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SYSTEM ANALYSIS OF IGFC WITH EXERGY RECUPERATION UTILIZING LOW-GRADE COAL

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ABSTRACT

Integrated Coal Gasification Fuel Cell Combined Cycle (IGFC) is expected to be the most efficient power generation system in coal fired power generation systems [1,2]. The Japanese project of the Strategic Technical Platform for Clean Coal Technology (STEP-CCT) aims a target efficiency of 65 % (HHV) with exergy recuperation. We have been analyzing the processes of the exergy recuperated Integrated Coal Gasification Combined Cycle (IGCC) and the Advanced IGCC (A-IGCC) [3] which is expected to be realized in 2040. Previous studies have indicated a limitation of the quantity of high temperature steam in the case of auto-thermal reactions with the fluidized bed coal gasifier in the A-IGCC, in particular for TIT 1500 °C class gas turbine. The Advanced IGFC (A-IGFC) system can reduce the exergy loss resulting from combustion, and its 'exergy recuperation' is appealing. The waste heat exhausted from the fuel cells is recycled to the gasifier for steam reforming in an endothermic reaction with a low exergy loss and a high cold gas efficiency. Our current study focuses on the optimization of the unit configurations of the A-IGFC including gasifier, compressor, solid oxide fuel cell (SOFC), combustor, gas turbine, heat recovery steam generator (HRSG), and steam turbine. The process simulator HYSYS®.Plant (Aspen technology Inc.) is employed in order to express the gasifier, the SOFC and the other units. The optimum construction over the whole system by numerical simulation was examined for higher energy utilization efficiency. Under ideal conditions using bituminous coal, we verified the power generation efficiency to be 64.5 % (HHV). However, utilizing low-grade coals, i.e., lignite and subbituminous coal, is deemed an important future energy resource to compensate for a decreasing supply of good-quality bituminous coal. For these low-grade coals, the power generation efficiency was as high as 53.6 % (HHV) under the following conditions: Gasifier inlet: coal 23.6 Kg/s (667 MJ/s), steam 16.44 kg/s; Reactor reforming gas: 30.0, 8.7, 2.0, 0.8, 0.3, 0.05, 0.24, 0.14, 0.1 and 5.5 kg/s for CO, CO₂, H₂, CH₄, C₂H₄, C₂H₆, C₃H₆, HCN, N₂ and H₂O respectively. The projected power outputs with this system were, SOFC: 214 MW; Gas turbine: 318 MW; Steam turbine: 86 MW.

KEYWORDS: IGFC, Exergy recuperation, SOFC, Power plant, Coal, Fluidized bed reactor

INTRODUCTION

In recent years, worldwide economic growth has been increasing the energy demand considerably. Preventing climate change greenhouse gases is also an important issue. These economic and environmental aspects demand the power stations to achieve much higher electric generation efficiencies. The IGCC technology has the potential for higher efficiency [4] and has been demonstrated as a commercial plant in Japan since 2010 [5].

High-grade bituminous coal is widely consumed in many industrial processes, especially for blast furnaces. However, it is very important to utilize the low-grade lignite and subbituminous coals for the electric power generation. Lowgrade coals contain more volatile and inherent moisture rather than inherent carbonate. As the product of the pyrolysis and the reforming process of volatile hydrocarbon, volatile tar and char, the syngas includes carbon monoxide and hydrogen. The IGCC system has a considerable potential to get CO_2 under control while utilizing the low-grade coals.

National Institute of Advanced Industrial Science and Technology (AIST) is an innovation research organization contributing to society through continuous advancement in technologies and support of Japanese industries. Energy Technology Research Institute (ETRI) of AIST has engaged in the field of high efficiency power station in the energy network as one of the key energy technologies. In 2007, Japan Coal Energy Centre (JCOAL) started a coal-gasification project sponsored by New Energy and Industrial Technology Development Organization (NEDO). Its aim is to develop a component-technology of high efficient electric power generation utilizing the moist and uncrushable coal [6-8]. Based on the plentiful experiences of elemental studies and cycle analysis of turbo machinery, we have been analysing the parametric studies of the IGCC and the advanced IGCC (A-IGCC) [3, 9-11] with exergy recuperation [12] to meet the target value of the project using state-of-the-art technologies.

