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Comparative Study on Different IGCC Systems with Quasi-Zero CO_2 Emission

Liqiang Duan*, Yongping Yang
Beijing Key Lab. of Energy Safety and Clean Utilization, Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, School of Energy and Power Engineering, North China Electric Power University, Beijing, 102206, P. R. China,
Tel: 86-10-80798472, Fax: 86-10-80798618, E-mail: Dlq@ncepu.edu.cn

Rumou Lin
Institute of Engineering Thermophysics, CAS, P. O. BOX 2706, Beijing, 100080, P. R. China
E-mail: Lrm@mail.etp.ac.cn

Abstract

This paper studies different IGCC systems with CO_2 recovery. In order to effectively reduce CO_2 emissions from the IGCC system, several kinds of IGCC systems with quasi-zero CO_2 emissions have been studied in this paper. The key parameters affecting the IGCC systems' performance have been analyzed and compared. The systems' performances have been investigated based on comparison of different IGCC systems. The obtained results show that integrating the IGCC system with an advanced thermal cycle is an effective and feasible way. The performances of the IGCC systems with O_2/CO_2 cycle and syngas separation are better than that with a simple semi-closed O_2/CO_2 cycle. The research achievements will provide valuable information for further study on IGCC systems with low CO_2 emissions.

Keywords: O_2/CO_2 cycle; IGCC system; CO_2 recovery; SOFC

1. Introduction

Currently, in the energy utilization field, to increase the energy utilization efficiency and simultaneously solve environmental pollution problem, is the key challenge that mankind faces. It is well known that the integrated gasification combined cycle (IGCC) is one of the advanced clean coal power generation systems. Though it is reputed as the cleanest coal-fired power plant, CO_2 emission cannot be greatly reduced by this technology and only proportionally reduced with the improvement of IGCC system efficiency. So, how to effectively reduce CO_2 emission from IGCC system is the main subject of researchers at present (Chiesa et al., 1998; Jin et al., 2000; Duan et al., 2002; Lin et al., 2002; Mathieu et al., 2005).

Generally, five ways to separate and recover CO_2 from IGCC system are summed up and analyzed as follows (Duan et al., 2002; Lin et al., 2002): (1) CO_2 separation and recovery from the exhaust fuel gas; (2) CO_2 sequestration before combustion; (3) CO_2 sequestration by a polygeneration system; (4) CO_2 recovery using integrated thermal cycles with fuel - oriented transfer; (5) CO_2 separation and recovery based on novel thermal cycle, for example, the semi-closed O_2/CO_2 cycle IGCC proposed by Chiesa (Chiesa et al., 1998). Its energy penalty for separating and recovering CO_2 will cause an efficiency decrease of about 7 percentage points. At present, many researchers focus on the O_2/CO_2 cycle method to separate and recover CO_2. One of the main advantages is that separating CO_2 does not consume energy as the combustion products is mainly composed of CO_2 and H_2O. However, its disadvantage is that O_2 production consumes great energy.

Based on the above research and the integration idea of a thermal system, this paper has compared several kinds of IGCC systems with zero-CO_2 emission. The paper aims to analyze the thermodynamic characteristics, environmental performance, comprehensive performance and parameter optimization rules of different IGCC systems, and compares the system performances of different IGCC systems with O_2/CO_2 cycle.

*Author to whom correspondence should be addressed

2. Different IGCC Systems with Quasi-Zero CO_2 Emission

2.1 The simple semi-closed O_2/CO_2 IGCC system with CO_2 recovery

Chiesa (Chiesa et al., 1998) has proposed a semi-closed O_2/CO_2 cycle IGCC system. The system flowchart is shown in *Figure 1*. The coal gasification section produces clean syngas from coal. Then syngas is burned in the gas turbine combustor using oxygen (produced from the air separation unit) as the oxidizer. So combustion products mainly consist of CO_2 and H_2O. After turbine expansion and heat recovery steam generator (HRSG), combustion gases are cooled to remove H_2O by condensation. The remaining stream is almost pure CO_2. Part of this stream, in order to conserve the mass balance of the cycle, is extracted from the power cycle; the remainder is recycled, after compression, as a diluting agent to gas turbine combustion; the stream removed from the cycle is compressed up to liquefaction of CO_2, rendering it available for storage or disposal. Oxygen necessary to gasification and to syngas combustion is produced by the air separation unit.

