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Introducing an integrated chemical looping hydrogen production, inherent carbon capture and solid oxide fuel cell biomass fueled power plant process configuration

Mahsa Aghaie [a], Mehdi Mehrpooya [a,b,*], Fathollah Pourfayaz [a]

[a] Renewable Energies and Environment Department, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran
[b] Hydrogen and Fuel Cell Laboratory, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran

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ABSTRACT

A novel integrated system is proposed which combines biomass gasification, chemical looping combustion, solid oxide fuel cell system and a steam power cycle. Sensitivity analysis is done for effective parameters to analyze the performance of the integrated system and investigation of the optimal operating condition. Because of some restrictions in the integrated system experiments, a chemical process simulator is used for analysis of the hybrid system. Products of this process are high-purity hydrogen and electrical power which are produced by chemical looping and solid oxide fuel cell (and a power cycle) respectively. The net efficiency of the system reaches to 55.8% with 100% carbon dioxide capture. Solid oxide fuel cell operates at 850 °C and 12 bar. Chemical looping system uses Calcium oxide metal oxide as oxygen carrier. Also carbonator, calcinator and hydrator reactors operating temperature are 800 °C 850 °C and 650 °C respectively.

1. Introduction

Carbon dioxide (CO_2) as a primary greenhouse gas (GHG), has significant effect on the climate change and become a widespread concern in the recent years [1]. Hence, reducing CO_2 emission seems urgent. Although there is increasing interest to use renewable energies such as solar, wind geothermal and biofuel [2,3]. Growing demand for energy and availability of low price fossil fuels leads to fossil fuels play a primary role in energy supply. CO_2 capture can be an effective method for reducing CO_2 emissions [4]. Utilizing hydrogen (H_2) as a clean fuel has been considered significantly in recent years [5]. Hydrogen can be produced by either fossil fuels or renewable resources [5]. Current H_2 production methods are producing GHG as much as fossil fuels systems. Thus, to consider H_2 as a clean energy resource, it is essential that H_2 be supplied from carbon neutral sources [6]. Now, although there are various H_2 production methods, most of them utilizes fossil fuels mainly from natural gas [6]. Biomass as a diverse and renewable resource, can be replaced by fossil fuels for hydrogen production [7]. Biomass mainly because of energy security, sustainability and its environmental positive effects is attracted more interests recently [8]. Biomass gasification is a more efficient way to produce valuable syngas and using the heat of gasification reaction [9]. Chemical looping combustion (CLC) is developed in mid-1990 [10]. It is a kind of combustion which uses metal oxide to produce oxygen. Chemical looping hydrogen production (CLHP) with three reactors can produce steam, H_2 and CO_2 separately. Different metal oxides are used in the chemical looping, among them, calcium sorbent-based looping processes also benefit from the use of limestone, as a natural material that is widely available, relatively inexpensive, and environmentally agreeable, as the sorbent feedstock [11]. Also CLHP rather than hydrogen production, can be utilized for carbon capture processes. Recently CLC method for carbon capture has been considered significantly. Several experiments to evaluate carbon capture efficiency with chemical looping combustion of biomass/coal in a 1 kW continuous reactor with Australia iron ore as oxygen are done [12]. They show that carbon capture efficiency and oxide oxygen fraction increases with the fuel reactor temperature. The biomass combustion in a continuous CLC unit using pine wood as fuel and iron ore as an oxygen carrier is investigated [13]. Based on their studies, for both of steam and CO_2 as gasifying agents, the highest carbon capture efficiency can be obtained in the 880–915 °C temperature range. Hence, it is proposed that recirculated CO_2 can be used without efficiency reduction. So to developing the combustion methods with gaseous fuels, other options based on the chemical looping cycles which produce

* Corresponding author at: Renewable Energies and Environment Department, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran.
E-mail address: mehrpooya@ut.ac.ir (M. Mehrpooya).

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Nomenclature

A	area (m^2)
D_{eff}	effective diffusivity
D_0	constant ($cm^2\ s^{-1}$)
d_p	average particle diameter
E	thermodynamic voltage (V)
$E_{act,an}$	activation energy for anode ($kJ\ mol^{-1}$)
$E_{act,cat}$	activation energy for cathode ($kJ\ mol^{-1}$)
E^0	thermodynamic voltage at standard condition (V)
F	faraday constant, 96,485 ($C\ mol^{-1}$)
G	gibbs free energy ($kJ\ mol^{-1}$)
i	current density ($A\ cm^{-2}$)
i_0	exchange current density ($A\ cm^{-2}$)
L	length (m)
P	pressure
P_0	standard pressure (1 bar)
R	gas constant, 8.314 $J\ mol^{-1}\ K^{-1}$
r_p	average pore radius
T	temperature (K)
T_0	standard temperature (298 K)
U_f	fuel utilization
V	voltage (V)
W_{elec}	electric power (kW)
γ_{an}	pre-exponential factor for anode ($A\ m^{-2}$)
γ_{ca}	pre-exponential factor for cathode ($A\ m^{-2}$)
δ	thickness
ε	porosity
η_{ohmic}	ohmic loss (V)
η_{act}	activation loss (V)
η_{conc}	concentration loss (V)

