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Pingping Li (✉ pingping.li.d@chnenergy.com.cn)

National Institute of Clean and Low Carbon Energy <https://orcid.org/0000-0002-7958-1770>

Xianlin Jin

Shenhua new energy company, Ltd.

Zhongshan Guo

Ningxia coal industry group coal to oil branch company

Xiaobin You

Shenhua new energy company

Hu Li

Ningxia coal industry group coal to oil branch company

Jinsong Yao

National Institute of Clean and Low Carbon Energy

Lilong Jiang

Shenhua new energy company

Chufu Li

National Institute of Clean and Low Carbon Energy

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Pingping Li^{1*}, Xianlin Jin², Zhongshan Guo³, Xiaobin You², Hu Li³, Jinsong Yao¹, Lilong Jiang², Chufu Li¹

(¹. National Institute of Clean-and-Low-Carbon Energy, Beijing 102209, China;

². Shenhua new energy company, Ltd., Beijing 100007, China;

³. Coal to oil branch company, Ningxia coal industry group, Yinchuan, 750411, China)

Abstract: As one of the significant part of IGFC (integrated gasification fuel cell) system, coal gasification technology has an important effect on system efficiency as well as technological process. To figure out what kind of gasifier technology could benefit IGFC system most, we select two representative gasifiers for comparison, which are E-Gas gasifier and Shell gasifier. In this study MW-level E-gas IGFC system and Shell IGFC system models are developed respectively, moreover, the energy analysis of two systems are carried out simultaneously. The results show that SOFC DC Power efficiency and system net plant efficiency of E-gas IGFC system are 52.82% and 50.89% , both higher than Shell IGFC system, which are 49.24% and 49.74%; under the same design conditions, gasifier with high content of CH₄ would be easier to obtain higher SOFC power efficiency as well as system net efficiency. The present work is helpful to provide gasifier selection suggestions for large-scale IGFC system.

Keywords IGFC, gasification, SOFC, efficiency, simulation

1. Introduction

In 2018, China's total coal consumption reached about 2.74 billion metric tons of coal equivalent (Mtce), takes a proportion of 59% in the total primary energy consumption.(China statistical yearbook 2019) As the largest consumer of coal as well as the largest emitter of energy-related carbon dioxide(CO₂), China has pledged internationally “to achieve the peaking of carbon dioxide emissions around 2030 and making best efforts to peak early”. Hence, In the coming decades, Green coal Power with high efficiency and near-zero emission will become the new direction of coal power (Lin J 2018)

IGFC is a new kind of power generation technology which combined coal gasification with fuel cell technique. Fuel cell owns extremely high energy density, which can transfer chemical energy of fuel to electrical energy directly, profit from that, the theoretical power efficiency of IGFC system can up to as high as 56%-58%. IGFC system also with the function of CO₂ gathering, CO₂ concentration of tail gas can even reach to 95%, with the help of CO₂ Capture and CO₂ storage (CCS) process, theoretically zero-CO₂ emission could be achieved (Grol E 2009, Romano M C 2011, Lanzini A 2014). Recently years, with the development of fuel cell technology, the cost of IGFC system is falling steeply, which makes near-zero CO₂ emission IGFC system the most promising coal

power technology around the world.

Solid Oxide Fuel Cells (SOFCs) are considered as the most suitable technology for IGFC system featuring high chemical-to-electrical efficiency, high energy density, and fuel flexibility. SOFC owns solid electrolyte, the cells can be made as thin as 8μm (US: Battelle Memorial Institute 2016), which makes SOFC well suited for premium baseload power generation in the range of few to hundreds megawatts. Various fuels can be used in SOFCs for power generation, including H₂, CO, methane, syngas and other kinds of carbon-based fuel. Several groups have shown that SOFCs can operate directly on hydrocarbon fuels, including higher hydrocarbons(Kee, R J 2004, Ghezel-Ayagh H 2013) Well known SOFC suppliers including Fuel cell Energy, Bloom Energy, GE , MHI, etc. Among that the most commercially successful SOFC company should be Bloom Energy, whom sold 687 , 622 sets of 100KW SOFC system in 2016 and 2017, their SOFC systems have been installed and applied in numerous famous companies such as Apple, Coca-Cola and so on.

In this paper we proposal a MW-level IGFC system technological process and built the model by using Aspen PlusTM software. To find out the effects of gasification technology on the efficiency of SOFC Power Island as well as IGFC system, we selected two representative gasification technologies, the E-gas gasifier and Shell gasifier. On the basis of simulation

results and experiment data, energy analysis is carried out either.