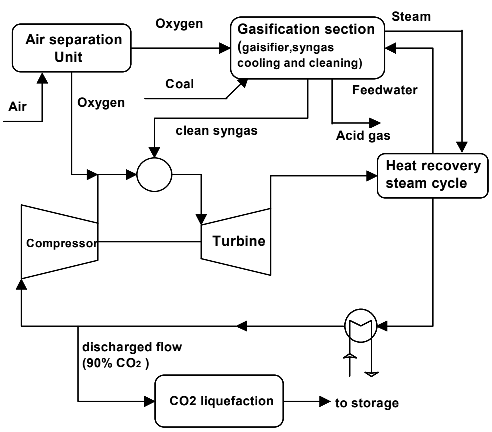

Figure1. Flowchart of the semi-closed cycle IGCC system with CO_2 recovery

Because combustion products mainly consist of CO_2 and H_2O, the main advantage of the system proposed by Chiesa (Chiesa et al., 1998) is that separation CO_2 from combustion gas does not consume extra energy. However, this system uses pure oxygen as an oxidizer. The air separation unit consumes larger energy, which results in a system efficiency decrease of 7.3% after recovery of CO_2. In addition, the change of the working fluid changes the optimized pressure ratio of the total system. The higher molecular mass and complexity of the CO_2 mixture versus air results in a lower temperature rise at the same pressure ratio. Because cycle performance mainly depends on the temperature of the working fluid, in order to obtain the same efficiency, a higher pressure ratio will be required. In contrast to the base open IGCC system with the optimized pressure ratio of 16, the optimized pressure ratio of the semi-closed IGCC increases to 42.

2.2 Three different IGCC systems with CO_2 recovery and syngas separation

In order to overcome the disadvantages and to improve the system efficiency, based on the development of key technologies and the synthesis of energy and environment, three different configurations of dual H_2/O_2 IGCC systems with CO_2 recovery were studied. They are dual-cycle IGCC system with H_2/O_2 cycle (as shown in *Figure 2*), IGCC system with steam-injected H_2/O_2 cycle and CO_2 recovery (as shown in *Figure 3*),

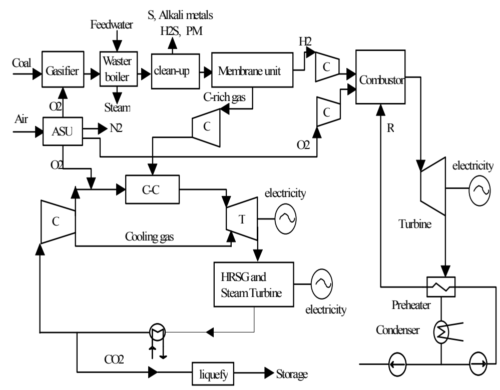

Figure 2. Flowchart of dual-cycle IGCC system with mixed H_2/O_2 cycle and CO_2 recovery

IGCC system with fuel cell combined cycle and CO_2 recovery (as shown in *Figure 4*), respectively.

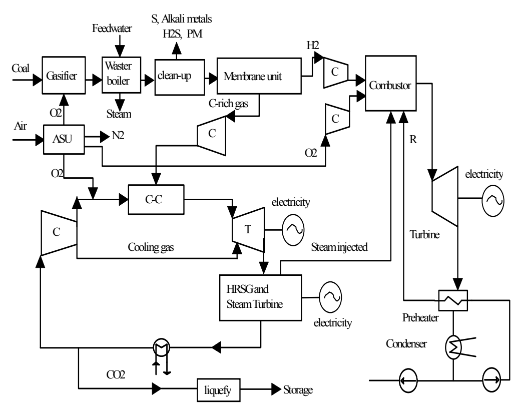

Figure 3. Flow diagram of IGCC system with steam-injected H_2/O_2 cycle and CO_2 recovery

In contrast to the IGCC system proposed by Chiesa (Chiesa et al., 1998), the three IGCC systems with CO_2 recovery are not a simple semi-closed cycle system, but dual cycle systems that consist of an O_2/CO_2 cycle and H_2 cycle system. As shown in *Figures 2, 3 and 4*, the clean syngas is first sent to the membrane separation unit. After that, syngas is separated into H_2-rich syngas and C-rich gas because the membrane employed in these systems is an advanced ceramics proton membrane (Bose et al., 2000; Balachandran et al., 2000; Roark et al., 2002). Its main advantage is that only H_2 can pass through the membrane; the purity of H_2 is very high.

