Chemical Engineering & Processing: Process Intensification 120 (2017) 134–147

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Introducing a hybrid multi-generation fuel cell system, hydrogen production and cryogenic CO_2 capturing process

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ARTICLE INFO

Keywords:
MCFC
Steam cycle
Ammonia-water absorption system
Cryogenic system
CO_2 capturing

ABSTRACT

A combined system containing molten carbonate fuel cell power plant, coal gasification, hydrogen production cryogenic CO_2 capture, Rankine steam cycle and ammonia-water absorption refrigeration system is introduced and analyzed. In this process, power, heat and cooling are produced. An electrochemical model is developed to validate the experimental results of the fuel cell. In this system at first coal burn with oxygen and produce synthesis gas which is primary fuel for molten carbonate fuel cell and hydrogen production. Outlet gases which contain carbon dioxide are sent to the cryogenic CO_2 capture system and hydrogen is separated from CO_2. Effect of key parameters on performance of the process is investigated. The power output from the system is 6.55 MW which 6 MW is gained from the fuel cell and 0.55 MW from the heat recovery and steam cycle. Also, this process produce 90 kmol/h hydrogen and 90% of the produced CO_2 is captured. Electrical efficiency of the hybrid system is 58% (LHV). Refrigeration duty (−30 °C) and the recovered heat are 101.2 kW and 22.11 kW respectively.

1. Introduction

In industrial processes both electrical power and refrigeration (at low temperatures) are required, such as food and chemical industries [1]. Combined cooling heat and power systems have developed in residential and commercial sections [2–5]. The demand for stable and clean energy supply is increasing [5]. According to the research done by Energy Information Administration [6] the world marketed energy consumption is projected to grow by 44% over the 2006 to 2030. Although there is increasing research and development interest in renewable energy across the world and fast growth has been seen in recent years [7–9]. For instance, solar energy is used as heat source for electrical power generation [10–12]. But it is still expected that fossil fuels (petroleum and other liquid fuels, natural gas, and coal) will continue supplying much of the energy use worldwide. Coal also has the highest carbon intensity among the fossil fuels: it is projected that by the year 2030, 46% of global CO_2 emission will come from coal [1]. According to the 2007 IPCC report, there is "very high confidence" that the markedly increasing greenhouse gases in the atmosphere are causing global warming and climate change [6]. Fuel cells are high efficiency and low polluting electrochemical devices, meant to convert the hydrogen chemical energy directly into electrical energy [2,13–15]. The use of fuel cells in power generation plants is considered because of many reasons such as [16–18]:

- The need of pollution reduction;
- The threat of near irreversible and fast oil prices rise;
- The wish of many countries to reduce foreign energy dependency.

Integration of the high temperature fuel cells are preferred in order to increase the overall electrical efficiency of the fuel cell power plants [19–21]. Hybrid MCFC system with supercritical CO_2 cycle based on the different process configurations is investigated [22]. In this study a new system in the case of supercritical CO_2 cycle is introduced. An hybrid MCFC system with a supercritical CO_2 Brayton cycle is investigated [23]. The results are compared with the conventional systems which use an organic Rankine cycle (ORC). MCFC hybrid systems for high efficiency CO_2 capture are studied [24]. The results show that the considered process configurations can capture 70–85% of CO_2 however the overall power increases about 20%. On the other hand, still some problems have to be solved in order to enable the commercial usage of the fuel cells. First of all, manufacturing costs have to be reduced and, at the same time, lifetime of the equipment has to be increased. High temperature FC's (about 650 °C) enables them to be

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http://dx.doi.org/10.1016/j.cep.2017.07.008
Received 6 April 2017; Received in revised form 30 June 2017; Accepted 6 July 2017
Available online 18 July 2017
0255-2701/

Nomenclature

A	Area, m^2
A_s	Specific area, m^{-1}
E_{thermo}	Thermodynamic voltage, V
E_{act}	Activation energy of anode or cathode, j. mol^{-1}
F	Faraday constant, 96488.5C. mol^{-1}
h	Specific enthalpy at real condition, kW
h_0	Specific enthalpy at environmental condition, kW
I	Current density, A.cm^{-2}
LHV	Lower heating value of fuel, kj. kg^{-1}
M_i	Molecular weight of speciesi
M_{ij}	Average molecular weight speciesi and j
M_s	Mass flow rate of strong solution, kg. hr^{-1}
m_{fuel}	Mass flow rate of fuel, kg. s^{-1}
N_{cells}	Number of cells
n_i	Moles rate of species i, mol. s-1
OR	oxygen ratio P Total Pressure, bar
P_i	Partial pressure of species i, bar
P_o	Standard pressure, 1atm
R	Ohmic voltage loss
STCR	Steam to carbone ratio
T	Temperature, K
T_0	Standard temperature, 298K
U_{fuel}	Fuel utilization coefficient
V	Voltage of single cell, V
W	Work or electric power, kW
Z	Anode or cathode side voltage loss