2. MW-level IGFC system process

Fig.1 illustrates the process flow of MW-level IGFC system. In gasifier unit coal convert into raw syngas under high temperature and high pressure condition, then the raw syngas goes to purification unit, Whose function is to remove harmful contaminants such as sulfur, NH_3 , etc. Since SOFC operated at atmospheric pressure, before SOFC Power Island an expander is needed to decompress pure syngas and generate power at the same time, next, decompression syngas flows into SOFC Power island and generate power

Fig.1 The process flowsheet diagram of MW-level IGFC system

3. Gasification technology

Proximate Analysis (weight %)						
M _{ar} /%	A _{ar} /%	V _{ar} /%	FC _{ar} /%	LHV/(KJ/Kg)		
11.12	9.7	34.99	44.19	26151		
Ultimate Analysis (weight %)						
C _d /%	O _d /%	H _d /%	N _d /%	Cl _d /%	S _d /%	A _d /%
71.72	7.75	5.06	1.41	0.33	2.82	10.91

In IGFC system, the function of gasification unit is to convert coal into syngas that can be used as fuel of SOFC directly.

In general, syngas composition out of gasifier varies depending on following factors(Anne-Gae^ˆlle,2006):

- Coal composition and rank
- Coal preparation and feeding system(dry powder or slurry)
- Gasification condition: temperature, pressure, heating rate and so on.

In this study we choose Illinois No.6 coal as the feed.

either, since fuel utilization of SOFC is not exceeding 100%(usually no more than 85%), there are a portion of unspent fuel(CO , H_2)remained in the anode tail gas, a pure oxygen combustor is helpful to recover this part of heat value as well as enrich CO_2 concentration of tail gas, in that case CO_2 concentration of tail gas can up to 95%(dry basis). Anode and cathode heat exchanger can recover the heat of tail gas out of SOFC and preheat inlet gas simultaneously. The heat recovery steam generator unit (HRSG) with the function of heat recovery, steam supply and power generation.

Table.1 lists the proximate analysis of Illinois No.6.

Table.1 Proximate analysis of Illinois No 6 coal.

2.1 E-Gas™ coal gasifier technology

E-Gas™ coal gasifier technology owns over 20 years commercial experience, it was firstly designed and built into pilot by The Dow Chemical Company in 1975. In 1979 and 1983, 400 TPD(short tons per day per gasifier) and 1600 TPD E-Gas™ gasifier demonstration plants have been built respectively. In 1995, E-Gas™ coal gasifier with the scale of 2600 TPD was applied to Wabash riverigcc IGCC demonstration power plant which supported by DOE(U.S Department Of Energy)(NETL,2015).

As shown in Fig.2, E-Gas™ coal gasifier has the design of two stage and slurry feed. It also features an oxygen-blown, entrained-flow, refractory-lined gasifier with continuous slag removal. Advantages of CoP E-Gas™ coal gasifier are shown below:

- Two-stage gasification will boost the carbon

conversion and heat recovery efficiency.

- Separate Fire-tube syngas cooler can generate excess HP steam.
- Dry Char Recycle can decrease wasted water generation and carbon lost.

The second stage temperature of E-Gas™ coal gasifier is just about 1000°C, which is much lower than Shell gasifier(1400°C) and other gasifiers, as a result, E-Gas™ gasifier can generate a syngas having a moderate methane content of approximately 6 mole percent.

Fig.2 The diagram of CoP E-Gas™ coal gasifier

2.2 Syngas composition of two gasifiers

Table.2 lists the syngas composition of two gasifiers.

	Outlet of gasifier		Pure syngas ^(c)	
	E-gas	Shell	E-gas	Shell
Temperature/°C	1025	1079 ^(b)	316	316
Pressure/MPa	3.1	4.2	2.32	3.65
Composition/mol%				
AR	0.06	0.95	0.08	1
CH ₄	4.43	0.06	5.8	0.06
CO	28.67	57.97	37.7	59.8
CO ₂	15.49	1.43	20.4	1.58
COS	0.03	0.07		
H ₂	26.75	30.06	35.2	31.42
H ₂ O	23.15	2.52	0.1	1.3
HCl	0.08	0.09		
H ₂ S	0.69	0.81		
N ₂	0.2	5.67	0.6	6
NH ₃	0.44	0.36		

From Table.2 we can find that Shell gasifier owns higher gasification temperature and pressure, which means that we can obtain more power from expander; however, E-Gas gasifier possesses higher content of

CH₄ which is beneficial for SOFC's power efficiency(Sameshima S 2014, Lanzini A 2010)

Table.2 Outlet syngas composition of E-gas gasifier and Shell gasifier^(a)

(a) Data simulated by Aspen model and referenced by DOE report (NETL 2014, NETL 2015)

(b) .Mixed temperature of outlet syngas and syngas quench recycle

(c) Syngas composition from purification unit.