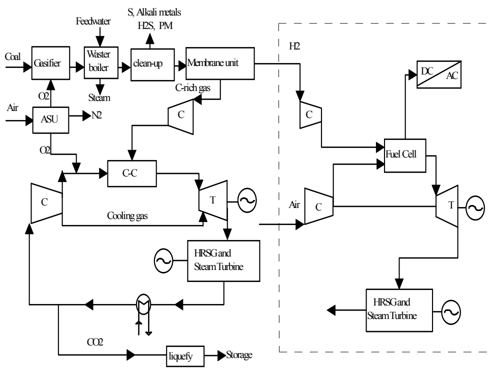

Figure 4. Flowchart of IGCC system with fuel cell combined cycle and CO_2 recovery

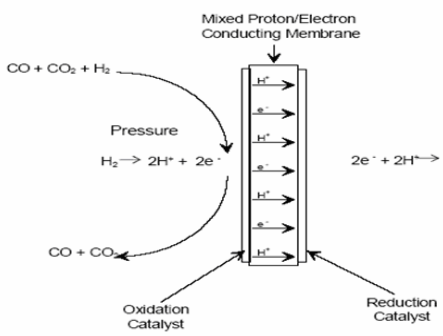

Figure 5. Schematic diagram of the ceramic proton membrane process for separating hydrogen from a mixture of gases

The process for hydrogen separation using a dense ceramic-based membrane is shown schematically in *Figure 5* (Roark et al., 2002). A syngas mixture (H_2, CO and CO_2) is passed across the membrane surface where hydrogen is oxidized catalytically. The protons and electrons generated are incorporated into the membrane and conducted to the reduction surface where the reverse reduction reaction occurs to produce pure hydrogen. The main advantages of separating hydrogen using a ceramic proton membrane are as following: (1) the membrane materials are relatively inexpensive and the system design is inherently simple, requiring no external circuitry or applied potential. (2) Since the membranes are nonporous, only hydrogen is transported without contributions from the break-through of other gases. Accordingly, secondary purification steps are not necessary. (3) The membrane system is highly versatile and can be used to facilitate numerous chemical processing applications by appropriately adjusting the catalysts. Currently, the main problem for this kind of membrane is how to increase its capacity for the utilization in a large-scale hydrogen separation and reduce its cost.

When the partial pressures of H_2 on two sides of the membranes are different, H_2 can be transported into the side of membrane with low pressure. The H_2 is driven by the partial pressure difference of H_2 on two sides of the membrane. In this paper, because the pressure of clean syngas is 20bar and the volume fraction of H_2 in syngas is 0.32, the partial pressure of H_2 in the clean syngas is about 6bar. While the pressure of pure H_2 permeated from the membrane is 1bar.

After the membrane separation unit, the C-rich gas is fed into the gas turbine combustor using pure oxygen as the oxidizer and constitutes an O_2/CO_2 cycle system same as the system proposed by Cheisa (Chiesa et al., 1998). H_2-rich gas can constitute an H_2/O_2 cycle or other advanced cycle system with high efficiency. The left parts of three IGCC systems with CO_2 recovery are the same and all semi-closed O_2/CO_2 cycle systems. The main differences of three IGCC systems lie in the right parts of system flowcharts, that is to say, the cycle systems composed by H_2-rich gas. The details are as follows:

(1) Dual-cycle IGCC system with mixed H_2/O_2 cycle and CO_2 recovery

H_2-rich gas constitutes a mixed H_2/O_2 cycle. As shown in *Figure 2*, O_2 is produced from an air separation unit (ASU). The feed water with low temperature is fed into the combustor of the H_2/O_2 cycle. Here, the inlet pressure of the turbine is 20bar and the inlet turbine temperature is 1300 °C. Because the working medium is pure steam, it can expand at a lower pressure. In this paper, the outlet pressure of the turbine is 0.05bar.

(2) IGCC system with steam-injected H_2/O_2 cycle and CO_2 recovery

H_2-rich gas also constitutes an H_2/O_2 cycle similar to *Figure 2*. The main difference (as shown in *Figure 3*) is that superheated steam, produced from HRSG, instead of liquid water, is fed into the combustor chamber of the H_2/O_2 cycle. The exergy loss caused by heat transfer in the combustor will be greatly reduced and the system efficiency will be improved. The parameters of steam injected into the combustor of the H_2/O_2 system are as follows: P= 22bar, T=540 °C. When H_2 is burned in a combustor in pure O_2, the adiabatic flame temperature is extremely high. When enough steam is fed into the combustor, theoretically it is enough to decrease the outlet temperature of the combustor to 1300 °C, though it can bring a complex control problem.