A previous A-IGCC study [3] has pointed out the limitation of the quantity of high temperature steam for autothermal reactions in the fluidized bed coal gasifier, especially in the case of TIT 1500°C class gas turbine. The IGFC technology can reduce exergy loss owing to combustion and is characterized optimistically by its 'exergy recuperation'. The waste heat exhausted from the fuel cells is recycled to the gasifier for steam reforming in an endothermic reaction with low exergy loss and high cold gas efficiency. Our current study is focused on the optimization of the unit configurations of the IGFC including the combustor and the HRSG.

PROCESS DISCRIPTION AND METHODOLOGY

COMPARISON OF SIMULATION PROGRAM

It is well known that thermodynamic method in a textbook deals easily the cycle calculation of the gasturbines. Air is compressed in the compressor, fuel burns in the combustor, the exhaust gas expands in the gas-turbine and goes through a heat exchanger. The values used in the cycle calculation are the mole fractions of the components, specific heat, universal gas constant, enthalpy, temperature and pressure. If the gas is in the ideal state and methane gas burns in the combustor completely, the components are O_2 , N_2 , CH_4 , CO_2 and H_2O . In this case the number of components is just 5, so the calculation of gas properties is very easy. We can use a pocket calculator and process simulators. Either will do.

In the case of IGFC, the main components of the process are coal gasifier, air compressor, reformer, SOFC, combustor, gasturbine, HRSG, condensing turbine, and heat exchanger. In addition, components of syngas pumped to the anode of SOFC are CO, CO₂, H₂, CH₄ (Methane), C₂H₄ (Ethylene), C₂H₆ (Ethane), C₃H₆ (Propene), HCN, N₂ and H₂O, which are 10 components. Also, temperature and pressure in the SOFC are 1000 °C and 1.0 MPa, respectively, so that the Peng Robinson

	thermo-	coal	SOFC	steam	pinch	HRSG	equation	solver	target
	dynamic	gasifi-			point		of state		value of
	database	cation			temper-				solution
					ature				
HYSYS.®	original	no	no	ASME	support	support	Peng-	Wegstein,	adjust,
plant				steam tables			Robinson	secant,	set
_				(IFC-67)			, others	broyden,	
								tolerence	
Simulink®+	NASA			wet air				weighted	
Thermolib®			support					residual	
							PV=	loop	
Excel®	1160	no			no	no	nRT	solver	goalseek
Visio®	IANAE		no	no				method	method
BASIC	BURCAT		110	110				Newton	
	DURCAI							method	

 Table 1
 Comparison of process simulation program of analysing IGFC

Cool elements (det)						
Coal elements	(dal)	value				
С	[wt%]		69.4			
Н	[wt%]		4.9			
Total S	[wt%]		0.1			
Combustible S	[wt%]		0.04			
Noncombustible S	[wt%]		0.06			
N	[wt%]		0.9			
0	[wt%]		24.7			
HHV	[kJ/kg]		28200			
Specific heat	[kJ/kg-K]		1.8			
Material supply to the	ne gasifier	IGCC	A-IGCC	A-IGFC		
Coal	[kg/s]	23.63	23.63	23.63		
Temperature	[°C]	200	200	200		
HHV	[MW]	667	667	667		
O ₂	[kg/s]	10.6	7.9	7.9		
Temperature	[°C]	700	700	700		
H ₂ O	[kg/s]	16.4	16.4	16.4		
Temperature	[°C]	700	700	700		
Syngas molar fractio	n	IGCC	A-IGCC	A-IGFC		
СО		0.388	0.399	0.399		
CO ₂		0.084	0.074	0.074		
H ₂		0.334	0.385	0.385		
CH ₄		0.019	0.019	0.019		
C_2H_4		0.004	0.004	0.004		
C_2H_6		0.001	0.001	0.001		
C_3H_6		0.002	0.002	0.002		
HCN		0.002	0.002	0.002		
N ₂		0.002	0.002	0.002		
H ₂ O		0.165	0.113	0.113		
Total mass flow	[kg/s]	50.66	47.99	47.99		
Temperature	[°C]	841	831	831		