3. SOFC Power island

SOFC cell includes cathode, electrolyte as well as anode part. Fuel supplied to anode can be pure H₂, CO, CH₄ or a mixture of them. Electrochemical reactions of fuel and O₂ occur at the anode/cathode interface separately, then, charged ions flow over electrolyte surface, generate potential difference and electrons flow in the outer circuit, finally, low voltage direct current (DC), water as well as CO₂ generated (Cheng J 2004). It's worth to noting that not all fuel components can react with O₂ at the anode interface directly, almost all CH₄ and vast majority CO will having steam reforming reactions(equation 4) and water-Gas Shift (WGS) reactions (equation 3) to generate H₂, as a result, most of Nernst potential and current were produced by H₂ direct oxidation (Jin X F 2018, Zhu H 2005). The reaction equations in SOFC are listed as below:

As shown in Fig.3 SOFC power island model using a Gibbs module (SOFC) of Aspen plus to simulate the electrochemical process in SOFC anode, then specify the operating temperature, pressure, etc, Using a separate module (MEM) simulate O²⁻ penetration process of cathode simply, heat module (CA-HEAT) is set to simulate heat balance of SOFC cathode as well as the heat carry out by air (Obara S 2015, Doherty W 2010, Zhang W 2005)

Fig.3 SOFC Power Island model based in Aspen Plus

The performance of SOFC can be influenced by several parameters, for instance, composition (H₂, CO, CH₄), C/H ratio, temperature, pressure and so on. We can use below equations (5-10) to calculate the output current, voltage and efficiency of SOFC:

$$n_{e0} = n_{fuel} \times (2 \times X_{H_2} + 2 \times X_{CO} + 8 \times X_{CH_4}) \quad (5)$$

$$I = n_e^- F / t \quad (6)$$

$$U_f = \frac{n_e}{n_{e0}} \quad (7)$$

$$E = E_0 - \frac{RT_{avg}}{nF} \ln \frac{X_{H2O}}{X_{H2} X_{O2}^{0.5}} \quad (8)$$

$$V = E - i \times ASR \quad (9)$$

$$\eta_{DC} = \frac{P_{DC}}{Q_{syngas}} \quad (10)$$

n_{e0} is the mole number of maximum electron transfer, n_{fuel} is the mole number of fuel, X is the mole fraction of component (H_2 , CO , CH_4), I is the current(A), n_e^- is actual number of electron transfer, F is the Faraday constant (96485 sA/mol), U_f is the fuel utilization, E and E_0 is the Nernst voltage(V), V is the output voltage(V), i is the current density(mA/cm^2), ASR is the area specific resistance($\Omega \cdot cm^2$), P_{DC} is the DC output power of SOFC, Q_{syngas} is the input heat of the inlet syngas of SOFC, η_{DC} is the DC power efficiency SOFC.

ASR is a significant parameter to evaluate electrochemical performance of fuel cell and power supply system (method and material), which can be exacted from experiment test. Fig.4 shows the ASR data exacted from a self-design 5KW SOFC test platform. From Fig.4 we can acquire that When the current density is in the range of 300-400 mA/cm^2 , the ASR is almost stable at about $0.3\Omega \cdot cm^2$.

Fig.4 The relationship between ASR and current density

Design parameters and simulation results of SOFC Power Island in E-gas IGFC system and Shell IGFC system are shown in Table.3

As shown in Table.3 E-Gas IGFC system possesses higher n_{e0} than Shell, this is mainly due to the high content of CH_4 of E-gas gasifier. When the fuel utilization is the same, system with higher n_{e0} can obtain higher current and is easier to achieve higher output power and power efficiency.

Table.3 Design parameters and simulation results of SOFC Power Island

Parameters	E-gas	Shell
SOFC inlet temperature ($^{\circ}C$)	700	700
SOFC outlet temperature ($^{\circ}C$)	800	800
Stack operating pressure (MPa)	0.12	0.12
fuel utilization(U_f ,%)	80	80
DC-AC efficiency (%)	97	97
ASR ($\Omega \cdot cm^2$)	0.3	0.3
n_{e0} (kmol/h)	30.04	28.59
Single cell voltage (V)	0.850	0.856
Current /A	630.6	601.2
Voltage/V	867.3	873.1
Current density(i , mA/cm^2)	372	354
DC Power(P_{DC} , KW)	546.9	524.9
AC Power (KW)	530.5	509.2
DC Power efficiency(η_{DC} ,%)	52.82	49.24

4. Pure oxygen combustion and HRSG

Pure oxygen combustor was set to burn unspent fuel of anode outlet gas further. We feed sufficient oxygen into combustor as oxidant and make sure 1% excess of oxygen at the same time. From the simulation results we can see that the CO_2 (dry basis, mole%) content of tail gas from oxy-fuel combustor is up to 96.6%. After process of drying, compression, distillation and purification, CO_2 products with nearly 100% purity are finally obtained.

