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Review

Hydrogen production, storage, transportation and key challenges with applications: A review

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A R T I C L E I N F O

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A B S T R A C T

The energy demand worldwide has increased significantly with the increase in population. This is because energy is needed in almost every activity. For example, in industry, working, cleaning, transportation and commuting from one place to another. The majority of energy being used is obtained from fossil fuels, which are not renewable resources and require a longer time to recharge or return to its original capacity. Energy from fossil fuels is cheaper but it faces some challenges compared to renewable energy resources. Thus, one of the most potential candidates to fulfill the energy requirements are renewable resources and the most environmentally friendly fuel is hydrogen (H_2). Hydrogen exists mostly in plant materials and is not readily available in nature. It is necessary to produce hydrogen from available feedstock (water), which covers 70% of the earth. Moreover, hydrogen under standard pressure and temperature has an important merit; it can be obtained from renewable resources. Although, currently it is produced from fossil fuels. Hydrogen as a fuel is nonmetallic, non-toxic and can generate higher energy than gasoline on a mass basis. However, to employ hydrogen as a fuel, extensive research is essential to investigate and design on-board applications. Also, the cost of producing hydrogen (renewable) is expensive compared to gasoline (fossil). Thus, the production of H_2 from renewable resources and from fossil fuels requires tremendous effort. One of these efforts is to generate H_2 from biofuels as it is considered a promising technique that can help manage hydrogen from food waste. In addition, hydrogen storage materials are still lacking in both volumetric and gravimetric density. In this review, the key challenges that hydrogen industry are confronting are introduced and highlighted to facilitate the use of hydrogen as an alternative energy.

1. Introduction

With increasing global population, industrialization and urbanization, energy demand is rapidly rising [1]. Currently, about 85% of the overall energy consumption worldwide is obtained from non-renewable resources, namely, coal, natural gas and oil; contributes to environmental issues (global warming), economic issues and political crises. These resources are finite and its reserves worldwide are depleting which results in increasing price. The depletion of finite fossil fuels is a critical issue that needs to be overcome for a sustainable energy future.

The exploration of new energy system arose during the oil crisis, in 1970, and the carbon dioxide level in the atmosphere increased which currently contributes to climate change. Moreover, development of new energy systems from renewable or sustainable resources is challenging [2]. Therefore, research is ongoing to harness the renewable resources. These resources can be utilized to generate hydrogen as a source of energy. The renewable resources are location dependent, difficult to store and transport.

The existence of hydrogen as a chemical substance in nature, with the molecular formula of H_2, is not readily available and it is often in the form of compounds called hydrides with a negative or anionic character, denoted (H^-). The direct production of hydrogen in industry comes from steam reforming of hydrocarbons. As well as this, other technologies include, for example, electrolysis and thermolysis [3–5].

Hydrogen is abundant and is the most available renewable energy. Furthermore, only water vapor is produced from the combustion of hydrogen. Thus, it is considered as the cleanest energy source [6]. Hydrogen is also deemed to be the suitable solution to the

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environmental problems if it is produced from renewable resources. The advantages of hydrogen are zero emission of greenhouse gases if it is produced using renewable energy; high energy density between 120 MJ/kg (Lower Heating Value, LHV) and 142 MJ/kg (Higher Heating Value, HHV) [7,8]. The viability and utilization of hydrogen requires assessing, for example, storage capabilities, energy density versatilities, transport and environmental impact.

The production of hydrogen from biofuel resources is considered one of the most promising techniques due to its high organic content and availability. The nutrients stored in food waste are in the form of macromolecules which need to be hydrolyzed into micromolecules before used by microorganism to produce biofuels. Therefore, hydrolysis process of food waste is regarded as the limiting step for biofuel production. Han et al., [9–11] developed new techniques of solid state and dark fermentation based on food wastes. Their model of a combined bioprocess can effectively accelerate the hydrolysis rate, enhance the raw material usage and modify biogas yield. It seems a promising method for biogas production. In addition, techno-economic feasibility study of the proposed bioprocess has also been evaluated [10]to see the effect of the economic impact in hydrogen production techniques.

Production cost of hydrogen needs to be reduced to become a common energy source. Hence, the current and future energy systems need to be economically effective, practical, reliable and sustainable with low environmental impact [12].

2. Hydrogen production

Hydrogen can be produced from both renewable technologies and fossil fuels. Generation of hydrogen from fossil fuels can be through steam reforming, partial oxidation, autothermal oxidation and gasification. Generation of hydrogen from renewable sources can be through gasification of biomass/biofuels and water splitting by solar energy or wind energy.