 Table 2 Elemental analysis and gasifier conditions of sub-bituminous coal [10]

Kabadi-Danner (HYSYS \mathbb{B} .Plant) fits well as the equation of state of H_2O .

Table 1 compares the process simulation program for analysing the IGFC. HYSYS®.Plant and ASPEN PLUS® (Aspen technology Inc.) are the data flow programming language. They are served as the unit operations of their thermodynamic databases. Simulink® (MathWorks Inc.) with Thermolib® (EUtech Scientific Engineering GmbH) is also a data flow programming language. HYSYS®.Plant supports thermodynamic databases, ASME steam tables (IFC-67), pinch point temperature difference in heat exchanger, HRSG, Peng-Robinson, and other equations of state, wegstein solver, and functions of adjust and set value. Simulink® with Thermolib® supports NASA thermodynamic database, wet air, the ideal gas equation of state, and the weighted residual loop. Microsoft Office Excel® and Visio® can accept JANAF and BURCAT [13] thermodynamic databases, solver method, and goalseek method.

We chose HYSYS®.Plant because IGCC and IGFC have the component of HRSG and condensing turbine. HYSYS®.Plant does not support coal gasification process or SOFC. Instead of the simulating coal gasification, we adopted the syngas components gasified from sub-bituminous coal (see Table 2) and required the heat input that was published in this project. The open circuit voltage and the irreversible voltage drop of the SOFC were simulated using Milewski's formula [8, 16-18] that combining a spreadsheet, component splitter and Gibbs reactor in HYSYS®.Plant.

The data flow programming language must allocate the input and output of material stream (mole fraction, vapour fraction) and the energy stream (temperature, pressure, specific heat, enthalpy, entropy) from the components of the unit operations. Since HYSYS®.Plant is one of the data flow programming language and the coal-gasified syngas contains several hydrocarbons, the matrix size of the SOFC spreadsheet became an order of magnitude larger than the number of gas components, this complicated the process flow of the IGFC. Table 3 summarize the basic unit operations, the material and energy of IGFC process. The components of material and energy inputs/outputs must be allocated in each unit operations.

Since we have previously studied the IGCC and the A-IGCC plant system with TIT 1500 °C and TIT 1700 °C class gas turbines using HYSYS®.Plant [3] we adopted the same target and parameter values to analyze the IGFC plant system. The study assumes an ideal operation conditions that might be difficult to achieve now, but worth undertaking for what we can be obtained in return, provided the necessary technologies are developed in the future.

COAL GASIFICATION PROCESS

Figure 1 shows the basic structure of IGFC. The structure of the gasification system, the preconditions for the gasification and the syngas compositions are the same as in the previous reported study [3]. The twin circulating fluidized bed coal gasification system consists of a pyrolyzer of coal, a steam reforming gasifier of char and a partial oxidizing furnace for char. Coal supplied to the gasifier is first pyrolyzed, from which obtained char is reformed with steam to form H₂, CO and CO₂. This endothermic reaction allows exergy recuperation from thermal to chemical exergy. The remaining chars are oxidized in the partial oxidizing furnace and more CO