The HRSG produces steam to drive the subcritical steam bottoming cycle after meeting the low pressure (LP) and HP process steam needs. HRSG is a horizontal gas flow, drum-type, multi-pressure design that is matched to the characteristics of the high temperature exhaust gas. High-temperature gas is conveyed through the HRSG to recover the quantity of thermal energy that remains. High-pressure steam for power generation, and high-pressure and low-pressure process steam are generated at the same time. High temperature exhaust gas travels through the HRSG gas path and exits at about $132^{\circ}C$. (Celis C 2017, Zimmer, Gerta 2008, Chaibakhsh A 2008).

5. Energy analysis of IGFC system

Table 4 lists the simulation results of all the power generation and power consumption units of two researched IGFC systems. Here, net plant efficiency (η) is used to evaluate IGFC system performance, η defined by reference in traditional power plant as below:

$$\eta = \frac{Net\ power}{Q_{coal}} \times 100\%$$

Q_{coal} is the heat input of coal(LHV); Net Power is the result of power generation subtract power consumption

which produced by rotating device such as blower, pump, compressor and so on, what's more, transform losses, DC-AC losses and some other losses are also take into consideration to increase the accuracy of system energy analysis. It's worth to emphasis that the energy analysis is conduct under the same coal rank, coal feed and system process as well as operating parameters.

Table.4 The energy analysis of IGFC system with E-gas gasifier

	and Shell gasifier	
	E-gas	Shell
Power generation summary, W		
SOFC	530539	509126
Expander	38192	46486
Steam Turbine	132000	132977
Total Gross Power	700731	688589
Power consumption summary, W		
Coal, ash dealing	3120	2796
O ₂ Compressor	5700	8285
N ₂ Compressor	0	2500
Transform losses	2700	2700
Liquid pump	719	1286
Syngas recycle compressor	967	633
Purification unit	4612	4612
Total Auxiliaries	17818	22812
Net Power	682386	666939
Coal feed/kg·h ⁻¹	184.6	184.6
Coal LHV/kJ·kg ⁻¹	26151	26151
Net plant efficiency (LHV)	50.89	49.74
η/ %		

From Table.4 we can acquire that, the net plant efficiency of E-gas IGFC system is 50.89%, 1.15% higher than Shell IGFC system. Shell IGFC system owns higher power generation of Expander and HRSG profit from high gasification operating pressure and temperature, correspondingly, E-gas IGFC system possess higher SOFC output power because of high content of methane.

Fig.5 Power generation distribution pie charts of two IGFC systems

As shown in Fig.5 SOFC's power generation ratio is up to almost 75% in both two IGFC systems, in other words, improve the output power and efficiency of SOFC will boost SOFC efficiency more effectively.

6. Conclusion

The efficiency of IGFC system can be affected by numerous factors, find out and investigate on the key factor is beneficial to improve system efficiency as well as reduce power generation cost efficiently.

In this study two representative gasification technologies were selected to investigate on the relationships among the gasifier, SOFC Power Island and IGFC system efficiency. MW-level E-gas IGFC system and Shell IGFC system models were developed using Aspen plus. Moreover, energy analyses were carried out for the two systems. Consequently, the following conclusions were obtained:

(1) SOFC DC power efficiency of E-gas IGFC system is 52.82%, 3.58% higher than Shell IGFC system. Higher content of methane is the main reason for E-gas system to obtain higher current, output power and power efficiency.

(2) The net plant efficiency of E-gas IGFC system is 50.89%, 1.15% higher than Shell IGFC system. Shell IGFC system owns higher power generation of Expander and HRSG, However E-gas IGFC system possess higher SOFC output power.

(3) SOFC's power generation ratio is up to almost 75% in both two IGFC systems, improving the AC power and efficiency of SOFC will boost SOFC efficiency more effectively.

When take a comprehensive view of IGFC system as a whole, besides gasifier's selection, we can also focus on following aspects to optimize IGFC system efficiency:

- Take fuel recycle into consideration to improve the overall utilization of SOFC. Optimize fuel single pass utilization and recycle ratio, seek optimal operation point.
- Enhance stack's seal capacity and anti-pressure capability; improve operating pressure of SOFC Power Island (Muramoto A 2017, Virkar A 1997).

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Figures

Figure 1

The process flowsheet diagram of MW-level IGFC system

Figure 2

The diagram of CoP E-Gas™ coal gasifier

Figure 3

SOFC Power Island model based in Aspen Plus

Test temperature: 750°C, fuel : syngas

Figure 4

The relationship between ASR and current density

Figure 5

Power generation distribution pie charts of two IGFC systems