(3) IGCC system with fuel cell combined cycle and CO_2 recovery

H_2-rich gas from the membrane separation unit is sent to a solid oxide fuel cell combined cycle system. As shown in *Figure 4*, compressed H_2 is sent to the anode of the fuel cell, while compressed air used as an oxidant is sent to the cathode. After the electrochemistry reaction process, the exhaust from the fuel cell with high temperature enters into the small gas turbine and produces electricity. Here, the fuel cell system acts as the combustor of a small gas turbine. The exhaust from the small gas turbine with high temperature enters into a HRSG. Steam produced from HRSG drives steam turbine and produce further electricity.

The operating temperature of SOFC is the highest among all kinds of fuel cells and it is better suited for coupling with a gas turbine (Dawn et al., 1997; Campanari, et al., 1998; Massardo et al., 2002). With an outlet temperature in the range of 850°C–1000°C, the efficiency of the cell alone is about 50%. When coupled with a gas turbine combined cycle, the SOFC combined cycle can achieve a higher efficiency. So, the overall efficiency of the IGCC system will greatly be improved when it is integrated with SOFC.

3. Case Studies and Evaluation Criteria of System Performance

For the three different IGCC systems with CO_2 recovery, their left parts are all semi-closed O_2/CO_2 combined cycle systems. ***The left part of the system configuration*** is as follows: a large-scale commercial IGCC power system, a heavy duty gas turbine with an inlet temperature of 1288 °C, a steam system with a double-pressure and reheating system, an entrained flow gasifier with oxygen of 98%, a low temperature clean-up subsystem, a cryogenic ASU and a ceramic proton membrane separator. The main parameters of the base IGCC system are shown in TABLE I.

3.1 Evaluation criterion for system thermal performance

This paper employs the net IGCC system efficiency (η_{ig}) as the evaluation criterion of system thermal performance.

$$\eta_{ig} = \frac{N_{tot}(1-\eta_e)}{Gcl \times Hu} \quad (1)$$

For the dual-cycle IGCC system with a mixed H_2/O_2 cycle and IGCC system with steam-injected H_2/O_2 cycle and CO_2 recovery:

$$N_{tot}=Ngt+Nst+Nho \quad (2)$$

TABLE I. MAIN PARAMETERS OF BASE IGCC SYSTEM

Entrained flow gasifier	
operating pressure	38.9bar
operating temperature	1245 °C
Raw syngas components (volume)	
CO -0.44052	H_2-0.30834
N_2 - 0.01623	CH_4-0.00047
COS-0.00002	H_2O-0.12731
CO_2 -0.1054	H_2S-0.00171
Clean syngas components (volume)	
CO -0.46886	H_2-0.32818
N_2 - 0.01727	CH_4-0.0005
COS-0.00002	H_2O-0.08196
CO_2 -0.10321	
Large-scale gas turbine	
T_3	1288 °C
Pressure ratio π	18
air compressor efficiency	0.875
turbine internal efficiency	0.90
Heat recovery steam generator	
high pressure evaporator	110 bar
low pressure evaporator	6 bar
live steam temperature	550 °C
reheat steam temperature	550 °C
Air separation unit	
inlet compressed air pressure	12bar

For an IGCC system with fuel cell combined cycle and CO_2 recovery:

$$N_{tot}=Ngt+Nst+Nfc+Nfcgt+Nfcst \quad (3)$$

3.2 Evaluation criterion for environmental performance

CO_2 specific emission (G_{CO2}) is given as the evaluation criterion of system environmental performance.

$$G_{CO2}=G_{CO20}\,(1-X_{CO2}) \quad (4)$$

3.3 Comprehensive performance evaluation criterion of IGCC system

In order to comprehensively evaluate IGCC system performance, we use here a comprehensive performance index (I_{EP}) of energy consumption and environmental pollution (Duan et al., 2004). I_{EP} is only related to both the fuel cost and the CO_2 emission cost, not taking into account components' investment cost. The index uses international currency (for example, dollar) to quantify the advantage of the thermal efficiency and environmental performance of the IGCC system. It is defined as follows:

$$I_{EP}=C_Eb+C_PG_{CO2} \quad (5)$$

From equation (5), we know I_{EP} is a multi-objective function, concerning system efficiency and environmental effect. Here, C_E and C_P can be changed with the change of fuel types and local situations. C_P can be determined according to the international CO_2 emission penalty price per kilogram.