Greek letters

ΔEx	Exergy change, kW
ΔG	Gibbs free energy change, kj. mol^{-1}
ΔH	Heat of reaction, kj. mol^{-1}
A	Transfer coefficient, 0.5
γ	Pre-exponential factor of anode or cathode, A.cm^{-2}
η_{act}	Activation loss, V
η_{cone}	Concentration loss, V
$\eta_{elec(final)}$	Final electrical efficiency
η_{Ex}	Second law efficiency
$\eta_{net\ overal}$	Net overall efficiency
η_{Overal}	Overall efficiency
η_{ohmic}	Ohmic loss, V

Subscripts

a	Absorber
ABC	Absorption cycle
AC	Electrical power output with conversion to alternating current
act	Activation g generator
AGR	Anode gas recycle HHV higher heating value of fuel
an	Anode
cat	Cathode out outlet
ch	Chemical
comp	Vapor compression cycle
con	Power consumption
elec	Electrical efficiency
equi, ABC	Equivalent power for absorption chiller
fuel	Fuel inlet to system
g	Generator
HHV	Higher heating value of fuel
in	Inlet
k	Kinetic
out	Outlet
real	Real condition
SC	Steam cycle
ST	Steam turbine

integrated with bottoming power cycles and this point increases the waste heat recovery of the exhaust gases. Also there is no need to used expensive catalysts ((Pt. based).

The main advantage of the molten carbonate fuel cell (MCFC) power generating system is high efficiency and cogeneration capability compared with low-temperature fuel cells[25]. This is because of the high operating temperature (650 °C) of the MCFC [26]. MCFC power-generating systems of MW size are expected to become one of the major electric power plants in the future and their gross system efficiency has been reported as 45–50% [27]. Integration of a MCFC and a Brayton cycle along with a bottoming ORC is investigated [28]. Reported electrical efficiency of the system in this work is 56.25%. Integration of the MCFC for carbon dioxide capture is studied [29]. Two different gas circulation systems are analyzed. The net electrical efficiency is 51.8% and the carbon capture ratio is about 85%. Hybrid MCFC with gas turbine exhaust gas and capture CO_2 process is investigated [30]. A combined CHP MCFC and fuel cell plant with a separate CO_2 supply is proposed [31].

Fuel cells cannot produce power on their own due to the fact that hydrogen in nature is not present in enough quantity [32]. Therefore, the fuel must be obtained from primary sources, which at present time are mainly fossil fuels (e.g. oil or natural gas) [2,33,34]. For this reason a reforming unit is needed to convert primary fuels in hydrogen, that can later be fed to the fuel cells [35]. On other the hand, there is limits on CO_2 emissions this urges fossil fuel power plants to a significant degree [36–39]. The U.S. Department of Energy (DOE) is now promoting research and development efforts on clean coal technologies aggressively aiming at up to 60% thermal efficiency with more than 90% CO_2 captured [6]. Many research efforts have been conducted on IGFC with MCFC design and analysis but most of them fall short in the following aspects:

Experimental investigation on an MCFC- GT system which can capture the carbon dioxide is done [40]. In this study CO_2 emission decreases up to 50%.

Integrated MCFC and power cycle systems are investigated based on the ability of the CO_2 separation [41]. The results indicate that, 80% separation is achievable in the condition that electrical efficiency is fixed.

Different studies and hypothesis have been proposed to integrate high temperature fuel cells and gas turbine (e.g. [42–44]). In [42], the predicted performance for a 220 kW, pressurized SOFC, directly coupled with a micro gas turbine is reported. The hybrid cycle shows 57% expected efficiency. Performance of a 20 MW, ambient pressure, internal reforming MCFC-based power plant fueled with natural gas is investigated [43]. In this case, gas turbine is coupled with the fuel cell via heat exchangers and efficiency of the system is about 75%. Similar results are stated for 1 MW size in [44]. A process configuration similar to the one discussed in this work, 250 kW range, [32] is reported. Exhaust hot gases from the hybrid MCFC systems can supply the required heat duty in the absorption refrigeration systems (ARS). So moreover