gasifier. Thermodynamic equilibrium analysis is usually used to assess the optimal operation conditions by uncovering the relationship between the operation condition and product compositions at thermodynamic equilibrium state [18–20]. Thermodynamic equilibrium model has a good ability in predicting syngas compositions for different types of feedstock at a wide range of reaction conditions. There are stoichiometric and non-stoichiometric thermodynamic equilibrium models [21]. The former is based on the equilibrium constants of independent reactions, while the latter is based upon the Gibbs free energy minimization of reaction system. The non-stoichiometric model is more suitable for complex reaction systems [21,22]. Therefore, the non-stoichiometric thermodynamic equilibrium model can be employed due to the complexity of mixtures of sewage sludge and torrefied biomass.

In current work, the non-stoichiometric thermodynamic equilibrium model for co-gasification of wet sewage sludge and torrefied biomass is established based upon the Gibbs free energy minimization. The effect of torrefaction severity, mixing ratio, and gasification temperature on solid carbon formation behavior, carbon conversion, dry syngas composition, and hydrogen yield are also addressed. The optimal condition and mixing ratio of wet sewage sludge are determined by the maximum hydrogen yield.

The main novelties of this work are to investigate firstly the co-gasification of wet sewage sludge and torrefied biomass, and to identify the influence of torrefaction severity and mixing ratio on carbon conversion behavior, hydrogen production based on the non-stoichiometric thermodynamic equilibrium model.

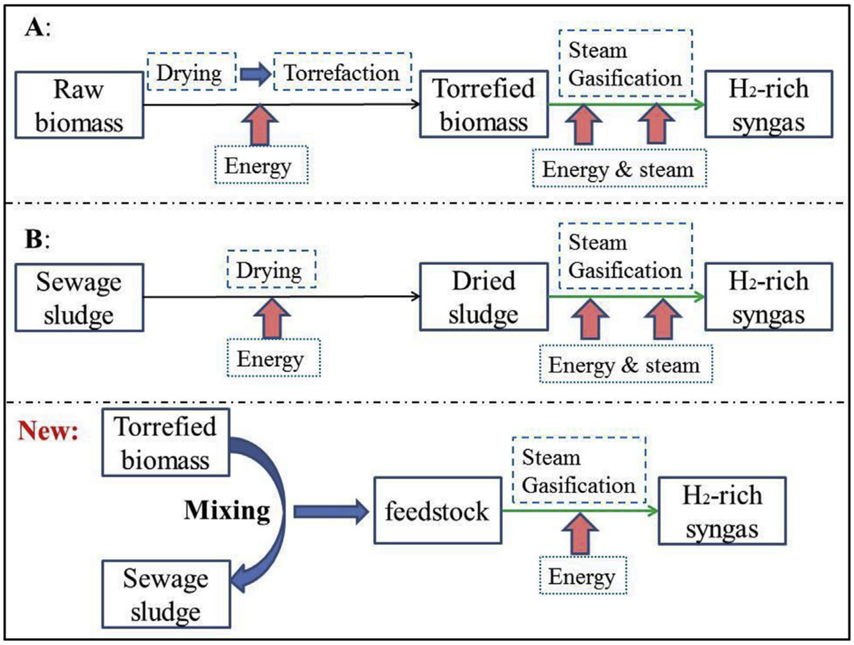

Fig. 1. Descriptions for different gasification scenarios.