4. Parameter Study and Performance Analysis of Three Different IGCC Systems with CO_2 Recovery

4.1 DC-IGCC system with CO_2 recovery

The pressure ratio (π) of a semi-closed gas turbine is a very important parameter in design optimization of a combined cycle system. For dual-cycle IGCC system with mixed H_2/O_2 cycle, there also exists an optimized pressure ratio (π_{opt}) at a given turbine inlet temperature. *Figure 6* shows different IGCC systems efficiency versus the pressure ratio of the compressor. The optimized pressure ratio for the base IGCC system without CO_2 recovery is smaller (π_{opt}=16), while for the simple semi-closed O_2/CO_2 IGCC system proposed by Chiesa (Chiesa et al., 1998), π_{opt} is the biggest and equal to 42. π_{opt}(about 36) of the DC-IGCC system with mixed H_2/O_2 cycle is smaller than that of the simple semi-closed O_2/CO_2 IGCC system. Because the working fluid is different and the molecular mass of CO_2 is bigger than air, the optimized pressure ratios of the simple semi-closed O_2/CO_2 IGCC system and DC-IGCC system are all bigger than that of the base IGCC system. It is also known that the system efficiency of DC-IGCC when π_{opt} is equal to 42 is only about 4 percentage points lower than that of the base IGCC system (η_{ig}=46%) at the point of π_{opt}, while 3 percentage points higher than that of the simple semi-closed IGCC system. The main reason is that the semi-closed O_2/CO_2 system is integrated with an H_2/O_2 cycle system with high efficiency. In addition, because the pressure of clean syngas is

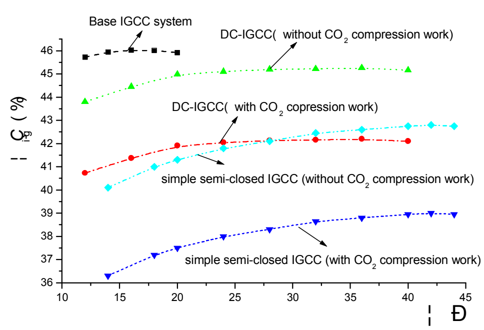

Figure 6. η_{ig} of different IGCC systems versus π

20bar, enough to separate H_2 by the ceramic proton membrane, the extra energy consumption for separating H_2 is not necessary.

4.2 IGCC system with steam-injected H_2/O_2 cycle and CO_2 recovery

Though the DC-IGCC system has a high efficiency after separating and recovering CO_2, a big potential to improve the system performance exists. The unsaturated feed water with high pressure is fed into the combustor of the H_2/O_2 cycle. Its temperature is about 100 °C, however the theoretical combustion temperature of H_2 with O_2 is 3000 °C - 4000 °C or so. So there is a big exergy loss of heat transfer in the combustor of H_2/O_2 cycle. The largest exergy loss is in the combustor, accounting for 78% of the overall exergy loss of the H_2/O_2 cycle system (Duan et al., 2004). This indicates that reducing the exergy loss of the combustor is the key measure to improve this H_2/O_2 cycle. When steam, instead of liquid water, is fed into the combustor chamber of the H_2/O_2 cycle, the exergy loss caused by heat transfer will be greatly reduced and the system efficiency will be improved. Here, the HRSG of a semi-closed combined cycle may generate steam for the H_2/O_2 cycle. With the increase of steam fed into the combustor of the H_2/O_2 cycle, the overall system efficiency of the IGCC system with steam-injected H_2/O_2 cycle will be improved gradually.

Figure 7 shows the effect of steam injection coefficient (R_S) on exergy loss distributions in the

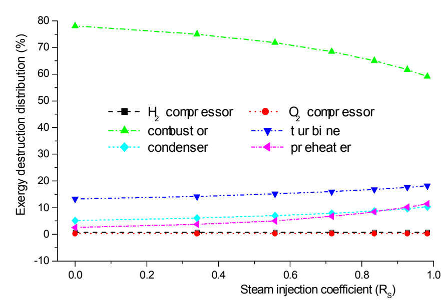

Figure 7. Effect of R_S on exergy destruction distributions in H_2/O_2 cycle.