2.1. Hydrocarbon

Obtaining hydrogen from hydrocarbon (mainly from natural gas) can be differentiated by three means of chemical reactions such as [13]; (i) Steam CH_4 (Methane) reforming (SMR), (ii) Partial oxidation (POX) and iii) Autothermal reforming (ATR). In each of the processes, other reactants are also involved. For example, in SMR, steam (other reactant) reacts with hydrocarbon and results in endothermic reaction, or oxygen as another reactant for POX which results in an exothermic reaction. When two reactions are combined (SMR and POX), then it is termed as ATR.

2.1.1. Steam methane reforming (SMR)

SMR method produced high hydrogen yield efficiency of approximately 74% with an estimated cost of around $1.8 kg^{-1} [14]. In addition, it is considered as the priceless commercial substance to obtain H_2 [15]. The steps in this process include removal of impurities, catalytically reforming or synthesis gas (syn-gas) generation, water gas shift (WGS) and methanation or gas purification. So, as to obtain the desired purified hydrogen and prevent coke formation on the catalyst surface, the operating parameters for the reforming reaction are selected at temperatures of 700–850 °C, pressure of 3–25 bars and steam to carbon ratio of 3.5 [16]. The catalysts used for the reforming reaction can either be non-precious metals, typically nickel, or precious metals which are typically platinum and rhodium. However, due to the severe limitations on both mass and heat transfer, the catalyst effectiveness is typically minimal of 5%. Hence, non-precious metal catalysts are universally used [17]. The produced H_2 from the chemical reaction are then purified using a pressure swing adsorption unit [18]. The main chemical reactions for steam methane reforming are as follows:

Reformer: $C_nH_m + nH_2O \leftrightarrow nCO + \left(n+\frac{m}{2}\right)H_2$

Water gas shift reactor: $CO + H_2O \leftrightarrow CO_2 + H_2$

Methanator: $CH_4 + H_2O \leftrightarrow CO + 3H_2$

2.1.2. Partial oxidation(POX)

For POX, the H_2 is generated through the conversion of steam, oxygen and hydrocarbon. This method can be done non-catalytically and catalytically. It is more sulfur tolerant than SMR if operated non-catalytically. However, temperature ranges are 1150–1315 °C (also at 1300–1500 °C, to ensure complete conversion and reduce carbon formation or soot); and the feedstock can range from methane, heavy oil and coal. For the catalytic process, the working temperature is about 950 °C and the feedstock ranges from methane to naphtha.

The reaction include in POX are as follows:

Reformer: $C_nH_m + nH_2O \leftrightarrow nCO + \left(n+\frac{m}{2}\right)H_2$

$$C_nH_m + nH_2O \leftrightarrow nCO + \left(n+\frac{m}{2}\right)H_2$$

Water-Gas Shift Reactor: $CO + H_2O \leftrightarrow CO_2 + H_2$

Methanator: $CO + 3H_2 \leftrightarrow CH_4 + H_2O$

2.1.3. Autothermalre forming(ATR)

The ATR is the combination of SMR and POX, where partial oxidation is used to produce heat and steam reforming to increase the hydrogen production [19]. Thus, it results in a thermally neutral process. This process operates properly when both the oxygen and fuel ratio is controlled within a time span to prevent coke formation and likewise to control the reaction temperature and gas composition [20]. For the ATR reactor, the outlet temperature of the reactor is in the range of 950 °C to 1100 °C with gas pressure reaching up to 100 bars.

In ATR, the reforming and oxidation reaction occurs simultaneously as shown:

$$C_nH_m + nH_2O \leftrightarrow nCO + \left(n+\frac{m}{2}\right)H_2$$

2.2. Coal

Over millions of years, the formation of coal resulted from accumulated buried prehistoric vegetation including peat bogs or swamps. The main reason was the sediment build-up and the earth's crust movement [21]. Variety of coal gasification processes are also utilized in hydrogen generation such as fixed bed, fluidized bed or entrained flow. Industrially, high temperature entrained flow is used to maximize the conversion of carbon to gas [13]. During coal gasification, syngas is produced along with H_2 and CO, where the H_2 is extracted and the CO undergoes WGS reaction to produce more H_2 [13]. The gasification reaction is endothermic, thus it requires heat and is energy-intensive.

Typical reaction in the coal gasification is [13]:

$$C(S) + H_2O + heat \rightarrow CO + H$$

2.3. Biomass process

Another method for H_2production is the conversion from biomass which is one of the most considerable sustainable resources. A diversity of biomass resources can be used to convert to energy such as (I) energy crops, (II) agricultural residue and waste, (III) forestry waste and residue and (IV) industrial and community waste [21]. These energy production techniques based on biomass are mainly classified into two categories (I) thermochemical and (II) biological for H_2 production.

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