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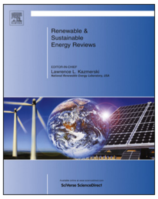

Potential hydrogen and non-condensable gases production from biomass pyrolysis: Insights into the process variables

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ABSTRACT

The objective of this paper is to develop more favorable hydrogen energy that holds the potential to realize zero-carbon emissions, thereby negating concerns over global warming and promoting an outlook free of the dependency on fossil fuels. Pyrolytic gas has much H_2, CO_2, CO, and light hydrocarbons, such as CH_4, C_2H_6, etc., as non-condensable gases (NCGs), which offer the potential for use in industrial, power and transportation fields. This paper emphasizes the influence of biomass characteristics and compositions, moisture content, particle size, heating rate, temperature, reactor system, and carrier gases and catalysts on the production of hydrogen and NCG. The composition of the NCGs varies widely depending on the properties of the biomass and moisture content, which play key roles on the mole fraction of hydrogen in the final products. A small particle size is favorable in the chemically controlled pyrolysis process for hydrogen production, while the reformation of NCGs into H_2 via a shift reaction is significant in increasing the total hydrogen formation in the presence of catalysts. A great deal of effort has been directed towards the system carrier gas in terms of hydrogen production, because it enhances the secondary decomposition reaction. Thermo-chemical and biological processes for hydrogen production from sustainable energy sources are also reviewed. In order to predict the maximum hydrogen formation of a given feedstock, the extent to which the processes are dependent on the heating rate and the temperature of the biomass in the reactor is investigated. It is our belief that this is a crucial assessment in establishing a link and developing a learning strategy between networks of biomass to hydrogen transformation-related activities and in assessing the current economic status of this pyrolysis process in achieving the ultimate hydrogen energy source.

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1. Introduction

With regard to the global depletion of fossil fuels and increasing environmental pollution, numerous endeavors have been attempted to advance technology and to find other renewable and environmental friendly energy sources [1]. The massive use of energy derived from fossil fuels contributes substantially to the release of greenhouses gases and toxic gases, such as CO_2, SO_2, NO_x and other pollutants, which causes many environmental problems such as acid rain [2,3]. With regard to these issues, some researchers have attempted to capture these toxic gases via hydration [4,5]. This study investigates and reviews developments in the quest for cleaner, renewable alternatives for the generation of heat and power from biomass [6–8]. Hydrogen is a latent and cleaner energy, which is considered as an alternative fuel for the future [9,10]. Amongst all conventional fuels, hydrogen holds the highest specific energy content (120 MJ/kg) and is the most widespread constituent in the Universe [11].

Biomass pyrolysis is a complex process in which several chemical reactions take place in both the gas and the condensed phase alongside the mass and thermal resistances involved in the pyrolysis process. Condensable vapor known as bio-oil, bio-crude, etc., and non-condensable gases (NCG) known as CO, CO_2, H_2 and light hydrocarbon gases (LHG), such as CH_4, C_2H_6, C_2H_4, etc., are generated by the pyrolysis process [12]. However, the total hydrogen production from the pyrolysis process is the sum of the synthesized hydrogen gas plus the hydrogen produced from the synthesized carbon monoxide via the water–gas shift reaction, and the LHGs play a key role in achieving this and hence, increase the efficiency of the process [13].

Quantitative information on the process variables, such as biomass composition, moisture content, particle size, heating rate, temperature and so on, is the basis for understanding the biomass thermal conversion pathways and in providing predictive gaseous products that can be used as clean fuels and chemical feedstock. Hydrogen yield and the distribution of NCG products are highly dependent on the feedstock type and quantity, as well as on the prevailing conditions of the reactor.

A key point related to thermo-chemical routes is that there is no practical and documented process for obtaining hydrogen from a biomass plant in terms of commercialization [14]. An economic survey showed that a plant efficiency of about 56–64% would be achieved, by means of the net higher heating value together with the hydrogen production cost (HPC), about 10–14 US$/GJ [15]. Gasification is a more mature technology than pyrolysis for hydrogen production and this process has to be recognized as a cost-effective and efficient pathway to generate fuel gas [16]. The economic analysis takes into account the feedstock costs when calculating the final fuel price, which is about 36–62% in the pyrolysis process [17]. The HPC from biomass by pyrolysis and gasification processes are expected to be in the range of 1.47–2.57 US$/kg and 1.44–2.83 US$/kg, respectively [18]. A capacity handling a quantity of 139,700 kg per day produces hydrogen at a price of 1.99 US$/kg by the gasification process, when the raw material cost is expected to be 46 US$ per ton on a dry basis [18].

