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Steam-Iron process as an alternative to Water Gas Shift reaction in biomass gasification ☆

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ABSTRACT

The Steam-Iron process has been studied in a set of fixed bed reactors at 800 °C. Iron oxides are inside the reactors, and the gas feed stream alternates between syngas from biomass gasification as reducing stream and water steam as oxidizing stream. The process has been modeled with Aspen Plus® simulation software, and an economic evaluation has been performed to determine the production cost of hydrogen via Steam-Iron process. Steam-Iron process may be an alternative to Water Gas Shift reaction with syngas from biomass gasification, but further research is needed to determine if it can be feasible with a carbon capture step, or with syngas from a different source.

Introduction

Emissions of combustion processes are the most important factor of greenhouse effect and the current and future climate change, due to its content of carbon dioxide. Fossil fuels are the most significant energy source in current energy system, and this situation leads to environmental issues, mainly due to the emission of gases with greenhouse effect. Fig. 1(a) shows the worldwide primary energy consumption by energy source in 2011. Fossil fuels represent 87% share of this energy consumption [1].

Nowadays, primary energy consumption is continuously rising. Renewable energies are also growing but they are still a minor contribution to global energy production. The growing energy demand, the depletion of fossil resources and the accentuation of climate change raise serious concerns about the future energy system [2]. Thus, energy researchers are looking at the possible alternative sources of energy to replace the fossil fuels. There are several primary energy sources available, such as nuclear energy, solar energy, wind energy, hydropower, geothermal energy and biomass energy, among others. In contrast with fossil fuels, these primary energy sources cannot be used directly as a fuel, and they must be

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converted to an energy carrier. The energy carrier must satisfy the following conditions [3]:

- It must be convenient fuel for transportation.
- It must be versatile or convert with ease to other energy forms at the user end.
- It must have high utilization efficiency.
- It must be safe to use.

Taking into account the previous issues, hydrogen appears to be one of the best energy carriers in the future energy system.

Currently, there are several pathways for hydrogen production. As shown in Fig. 1(b), 96% of the hydrogen is produced from fossil fuels (natural gas, coal and oil) [2]. The remaining 4% is obtained via electrolysis, and it can be considered as renewable hydrogen only if this electricity comes from a renewable source [4].

There is an increasing interest in hydrogen as a clean energy resource with a wide range of applications. Hydrogen is an important feedstock with many applications such as in the production of ammonia and fertilizers, upgrading of fuels, methanol synthesis and metallurgic processes. There is also an increasing interest in hydrogen as an energy carrier [6].

The Steam-Iron process is one of the oldest commercial methods for the production of hydrogen [7]. It was developed in the beginning of the 20th century by Messerschmitt and Lane [6,8,9], mainly for production of hydrogen for airships and balloons. This process is based on alternative cycles of reduction and oxidation of metal oxides (usually iron oxides, that is the reason of the process name), at temperatures between 750 °C and 950 °C [10]. In the first step of the process, iron oxide is reduced from hematite (Fe_2O_3) to magnetite (Fe_3O_4), wustite (FeO) or metallic iron. This reduction can be carried out with a wide range of fuels such as syngas from biomass gasification, natural gas, petroleum products, etc. Once the desired amount of magnetite, wustite or metallic iron has been formed, the reducing gas is switched to steam. In the second step of the process, hydrogen is produced by oxidizing the metallic iron or iron oxide with steam. Fig. 2 shows a basic scheme of the Steam-Iron process.

The resulting stream is composed by water steam and hydrogen, which can be separated in a condensation step. High purity hydrogen is obtained [11], so it is possible to use it directly in fuel cells.

Steam-Iron process has been replaced by the more economical an efficient steam reforming of natural gas [12–14]. In steam reforming process, steam reacts with methane at high temperatures in order to produce carbon monoxide and hydrogen (syngas) in the presence of a catalyst. Additional hydrogen can be produced through the water-gas-shift (WGS) reaction, which takes place in two phases, at high temperature and at low temperature [14]. Finally, a purification process is utilized through a PSA unit [15].

However, the Steam-Iron process is becoming more interesting due to its simplicity, the high purity of the hydrogen obtained and specially the possibility to use renewable energy sources such as biomass. In this work, Steam-Iron process is proposed as an alternative to conventional Water Gas Shift reaction after a biomass gasification process, which is the most common industrial pathway for the production of hydrogen. Due to the high purity of the hydrogen produced in Steam-Iron process, further purification steps via PSA are not necessary. Comparing this process with the conventional Water Gas Shift reaction from a life cycle analysis point of view, it has potential environmental advantages in terms of life-cycle abiotic depletion, global warming, ozone layer depletion and photochemical oxidant formation. However, it has a potentially unfavorable life-cycle energy performance, but a favorable renewability score [16]. In this way, it is possible to obtain green hydrogen.

One of the main advantages of Steam-Iron process is that it can be intended as a hydrogen storage method [7,17–19]. In the reduction step, hydrogen is "produced" and stored in the reduced iron oxide. The theoretical maximum amount of hydrogen that can be stored and transported as the reduced oxide is 4.8%, which corresponds to 537 L of hydrogen (STP)

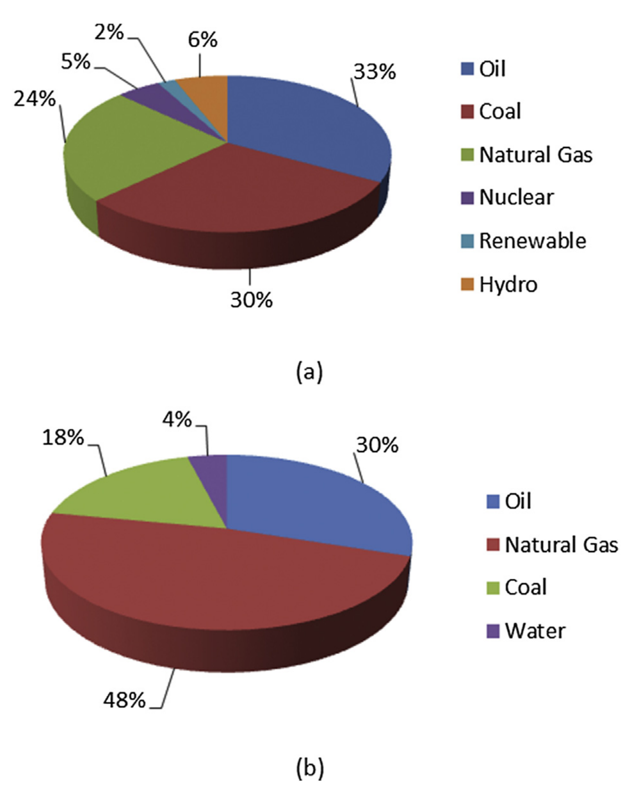

Fig. 1 – Global primary energy consumption (2011) [1] (a); hydrogen production pathways (2010) [5] (b).

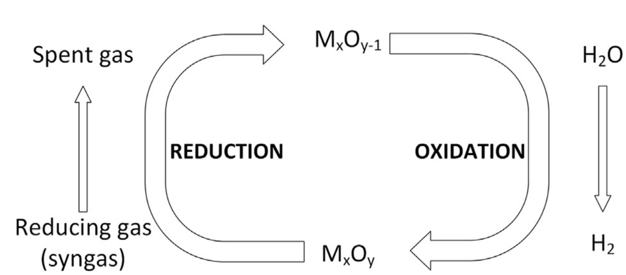

Fig. 2 – Steam-Iron process.