H_2/O_2 cycle. The exergy losses of the H_2 compressor and O_2 compressor are quite stable. The exergy losses of turbine, condenser and preheater are increased with the increase of R_S. The exergy loss of the combustor is decreased quickly. Because the mass flow of steam injected to H_2/O_2 system (G_S) will be increased with the increase of R_S, the exergy loss caused by heat transfer in the combustor will be decreased. The proportion of the exergy loss of the combustor in the H_2/O_2 cycle will be decreased gradually.

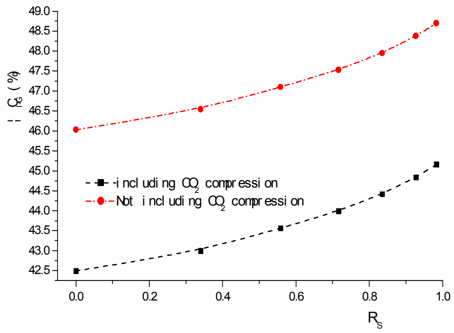

Figure 8. Variation of η_{ig} with R_S.

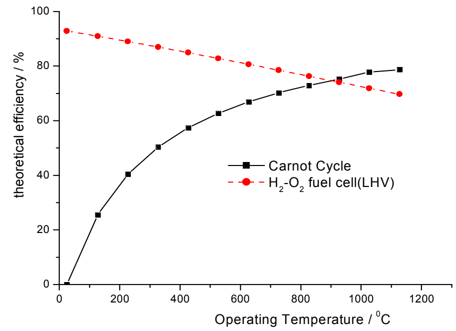

Figure 9. The theoretical efficiency of H_2-O_2 fuel cell and Carnot cycle versus temperature

As shown in *Figure 8*, the efficiency (η_{ig}) of IGCC system with the steam-injected H_2/O_2 cycle system is increased with the increase of R_S. Compared with the DC-IGCC system with mixed H_2/O_2 cycle (without steam-injection, R_S=0), η_{ig} is increased by 2.6 percentage points when R_S is 0.98. The results show the overall IGCC system performance is greatly improved by injecting steam, instead of water, into the combustor of the H_2/O_2 cycle. Compared with the DC-IGCC system, the efficiency of the IGCC system with a steam-injected H_2/O_2 cycle is increased by 2.7 percentage points. Compared with the base IGCC system without CO_2 recovery (η_{ig}=46%), the system efficiency is decreased by less than 1 percentage point.

4.3 IGCC system with fuel cell combined cycle and CO_2 recovery

(1) Effect of the operating temperature (T_{fc}) on the theoretical efficiency of fuel cell (η_{th})

As mentioned above, the fuel-to-electricity efficiency of the fuel cell system is not limited by the Carnot cycle. The mechanism of fuel-to-electricity of the fuel cell is inherently distinguished from that of heat to electricity of fuel. The theoretical efficiency of the fuel cell (η_{th}) can be achieved according to the following equation.

$$\eta_{th} = \frac{\Delta G}{\Delta H_{298}} \quad (6)$$

Here, ΔG will change with the change of the operating temperature and pressure.

Figure 9 shows the theoretical efficiency of the H_2/O_2 fuel cell (η_{th}) and the Carnot cycle versus temperature. η_{th} decreases with the increase of temperature, while the theoretical efficiency of the Carnot cycle increases with the increase in temperature. η_{th} reaches 93% at ambient temperature (25 °C). η_{th} decreases to 70% when the operating temperature is 1000 °C or so. At this condition, though η_{th} is lower, even lower than the theoretical efficiency of the Carnot cycle, η_{th} can be further elevated when the waste heat discharged from fuel cell is adequately utilized.