Material	Unit Unit twin circulating fluidized bed condition		compressor	ompressor			combustor	gas turbine	HRSG	condensing turbine		
and Energy		coal gasifier	condition		inner-reform	cathode	electrolyte	anode				
Components of material stream	sub- bituminous coal	Volatile hydrocarbon and volatile tar pyrolyzed from coal	CO, CO ₂ , H ₂ , CH ₄ , C ₂ H ₄ , C ₂ H ₆ , C ₃ H ₆ , HCN, N ₂ , H ₂ O	O ₂ , N ₂	rapid steam reforming of hydrocarbon on Ni catalyst on anode electrode	O ₂ , N ₂	O ²⁻	CO, CO ₂ , H ₂ , (CH ₄ , C ₂ H ₄ , C ₂ H ₆ , C ₃ H ₆ , HCN), N ₂ , H ₂ O, Fuel utilization factor, steam/carbo n	O ₂ , CO, CO ₂ , H ₂ , CH ₄ , C ₂ H ₄ , C ₂ H ₆ , C ₃ H ₆ , HCN, N ₂ , H ₂ O	O ₂ , CO ₂ , N ₂ , H ₂ O		
	H ₂ O, O ₂	H ₂ rich gas reformed with steam from char			shift reaction of CO on Ni catalyst on anode electrode							
		partialy oxidized from char										
	Steam		in		in						in	out
Sources and	H ₂	HVSVS Plant	out		out							
products of exergy recuperation	Syngas	® does not support coal	out		from anode exhaust			anode exhaust be recycled				
	Heat exchanger	gasification	in/out	in/out	in	in/out		in		in/out	in/out	in/out
Unit		Balance material and energy	spreadsheet	Compressor	spreadsheet	Compo- nent splitter	connect stream	spreadsheet	Gibbs reactor	Turbine	Heat exchanger	Turbine
HYSYS®. Plant		conditions of gasified coal	Gibbs reactor	Heat exchanger	Gibbs reactor			Gibbs reactor		Heat exchanger		Heat exchanger
			Component splitter					Mixer				

 Table 3
 Basic unit operations, material and energy streams of IGFC

is produced. The partial oxidizing reaction by circulating hot sands and unburnt char supplies the endothermic heat required. Compared to the normal gasifier, the total amount of the supplied oxygen can be reduced because the steam is the gasifying agent. Remaining hot solid particles, such as chars and sands separated from the CO gas, are then returned to the pyrolytic process of the gasifier as a heating medium. The gasifier in this study can supply syngases derived from the three reactions, pyrolysis, reforming with steam and partial oxidizing.

Since HYSYS®.Plant does not support the coal gasification process, we balanced the syngas compositions and the energy flow with our previously reported data on the performance of the IGCC and the A-IGCC. The supplied coal was fixed at 23.63 kg/s, *i.e.* 667 MW (HHV). In the IGFC system, the heat (steam at 700 °C) supply for reforming with steam is supplied by cooling the syngas generated in the gasifier. In the A-IGFC system, this heat supply was supplied from the SOFC or the gas turbine exhaust by energy conversion



Figure 1 Basic structure of IGFC

from thermal energy to chemical energy (*i.e.* chemical exergy recuperation occurred). The temperature of supplied coal was 200 °C. The required oxygen production power was assumed to be 0.36 kWh/Nm³, *i.e.* 0.8064 MJ/kgO₂ [3]. The coal-gasified syngas is composed of CO, CO₂, H₂, CH₄ (Methane), C₂H₄ (Ethylene), C₂H₆ (Ethane), C₃H₆ (Propene), HCN, N₂ and H₂O (see Table 2).

