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Techno-economic assessment of a plant based on a three reactor chemical looping reforming system

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ABSTRACT

Reforming by using chemical looping concept is an innovative and recent technology which is used to convert the hydrocarbon fuels into hydrogen (H_2). The overall process produces separate streams of H_2 and CO_2. The present study conducts a techno-economic assessment of a three reactor chemical looping reforming plant. The cost data are used for the plant's location to be in the United Arab Emirates. The effects of key operating parameters on the technical performance of the plant are investigated. In addition, the thermodynamic data from the model are also used to perform an economic assessment for calculating the cost of H_2 produced. The cost of H_2 production with CO_2 capture is 1.679 $/kg which is significantly low when compared to the case of steam methane reforming with CO_2 capture (about 2.39 $/kg). Furthermore, the cost of H_2 production in non-capture scenario is 1.404 $/kg which is comparable with the cost of H_2 production from steam methane reforming technology.

Introduction

Rising concentrations of greenhouse gases in the atmosphere have garnered the attention of scientific community. Consequently, efforts to mitigate the greenhouse gas emissions are growing significantly. Most of the efforts are directed towards improving energy efficiency, developing hybridized systems by integrating conventional and renewable energy systems and production of clean fuels [1]. Recognizing the intermittency of renewable energy sources, the interest in producing clean fuel such as hydrogen (H_2) has been particularly increasing [2]. Furthermore, about 60% of total global greenhouse gas emissions (of that 76% is CO_2 [3]) comes from the fossil fuels used directly in transportation, residences and industries [4], where CO_2 capture is difficult and expensive. Therefore, extensive replacement of fossil fuels by decarbonized fuels in these sectors is needed in order to stabilize the CO_2 concentration in the atmosphere [5].

Due to severe weather conditions, United Arab Emirates (UAE) is one of the largest energy consumers in the world on per capita basis [6]. The large energy usage is also reflected on the CO_2 emissions, about 18.57 tCO_2 per capita in 2012 [7]. Therefore, the UAE leadership has drafted “UAE Vision 2021” [8] to address the issues relating to sustainability, lowering of CO_2 emissions and diversification of the energy sources in order to achieve a balanced economic growth. To achieve these targets, the UAE needs to generate 24% of the energy from the clean energy sources [9]. As a result, many initiatives have been taken such as the installation of H_2 fuel cell in

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Nomenclature

AR	Air Reactor
BEC	Bare Erected Cost
CEPCI	Chemical Engineering Plant Cost Index
CLC	Chemical Looping Combustion
CLR	Chemical Looping Reforming
EPCC	Engineering, Procurement and Construction Cost
FR	Fuel Reactor
GT	Gas Turbine
HP	High Pressure
HRSG	Heat Recovery Steam Generator
IP	Intermediate Pressure
LHV	Low Heating Value
LP	Low Pressure
NETL	National Energy Technology Laboratory
OC	Oxygen Carrier
O&M	Operation and Maintenance
RGIBBS	Gibbs Reactor
RSB	Regulation and Supervision Bureau
SC	Steam Cycle
SR	Steam Reactor
SRK	Soave-Redlich-Kwong
ST	Steam Turbine
TC	Turbo-Charger
TOC	Total Overnight Cost
TPC	Total Plant Cost
TPRC	Total Product Cost
TRCLR	Three Reactor Chemical Looping Reforming
T&S	Transport and Storage
UAE	United Arab Emirates

partnership with AFC Energy [10] which can generate 300 MW by 2020 [11]. Since the UAE is one of the largest natural gas consumers in the world according to the 2014 statistics [12], this gas can be used to produce H_2 while capturing CO_2, which will avoid its contribution to the greenhouse effect. Since H_2 is an intermediate energy carrier, it is mainly produced from primary fossil fuels. The daily global production of H_2 is 1 billion m^3. Out of this, the share of different H_2 production technologies include 48% from steam reforming of natural gas, 30% from oil, 18% from coal and the rest is from electrolysis and other technologies [13,14]. The other technologies include the steam gasification, pyrolysis, thermal decomposition, auto-thermal reforming and H_2O-gas shift reaction [15,16]. Most of these technologies produce large amounts of greenhouse gases. Due to which, a CO_2 separation system mostly based on mono-ethanolamine [17] is utilized to extract CO_2 out of the gas mixtures [18]. In addition, a pressure swing adsorption system is applied to separate H_2 from other mixture components to obtain high quality H_2 [19]. These separation modules consume a significant amount of energy. The energy consumption of the CO_2 separation module is particularly high, which is estimated to be about 22% of the total H_2 production cost [20].

Chemical looping reforming (CLR) using three different reactors is an innovative way of producing H_2 while capturing CO_2 in separate streams [2]. As no additional separation modules are required, there is a minimum or no energy penalty. The whole process occurs in three steps by utilizing a transition metal oxygen carrier (OC) which loops among the three reactors. The formation of CO_2 and H_2O occurs in the fuel reactor (FR), generation of H_2 from steam in the steam reactor (SR) and oxidation of OC by the air in the air reactor (AR) as shown in Fig. 1. More detailed information about the process can be found in our previous work [2].

Previously, few studies regarding the thermodynamic performance have been performed which demonstrated the potential of using the CLR technology to produce H_2. The concept of H_2 production using three reactors was proposed by Chiesa et al. [21]. They compared two plant configurations, one of them utilizing a steam compressor and another one utilizing a combustor, with other commercially available commercial H_2 production technologies. They concluded that three reactor chemical looping reforming (TRCLR) process has vast potential of producing H_2 while capturing CO_2. In another similar study, Xiang et al. [22] introduced two FRs to ensure complete conversion of the fuel (syngas). The H_2 output was increased as full conversion of the syngas was achieved. Cormos [23] analyzed and compared the performance of the system using natural gas and syngas produced from coal gasification and laid down the methodology to evaluate the performance based on critical design factors. However, the previous studies did not investigate the sensitivity of the system to the key operating parameters, which is an important design consideration. Khan and Shamim [2] identified some of the key operating parameters which affect the performance of the TRCLR process. However, the system was not integrated with any power generation scheme. Techno-economic analysis of the CLR technology is another important area which did not receive much attention. Since the CLR technology is relatively new and it has only been tested at a pilot plant level, its commercial viability strongly depends on the cost of H_2 production compared to other competing technologies. There has not been any economic study pertaining to the CLR technology. There has been only one study related to chemical looping combustion (CLC) with humid air turbine power cycle [24] and many on CO_2 capture from conventional power plants [17,25]. In summary, the literature did not cover the detailed breakdown of the costs and comparison of H_2 production costs with that of other technologies. Hence, there is a significant gap in the literature in this area.

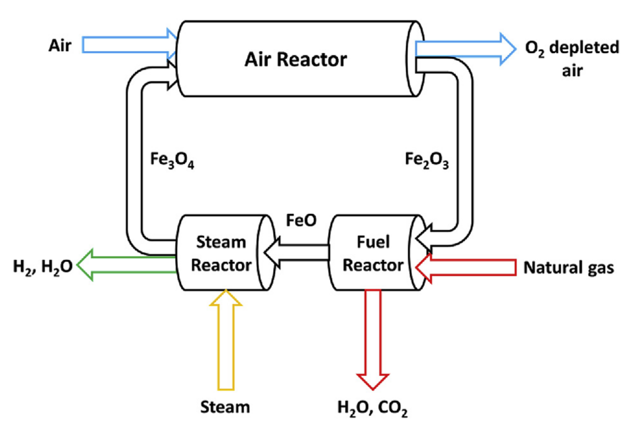

Fig. 1 – Schematic of a three reactor CLR process.