

Thermodynamics Process Simulation Based Design of High Performance Light Integrated Coal Gasification Fuel Cell Plant with Membrane-Based CO₂ Capture Technology

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Abstract—The Light Integrated Coal Gasification Fuel Cell (L-IGFC) plant technology is one of the most promising technologies in the coal utilization for power generation. It could reach maximum efficiency 60.32% in LHV when the operating pressure and temperature of SOFC are 3 atm and 850 °C, respectively. However, this plant has not equipped yet with CO₂ capture technology to mitigate CO₂ emission. In another issue, the integration of CO₂ capture technology in a plant system significantly could reduce the total system efficiency. Therefore, in this study, a membrane-based CO₂ capture technology which is equipped with heat recovery systems is established to remove CO₂ before entering into the SOFC module. The total efficiency of the proposed system is 62.50% which is 2.18 points higher than the reference system without CO₂ capture. Thus, the L-IGFC plant integrated with membrane-based CO₂ capture technology could avoid the efficiency penalty.

Keywords—Efficiency penalty, heat recovery system, L-IGFC plant, membrane-based CO₂ capture.

I. INTRODUCTION

The increase of population and economic growth has contributed to the increase in energy consumption in the world especially for fossil fuels consumption in the power generation plant. Many ways have been done in order to find an alternative solution in improving the efficiency of a power generation plant. One of them is light integrated coal gasification fuel cell (L-IGFC) plant. The L-IGFC plant is a system integration of solid oxide fuel cell (SOFC) in coal gasification power plant which recognized as one of high efficiency plants for electricity generation in a sustainable future [1]. It is one of the most promising technologies in the coal utilization for power generation. The L-IGFC plant has been designed and investigated thermodynamically with clean syngas as fuel for SOFC and could reach maximum efficiency 60.32% in LHV when the operating pressure and temperature of SOFC are 3 atm and 850°C, respectively [2]. However, this future power generation plant has not equipped yet with CO₂

capture technology to mitigate CO₂ compound. The use of fossil fuels for power generation and industrial process is one of the main causes of the anthropogenic CO₂ concentration increasing in the atmosphere [3]. The CO₂ emissions from fossil fuel combustion and industrial processes, account for 78% of the increase in greenhouse gas emissions between 1970 and 2010 [4]. Different approaches are also considered and adopted by various countries to reduce their CO₂ emission, one of them is carbon capture technologies [5].

Currently, the technology of CCS or also recognized as CO₂ capture technology has received a big attention in worldwide to reduce CO₂ emission [4][6][7]. However, integration of CO₂ capture technology in the power generation system could reduce significantly the total plant efficiency approximately 10% [8]. Therefore, in this study, a membrane-based CO₂ capture technology which is equipped with heat recovery systems is established to removes CO₂ compound without reduce the total efficiency of the plant. This study proposed a high efficiency L-IGFC system with membrane-based CO₂ capture technology and thermodynamically analyzes performance of the proposed system.

II. METHODOLOGY

A. The Light Integrated Coal Gasification Fuel Cell Plant

Aspen Plus has been used for modeling the whole system in the current study including the L-IGFC plant. The performance of SOFC in the system is analyzed and calculated by using Microsoft Excel software. The detail configurations, operational conditions, input parameters, and performance calculation of reference L-IGFC system could be referred to the previous published studies [1][2].

B. Water Gas Shift Reaction

The clean syngas before entering into the SOFC unit must be converted to a hydrogen-rich syngas when dealing with CO₂ separation in the L-IGFC system. The clean syngas will react with steam to produce more H₂ and CO₂ in two adiabatic tubular reactors packed with catalyst before entering into the CO₂ membrane. The water gas shift reaction which occurs in the reactors is:

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In this study, the water gas shift reactors of NETL/ DOE are adopted and have been verified with practical data [9][10]. The operating parameter of water gas shift reaction is shown in the following TABLE I.

TABLE I:

OPERATING PARAMETER OF WATER GAS SHIFT REACTION	
Number of reactor	2
Inlet temperature of reactor 1, °C	230
Inlet temperature of reactor 2, °C	232
Operating pressure, bar	40
Pressure drop, bar	0.69
Steam/ CO ratio	2
Type of catalyst	Cu/ZnO/Al ₂ O ₃
bed voidage (ε)	0.5
particle density (ρ), lb/ft ³	150
CO conversion, %	99.32

C. Membrane-Based CO₂ capture

The PolarisTM membrane has adopted to remove CO₂ emission from L-IGFC power plant [11][12]. In practical separation application, the pressure ratio across the membrane is between 5 and 15 [13] but in this study, pressure ratio 10 was chosen. The feed and permeate pressure of membrane are 10 atm and 1 atm, respectively with working temperature of membrane 10 °C. The separation properties of the membrane are shown in TABLE II.