PRE-REFORM ON CATALYST OF ANODE

The Ni catalyst of the anode of the SOFC can work as the inner-reformer [20]. As for the material stream, the coal-gasified syngas, a part of the recycled anode exhaust gas and a part of the recycled steam are mixed in the jet pump. Then the mixed gas is reformed with steam (Eq. 1) and shift reacted in the inner-reformer of the anode (Eq. 2). Reforming with steam is an endothermic reaction and the exergy is recuperated from thermal to chemical exergy.

$$C_n H_{2m} + nH_2 O = nCO + (m+n)H_2$$
(1)

The shift reaction is an exothermic reaction.

$$CO + H_2O = CO_2 + H_2 \tag{2}$$

Eq. 1 and Eq. 2 are very fast reaction because the product H_2 is consumed electrochemical reaction in an anode simultaneously [20]. It remains possible that the fuels C_nH_{2m} and CO directly bond with O^{2-} anion at the anode in an electrochemical reaction and releases electrons. The pre-reformed syngas components are the product of Gibbs reactor of HYSYS®.Plant.

CIRCUIT VOLTAGE OF SOFC

Figure 2 shows the singular cell of the SOFC. When syngas is completely steam reformed and shift reacted in the inner-reformer on the Ni catalyst of the anode. The anode inlet gas contains H_2 and H_2O , and the cathode inlet gas contains O_2 . O_2 in the cathode receives the electron, becoming O^{2^2} anion moves to the electrolyte, then bonds with H_2 on the anode and forms H_2O releasing the electrons.

When simulating the circuit voltage of the SOFC we did not use Gibbs free energy of formation as the open circuit voltage or Nernst loss as the irreversible voltage drop. We adopted Milewski's formula [8, 16-18]. It can integrate the material data and the change of structure into the formula. Milewski showed good agreement between the simulation



Figure 2 Singular cell of SOFC



results and real data from Siemens-Westinghouse Power Corporation 300kW SOFC unit. Figure 3 shows the equivalent electric circuit of the single cell [8, 18]. Milewski showed two types of resistances in the fuel cell: ionic resistance R_1 and electronic resistance R_2 . R_3 is an external load resistance. Here, we omitted many assumptions written in the original papers [8, 15-18].

$$I_1 = 2F\dot{n}_{H2}^{Anode_used} = 2F\dot{n}_{H2}^{Anode_inlet} \times \eta_f$$
(3)

where

$$\eta_f = \frac{\dot{n}_{H2}^{Anode_used}}{\dot{n}_{H2}^{Anode_inlet}} = \frac{\dot{n}_{H2}^{Anode_inlet} - \dot{n}_{H2}^{Anode_outlet}}{\dot{n}_{H2}^{Anode_inlet}}$$
(4)

when
$$\eta_f = 1$$
:
 $I_1 = I_{\text{max}} = 2F\dot{n}_{H2}^{\text{Anode}_{-inlet}}$
(5)

$$E_{\max} = \frac{R_0 T}{4F} \ln \frac{P_{O2}^{Cathode}}{P_{O2}^{Anode}}$$
(6)

$$i_{\max} \equiv 0.8$$
$$A_{cell} = \frac{I_{\max}}{i_{\max}}$$
$$r = R_{cell} \times A_{cell}$$

when
$$R_3 = \infty, \eta_f \approx 0$$
:
 $i_1 = \frac{(E_{\text{max}} - E_{OCV})}{r_1} = \frac{E_{OCV}}{r_2}$
 $\therefore E_{OCV} = \frac{E_{\text{max}}}{(\frac{r_1}{r_2} + 1)}$
(7)

when
$$R_3 \neq \infty$$
:

$$\frac{(E_{\max} - E_{SOFC})}{r_1} = \frac{E_{SOFC}}{r_2} \times (1 - \eta_f) + i_{\max} \times \eta_f$$

$$\therefore E_{SOFC} = \frac{(E_{\max} - i_{\max} \times \eta_f \times r_1)}{\left\{\frac{r_1}{r_2} \times (1 - \eta_f) + 1\right\}}$$
(8)

The internal area specific ionic resistance r_1 is expressed in the case ZrO_2/Y_2O_3 (0.90/0.10) is used as electrolyte material:

$$r_{1} = \delta \times 10^{-\left(A_{1}\frac{1000}{T} + B_{1}\right)}$$
(9)
$$A_{1} = -4.5864, B_{1} = 2.5921, \delta \equiv 25[\mu m]$$