Subscripts

An	anode
Cat	cathode
C	cell
Act	activation
E	electrolyte
(s)	solid
(g)	gas
op	operating
G	generation
P	pressure
d	diameter

Abbreviations

HHV	higher heating value
LHV	lower heating value
SOFC	solid oxide fuel cell
MCFC	molten carbonate fuel cell
PEMFC	polymer electrolyte membrane fuel cell
PAFC	phosphoric acid fuel cell
S/C	steam to carbon ratio
ST	steam turbine
SC	steam cycle
WGS	water-gas shift
YSZ	Yttria-Stabilized-Zirconia
CLC	chemical looping combustion
CLHP	chemical looping hydrogen production
GHG	greenhouse gas
PB	pine bark
CGE	cold gas efficiency
CaO	calcium Oxide
FeO	Iron Oxide

hydrogen in combination of CO_2 capture have been raised [14,15]. For instance, Chiesa et al. [16] proposed a system based on CLC method for producing hydrogen from natural gas with intrinsic carbon capture. According to their results, similar efficiency is obtained for chemical looping hydrogen production method and commercially available technologies. Fuel cells as clean, high efficient and high reliable power source are evolving for distributed power systems and portable systems [17,18]. Between all types of fuel calls, solid oxide fuel cells due to their high working temperature range (800–1000 °C), type of electrolyte (ceramic), compatibility with different types of fuels are more promising. Another advantage of SOFC is that its efficiency rises when pressurized in high temperatures, so can be used as a heat source for a gas turbine. Also SOFC can be integrated with gas turbines and other electricity generators [19]. There are several models available in the literature for SOFC-GT integrated systems [20]. Palsson et al. [21] simulated the combined system of SOFC and GT, which they reach the conclusion that efficiencies of more than 65% are possible at low pressure ratios. The attractive property of SOFC-GT systems is their high efficiency and minimal fuel combustion. Furthermore, SOFC power plants are one of the cleanest technologies to obtain electricity. In spite of these special properties, in the exhaust of these systems, there is considerable amount of CO_2. Hence, there is a growing interest to integrate CO_2 separation technologies to SOFC plants [22]. On the other hand, in the proposed model, part of syngas from gasifier enters chemical looping, so in the chemical looping CO_2 capture, both CO_2 from syngas and SOFC is captured. Integrated systems show higher net power efficiency towards the separated systems [23]. Feasibility of high efficient bioenergy SOFC-CHP system using a novel autothermal steam gasification reactor, is investigated [24]. Sensitivity analysis shows that with utilization factor less than 0.75, the SOFC off gases provide gasification heat; otherwise extra biomass must be combusted with overall efficiency penalty. Chemical looping can be done by various metal oxides. The calcium oxide is one of the old and useful oxides which was developed and demonstrated in calcium looping concept in 1960s [25] and 1970s [26] in the CO_2 acceptor gasification process Limestone is used as sorbent to promote the conversion of coal to hydrogen gas and now it is used as viable technology for CO_2 capture. Connell et al. [11] developed calcium looping process (CLP) using syngas from coal for CO_2 capture and hydrogen production. They found by techno-economic analysis that using CLP, cost of H_2 or cost of electricity can be reduced 9–12% compared to the conventional CO_2 capture and WGS technologies. Various combined systems can be found in the literatures. Xiang et al. [27] proposed a novel process for hydrogen and power generation with CLC with CO_2 capture. Sensitivity analysis based on steam/H_2 ratio, temperature and other parameters were done. Chen et al. [23] introduced the solid oxide fuel cell/gas turbine (SOFC/GT) cycle integrated with coal gasification and chemical looping hydrogen production (CLHP) for electric power production with CO_2 capture. Their results showed that the integrated plant has a net power efficiency of 43.53% with no CO_2 emissions. Exergy and energy analysis of an integrated system which include CLHP and SOFC/GT showed that overall energy and exergy efficiencies of the proposed systems are found to be 56.9% and 45.05%, respectively, with a total exergy destruction rate of 15,421 kW [28]. Chen et al. [29] investigated the exergy and energy efficiencies of a combined system of CLC and SOFC. They found that the plant net efficiency is 49.8% with ~100% CO_2 capture. Conceptual design and energy