TABLE II:

SEPARATION PROPERTIES OF MEMBRANE AT 10 °C [14]	
Gas Component	Mixed Gas Permeance (GPU ^a)
CO ₂	1,000
H ₂	85
CO	20
N ₂	10
CH ₄	10
H ₂ S	2,000

^a1 GPU = 7.501 x 10⁻¹² m³(STP)/(m².s.Pa)

III. RESULTS AND DISCUSSION

This study proposes a new configuration of L-IGFC plant which integrates with membrane-based CO₂ capture to remove CO₂ compound. The proposed configuration is shown in Fig. 1. The operating parameter of reference L-IGFC system has published in previous study [1][2]. The CO₂ membrane in the L-IGFC does not consume energy because it does not require vacuum pump during operation. The membrane is driven by pressure difference which is in this study, pressure difference 10 is chosen. The permeate pressure of the membrane is set to ambient pressure 1 atm while the feed pressure is 10 atm.

Approximately 88.88% of CO₂ compound will be captured from feed stream and will deliver to intercooling CO₂ compression through permeate stream. However, before

entering into the membrane unit, the desulphurized syngas is converted to hydrogen-rich syngas with CO₂ product through water gas shift reactors. Steam is required to convert CO₂ into H₂ and CO₂ through water gas shift reaction. This steam can be generated with borrowing heat from syngas cooler (steam drum unit) and return that heat after gain additional heat from multi-stream heat exchanger. The mass flow rate of water which is pumped to the steam drum is increase because the additional water mass flow rate will be used to generate steam for water gas shift reaction process and produce electricity through steam turbines (HPST2 and LPST2). The heat recovery system has applied in the water gas reaction process and membrane system. So, it could improve the total system efficiency and reduce the efficiency penalty.

The performance of L-IGFC system has analyzed and calculated by using Microsoft Excel software. In this study, the total system performance is compared to the reference system with parameter constraints is maintained. The net power output of this study is 27,169.62 kW which is higher 608.421 kW than reference system eventhough the electric power consumption of this study is higher than reference system. More detail performance comparison results is shown in the following TABLE III.

TABLE III:

PERFORMANCE COMPARISON WITH REFERENCE CASE		
	Reference System [2]	This Study
SOFC working temperature, °C	850	850
SOFC working pressure, bar	3.04	3.04
T _{outlet} of Dry Gas Desulfurization, °C	460	460
T _{inlet} to SOFC module, °C	509.7	509.7
T _{inlet} of steam to HRSG, °C	339.4	339.4
Mass flow rate of steam to HRSG, kg/h	68,000	68,000
Electric Power Output, kW		
SOFC(@i=0.2 A/cm ²)	13,384.53	12,625.86
HPST1	4,060.75	3,517.90
LPST1	12,160.23	10,852.03
Raw Syngas Expander	830.96	1,172.04
Clean Syngas Expander	None	57.82
Flue Gas Expander	2,453.51	2,507.55
HPST2	None	352.69
LPST2	None	3,256.41
Steam Turbine 1	None	393.29
Steam Turbine 2	None	850.56
Total	32,889.98	35,586.15
Electric Power Consumption, kW		
Air Compression	3,575.08	3,575.08
Pump	345.44	477.76
Nitrogen Compression	111.63	111.63
Drying Blower	7.83	7.83
O ₂ Separation and Compression	2,288.8	2,288.8
Intercooling CO ₂ compressions	None	1,955.43
Total	6,328.78	8,416.53
Net Power Output, kW	26,561.19	27,169.62
Net LHV efficiency, %	60.32	62.50
CO ₂ removal ratio, %	-	88.88

The working SOFC temperature and pressure are maintained same with reference case, 850°C and 3 atm, respectively. Beside of that the outlet temperature of dry gas desulphurization,