The internal area specific electric resistance r_2 is expressed:

$$r_2 = \delta / \sigma_e \tag{10}$$
$$\sigma_e = 7 \times 10^{-4}$$

$$SOFC \ power = E_{SOFC} \times I_3 \tag{11}$$

According to Milewski expression, the cathode, electrolyte and the anode are treated as component splitter, stream connection and the Gibbs reactor, respectively. The overhead fraction of oxygen from the component splitter is calculated as the function of the fuel utilization factor, molar flow of the fuel that bonded with O²⁻ anions, and molar flow of the cathode inlet oxygen. The anode outlet gas components are the production of the Gibbs reactor. The heat of formation in the Gibbs reactor is balanced to the sum of the electric power output and the increase of enthalpy in both the cathode and the anode. The electric loss at the inner resistance is not balanced to the part of the heat of formation since it is converted to the internal energy. 66.7 % of the gas from the anode exhaust gas is recycled again to the pre-reformer. The temperature of the SOFC was set to be about 1000 °C. The pressure of the cathode and the anode was set to be 1.0 MPa.

GAS TURBINE AND STEAM TURBINE

Thermal efficiency of gas turbine decreases due to pressure loss, mechanical loss, film cooling of gas turbine blades, etc. The simulation model is simplified to better grasp the characteristics of the system. In this analysis several losses are expressed, the decrease in the adiabatic efficiencies of the compressor and turbine, the pressure losses across the combustor and heat exchangers. The adiabatic efficiencies of the compressor, gas turbine and condensing turbine were set to be 89 %, 92 %, and 90 %, respectively (see Table 4). These values are challenging values [18] and somewhat higher than the previously studied IGCC and A-IGCC case (80 %, 85 %, and 86 %, respectively) [3]. Previous studied values are configured to achieve the target of the project under normal conditions within a feasible level of current gas turbine systems. The auxiliary consumption was assumed to be 5 % (HHV). Since the mass flow rate of oxygen is 10.6 kg/s, the total oxygen production power was calculated to be only 8.54 MW (HHV). The minimum approach temperature difference,

 ΔT_p , of HRSG was set to 30 °C. The flow rate of water in the HRSG was limited by having the pinch point temperature higher than ΔT_p . This also keep the exhaust gas from HRSG dry.

Table 4. Basic assumption for IGFC (A-IGFC) plant model

Parameter	IGFC/A-IGFC
Fuel	Sub-bituminous coal
Gasifier	Circulating fluidized bed
Air compressor adiabatic efficiency	89%
Air supply	400.0kg/s
SOFC cathode pressure	1.0MPa
SOFC anode temperature/pressure	1000°C/0.9992MPa
Gas turbine adiabatic efficiency Oxygen poduction power	92% 0.8064 MJ/kgO ₂
HRSG minimum approach temperature Heat exchanger pinch temperature difference	30°C 30°C
Condensing turbine adiabatic efficiency	90%
Condensing turbine inlet temperature/pressure	525°C/ 20MPa
Condensing turbine outlet pressure	0.005MPa

UNCONNECTED ENERGY STREAM

Most data flow programming languages often require complete connections of the unit operations. Incomplete connections and recycled streams often prevent the convergence of the solvers. However, the solver of HYSYS®.Plant has the flexibility to express the unconnected energy flows and the heat input. Gasification process requires heat input of 41 MW and over 700 °C. We expressed the heat input as a heat exchanger with the heat input that was not connected to the other unit operation. In addition we used a set operator and an adjust operator to set the target value. Thus we can get the solution of the IGFC plant system.

