Renewable and Sustainable Energy Reviews 44 (2015) 847–866

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A state-of-the-art review of biomass torrefaction, densification and applications

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ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form
10 November 2014
Accepted 27 December 2014

Keywords:
Torrefaction
Densification
Biomass pretreatment
Two-step gasification
Torrefied pellets

ABSTRACT

Torrefaction is a mild pyrolysis, which has been explored for the pretreatment of biomass to increase the heating value and hydrophobicity. Due to its potential applications for making torrefied pellets, which can be used as a high quality feedstock in gasification for high quality syngas production and as a substitute for coal in thermal power plants and metallurgical processes, torrefaction and densification have attracted great interest in recent years from both academia and bioenergy industry. This paper provides a comprehensive review of research progresses in this area, drawing on major contributions from two major research groups of the authors on torrefaction and densification at Canada and Taiwan as well as literatures. It is revealed that torrefaction of various biomass species and their major components, lignin, cellulose and hemicelluloses have been extensively studied in thermogravimetric apparatus (TGA) under both inert (N_2) and oxidative (O_2, H_2O) environments to elucidate the weight loss as a function of temperature, particle size and time. It was found that the higher heating value and saturated water uptake of torrefied biomass were a strong function of weight loss, which represents the degree of torrefaction. When torrefied sawdust is compressed into torrefied pellets, more mechanical energy is consumed and higher die temperature is required to make torrefied pellets of similar density and hardness as regular pellets. Simple economics analyses based on laboratory scale experimental data showed that because of the potential savings from pellets transport, handling and storage logistics, the overall cost for torrefied pellets can be lower than regular pellets in European market for both European and Canadian pellets. The gasification could be improved in terms of both energy efficiency and syngas quality because of the removal of oxygenated volatile compounds from torrefied biomass.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.12.039
1364-0321/

1. Introduction

With increasing global population and rising living standards, there has been a significant growth in energy demand worldwide over the last several decades. This leads to diminishing fossil fuel reserves, serious environmental pollution and high greenhouse gas (GHG) emissions. To address these challenges, many efforts in developing renewable energy and alternative fuels have been carried out and substantial progress has been made. Although the applications of renewable energy grow rapidly lately, their applications are still limited due to the high cost, poor technology reliability, and limited resource availability. Among the renewable energy and alternative fuels under development, biomass energy or bioenergy is one of the promising resources to match the requirements of substituted fossil fuels for reducing GHG emissions.

Biomass can be considered as one of the solar energy resources. Plants grow by absorbing carbon dioxide from the atmosphere as well as water and nutrients from soils followed by converting them into hydrocarbons through photosynthesis. All carbon contained in biomass is gained from carbon dioxide; in other words, carbon is cycled in the atmosphere when biomass is consumed as a fuel. Therefore, biomass is referred to as a carbon neutral fuel when it is burned [1]. On account of the wide distribution of biomass on the Earth's surface, bioenergy has a great potential as a low-carbon source for large-scale energy production. In fact, bioenergy is the largest renewable energy source so far, which accounts for around 10% of primary energy demand in the world, according to the International Energy Agency (IEA) [2].

Biomass can be transformed into gas or liquid fuels via a variety of methods, such as gasification, pyrolysis, anaerobic digestion, fermentation and transesterification. It can also be utilized as a solid fuel and burned directly for the generation of heat and power. However, biomass is characterized by its high moisture content, low calorific value, hygroscopic nature and large volume or low bulk density, which result in a low conversion efficiency as well as difficulties in its collection, grinding, storage and transportation. For those reasons, biomass is usually blended with coal for co-firing rather than used alone in power plants [3]. In the past, a number of biomass pretreatment methods have been developed to address the aforementioned disadvantages. Among the explored biomass upgrading methods, torrefaction and densification (or pelletization) are two noticeable routes for solid fuel production. A search for the number of journal papers in Scopus (Sciencedirect.com) made on November 4, 2014, using the keyword of "torrefaction" and restricted to Abstract, Title, Keywords, showed more than 449 papers published in this subject, as displayed in Fig. 1a. Similarly, using the keywords of "biomass" and "pelletization" reveals a growing interest in this area, as shown in Fig. 1b. The profiles in Fig. 1 suggest that the research and development of torrefaction and densification for bioenergy applications are very active worldwide.

Torrefaction and densification have demonstrated numerous merits in improving the properties of biomass, and possess a great potential for industrial applications. Torrefaction was recently reviewed by van der Stelt et al. [4] and Chew and Doshi [5], with a focus on the torrefaction without covering densification of torrefied biomass to torrefied pellets. This review is intended to provide a comprehensive overview of recent development in the torrefaction and densification process with a focus on the fundamental characteristics of biomass torrefaction for the production of torrefied pellets and the properties of torrefied pellets. Their potential industrial applications and economics will be discussed as well.

2. Lignocellulosic structure and properties of biomass

The constituents in biomass include cellulose (a polymer glucosan), hemicelluloses (which are also called polyose), lignin (a complex phenolic polymer), organic extractives and inorganic minerals (also called ash). The first three constituents are the main components in biomass and their weight percents depend on biomass species. For example, the softwood typically consists of 42% cellulose, 27% hemicelluloses, 28% lignin and 3% organic extractives; the hardwood comprises 45% cellulose, 30% hemicelluloses, 20% lignin and 5% organic extractives [6]. Inorganic minerals are usually less than 1% of the content in wood. A clear understanding of the nature and behavior of these constituents is conducive to elucidating biomass torrefaction and densification characteristics.

Cellulose is a linear homopolysaccharide composed of β-D-glucopyranose units linked together by (1→4)-glycosidic bonds [7]. Crystalline and amorphous structures are contained in cellulose and can be expressed by $(C_6H_{10}O_5)_m$ where subscript m is the degree of polymerization. Hemicellulose is a branched mixture of various polymerized monosaccharides, such as xylose, glucose, mannose, galactose, arabinose and glucuronic acid [8]. Its basic structure can be represented by $(C_5H_8O_4)_m$. Lignin is a three-dimensional, highly branched and polyphenolic substance that consists of an irregular array of variously bonded "hydroxy-" and "methoxy-" substituted phenylpropane units [9]. Its chemical formula is represented by $[C_9H_{10}O_3\cdot(OCH_3)_{0.9-1.7}]_m$ [10]. Based on the chemical formulas of the three constituents, the atomic O/C