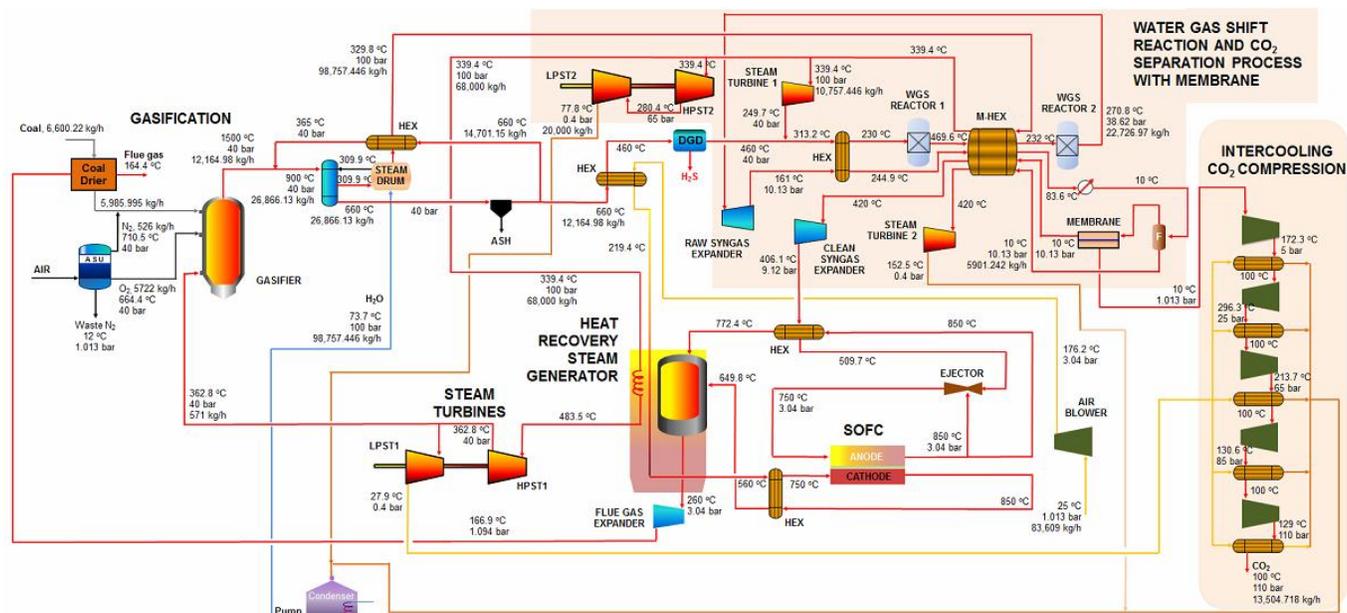


Fig. 1. Process Flow Diagram of the L-IGFC Plant with Membrane Based CO₂ Capture Technology

inlet temperature to SOFC and to heat recovery steam generator as well as mass flow rate of steam are also maintained. In this study, the reference L-IGFC system, water gas shift reactors with CO₂ membrane, and intercooling CO₂ compression have been analyzed.

There is no significant changing occurred on the reference L-IGFC system unless the increase of mass flow rate of pumped water for steam drum and decreasing of inlet temperature of steam turbines (HPST1 and LPST1). The increase of water mass flow rate that pumped to the steam drum is occurred because of addition of the amount of water needed to generate steam for water gas shift reaction and electricity production through HPST2 and LPST2 in water gas shift reaction subsystem. It is followed by energy consumption of water pump. The inlet temperature decreasing of HPST1 and LPST1 is occurred because heat transfer to the steam is not enough.

Fortunately, this reduction can be covered by power generation in the water gas shift and CO₂ membrane subsystem. Through utilization of waste heat and heat recovery system in multi-stream heat exchanger, the total electric power output reduction can be avoided. Four steam turbines are added to this proposed system in order to expand and generate energy from high temperature steam after waste heat recovery process. This proposed system can raise the total electric power output 2,696.17 kW compared to reference case.

The electric power consumption of this proposed system is higher than the reference case because it requires energy to pump the water that will deliver to the steam drum as well as need energy to compress CO₂ to the storage with final CO₂ pressure 110 bar. Although in such case, the net power output of the proposed system is still higher 608.421 kW compared to reference case. Thus, the total efficiency of the L-IGFC plant integrated with membrane-based CO₂ capture technology is 62.50% which is 2.18 points higher than reference case and

could remove 88.88% CO₂ compound in the L-IGFC plant.

IV. CONCLUSION

The L-IGFC plant with membrane-based CO₂ capture technology was proposed. The total efficiency of the plant including intercooled CO₂ compressions is 62.50% in LHV which has 2.18 points higher than the reference system without CO₂ capture technology. This proposed system could remove 88.88% CO₂ compound from the system. The integration of membrane-based CO₂ capture technology and heat recovery system for steam generation in the L-IGFC plant could avoid the system from energy penalty.

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