In this paper, reports relating to the direct biomass pyrolysis process for hydrogen production and the consequent production of NCGs are classified and summarized according to biomass compositions, moisture content, particle size, heating rate, temperature, reactor, and carrier gas effect. It should be noted that there have also been studies focused on hydrogen production by pyrolysis using different catalysts with the aim of maximizing the final product. Therefore, this work is useful in addressing those new opportunities in the development of hydrogen energy for reducing emission problems, improving energy security and sustaining long-term future applications.

2. An overview of hydrogen production technology

Hydrogen is a colorless, tasteless, odorless gas, which is lighter than air and thus, rises in the environment. Hydrogen cannot be found in a free state in nature because it is very reactive and therefore, it is found in combination with other elements. Natural sources, for example, biomass, hydrocarbons, water, etc., are the major feedstock for hydrogen formation because these sources are widespread [19]. Table 1 shows the combustion and explosion properties of hydrogen [20].

Hydrogen energy delivers power with zero carbon emissions, a pollution-free environment, and clean fuels for industry, buildings and transport, which is why it appears as such a promising energy source. Hydrogen production has a chance to emerge as an important economic possibility in the near future. The key question is to determine from which source hydrogen can be produced in a sustainable manner in large quantities and at acceptable cost. An important aspect to avoid is that hydrogen becomes just a more expensive way of harnessing fossil fuels [21]. A hydrogen-based sustainable energy system is described pictorially in Fig. 1 [22]. As hydrogen could become the “next energy”, Fig. 2 illustrates the future that hydrogen energy could deliver.

Large-scale centralized power plants (LSCPs) and small-scale generation plants (SSGPs) are two distinct pathways by which to form hydrogen from biomass. Distributed generation, decentralized generation and embedded generation are other alternative classifications of SSGPs. It should be noted that LSCPs require distributed generation systems that operate nearer the point of use [23]; thus, LSCPs might become important in the longer time scale. Based on distributed generation pathways, hydrogen formation currently occurs mainly by means of the water electrolysis process, whereas hydrogen from natural gas (NG) and coal reforming processes are seen as medium-term policies [24]. From the aspect of transportation, the distributed formation of hydrogen offers advantages over centralized generation. Generally, centralized distribution encounters substantial infrastructure obstacles that are completely absent in the distributed generation process. It can be seen from Fig. 2 that larger amounts of hydrogen formation might be possible if based on a mainly large-scale hydrogen generation policy. Aside from the large-scale policy, biomass or existing fossil fuel with CO_2 sequestration should be understood as applicable to larger centralized hydrogen formation plants. It can be seen from Fig. 2 that distributed hydrogen formation should be implemented in the short and medium term.

Table 1
Combustion and explosion properties of hydrogen.

Properties	Hydrogen
Density (kg/m^3)[a]	0.084
Heat of vaporization (J/g)	445.6
Lower heating value (kJ/g)	119.93
High heating value (kJ/g)	141.8
Thermal conductivity (mW/cm/K)[a]	1.897
Diffusion coefficient in air (cm^2s)[a]	0.61
Flammability limits in air (vol%)	4.0–75
Detonability limits in air (vol%)	18.3–59
Limiting oxygen index (vol%)	5.0
Stoichiometry composition in air (vol%)	29.53
Minimum energy of ignition in air (MJ)	0.02
Auto ignition temperature (K)	858
Flame temperature in air (K)	2318
Maximum burning velocity in air (m/s)[a]	3.46
Detonation velocity in air (km/s)[a]	1.48–2.15
Energy of explosion mass related g TNT (g)	24.0
Energy of explosion volume related g TNT (m^3)[a]	2.02

[a] Values are in at STP conditions.