RESULTS AND DISCUSSION

Figure 4 shows the performance of the IGFC system when utilizing the sub-bituminous coal, and coal gasified syngas composition is shown in Table 2. The fuel utilization factor is varied from 40.0 % to 75.5 %. If the fuel utilization factor was larger than 76.0 %, the calculation was not solved due to the temperature cross in the heat exchanger. If the fuel utilization factor is 40.0 %, the SOFC electric power is 180 MW, the gas turbine output power is 341 MW, the condensing turbine output power is 88 MW, and the total efficiency is

58.5 %. The net efficiency reaches to 53.5 %. If the fuel utilization factor is 75.5 %, the SOFC electric power is 242 MW, the gas turbine output power is 285 MW, the condensing turbine output power is 89 MW, and the total efficiency is 58.4 %. The net efficiency reaches to 53.4 %. While the fuel utilization increases, the SOFC electric power increases to almost compensate the decrease of the gas turbine output power. The maximum total efficiency is achieved when the fuel utilization factor is 52.0 %, but the effect of the fuel utilization factor seems very small.



Figure 4. Effect of fuel utilization factor on IGFC performance

Table 5. States in Fig. 1 when $\eta_f = 52 \%$

Flow No.	Temperature °C	Pressure MPa	Mass Flow Kg/s
1	831.9	1.000	
2	929.5	0.999	
3	15.0	0.101	400.0
4	484.7	1.180	
5	998.6	1.000	
6	1260.0	0.999	
7	709.9	0.111	
8	593.4	0.111	
9	180.2	0.101	
10	33.0	20.0	67.2
11	525.0	20.0	
12	32.9	0.005	
13	700.0	3.5	16.44

Although we could easily find the convergence of the solver on the previous studied IGCC and A-IGCC cases [3], it is difficult to converge the parametric study on the A-IGFC cases. Many papers on IGFC process only deal with CH_4 , H_2 and CO fuels. Spreadsheets of the IGFC and the material stream (steam, H_2 , syngas) are very complicated. Many

recycled material stream prevent convergence of solver. Therefore we are now struggling to find out sensitivity analysis of simulation factors in the HYSYS simulation model. Figure 4 is the case when the adiabatic efficiency of compressor, gas turbine and condensing turbine are set to be 89%, 92% and 90%, respectively, which are the also very challenging values. In this study we obtained 53.6 % HHV.

CONCLUSIONS

The performance analysis of the IGFC when utilizing the sub-bituminous coal was studied. The spreadsheets of the IGFC and the material stream are very complicated. Many recycled material stream prevent convergence of solver. Heat input to gasifier and heat input to steam are not supplied from the SOFC recycled process. Recycled anode exhaust gas would improve the heat input and efficiency, but recycled material stream would also prevent convergence of solver. Therefore we obtained only few answers for HYSYS simulation model. The IGFC system, which had a net thermal efficiency of 53.6 % was obtained. And the adiabatic efficiency of compressor, gas turbine and condensing turbine are set to be 89%, 92% and 90%, respectively, which are the also very challenging values. A-IGFC system would become feasible provided the syngas purification was realized at high temperature. Further study is expected as a next step on investigating the better integration of the IGFC power systems.

NOMENCLATURE

A _{cell}	Area of electrolyte	
A_1, B_1	Factors depending on electrolyte material	
E	Circuit voltage	V
F	Faraday's constant	C/mol
G	Gibbs energy	J/mol
HHV	Higher heating value	
i, I	Current density, Current	A/cm^2 , A
n	Molar flow	mol/s
Р	Pressure, Partial pressure	
\mathbf{R}_0	Universal gas constant	
r, R	Area specific resistance, Resistance	$\Omega.cm^2, \Omega$
Т	Temperature	°C or K
TIT	Turbine inlet temperature	
ΔT_p	Minimum approach temperature difference	in HRSG
δ	Electrolyte thickness	
$\eta_{\rm f}$	Fuel utilization factor	
σ_{e}	Electric conductivity of electrolyte	S/cm
	- •	

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