(2) Effect of operating pressure on the actual thermal efficiency of SOFC system

One of the merits of SOFC plus gas turbine combined cycle is the fact that pressurization of the fuel cell results in increased efficiency. The literature (Bevc et al., 1996) gives data for an increase in cell voltage with operating pressure at a given current density. Based on this data a relationship of the following form is used for the variation of fuel cell efficiency η_{fc} with operating pressure P_{fc} when the operating temperature (T_{fc}) is 850 °C.

$$\eta_{fc} = \eta_0 \times (1 + \frac{59}{650} \log P_{fc}) \quad P_{fc} \geq 1\text{bar} \quad (7)$$

According to the literature (Bevc et al., 1996) when T_{fc} is 850 °C, η_0 is equal to 0.52. On the base of the above assumption, *Figure 10* shows the actual efficiency of an H_2/O_2 fuel cell (η_{fc}) versus P_{fc} at a given operating temperature (T_{fc}). η_{fc} increases with the increase of P_{fc}. The increase of P_{fc} is propitious to the improvement of fuel cell performance. When P_{fc} is greater than 25, η_{fc} increases slowly. At a given operating pressure, η_{fc} decreases with the increase of the operating temperature.

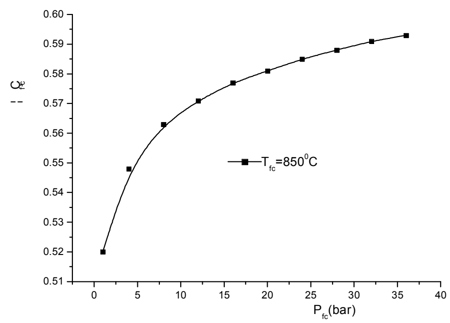

Figure 10. η_{fc} *of* H_2-O_2 *fuel cell versus* P_{fc}

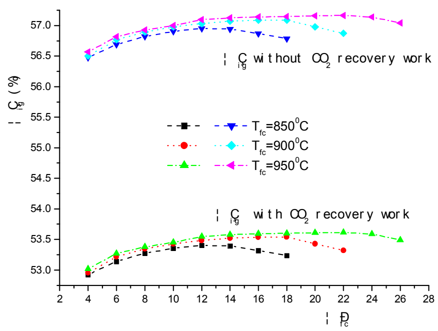

Figure 11. η_{ig} *versus pressure ratio* π_{fc}

(3) Effect of pressure ratio of small gas turbine on the overall IGCC system efficiency

Figure 11 shows the overall IGCC system efficiency versus the pressure ratio of small gas turbine (π_{fc}). When the operating temperature is given, an optimal operating pressure (or pressure ratio) exists. With an increase of the operating temperature, the optimal pressure ratio increases. In addition, when the operating temperature and pressure are given, η_{ig} without CO_2 recovery work is greater than η_{ig} with CO_2 recovery work. CO_2 recovery through the stage compression mode (CO_2 will be compressed to 80bar and liquidized) leads to a big efficiency decrease of 3.5 percentage points, which indicates that a big potential to improve the system performance by applying the lower energy consumption technology of CO_2 recovery still exists. As shown in *Figure 10*, the overall IGCC system efficiency is greatly improved when integrated with a fuel cell combined cycle. When the operating temperature is 850 °C, the maximum η_{ig} with CO_2 recovery work can reach 53.4%. Compared to the base IGCC system without CO_2 recovery, after recovering CO_2, the system efficiency of the IGCC system does not decrease, but increases by 7 percentage points. With the increase of T_{fc}, the maximum η_{ig} and the optimal pressure ratio all increase.

TABLE II. PERFORMANCE COMPARISONS OF DIFFERENT IGCC SYSTEMS WITH CO_2 RECOVERY

	Case 1	Case 2	Case 3	Case 4
π	18	23	23	23
π_{fc}	-	-	-	12
T_3	1288	1288	1288	1288
T_4	588	725	725	725
T_{fc}	-	-	-	850
P_{fc}	-	-	-	12
R_S	-	0.0	1.0	-
Ngt	279500	286140	286140	286140
Nst	184150	305680	169000	291640
Nho	-	145930	312950	-
Nfc	-	-	-	184700
Nfcgt	-	-	-	42900
Nfcst	-	-	-	18300
η_{ig}	0.46	0.425	0.452	0.532
b	0.293	0.317	0.298	0.253
X_{CO2}	0.0	1.0	1.0	1.0
G_{CO2}	0.86	0.0	0.0	0.0
C_E	0.0379	0.0379	0.0379	0.0379
C_P	0.016	0.016	0.016	0.016
I_{EP}	0.025	0.012	0.011	0.0096

5. Comparisons of Different IGCC Systems with CO_2 Recovery

When C_P is 0.016$/kg and C_E is 0.0379 $/kg, TABLE II shows an overall performance comparison of different IGCC systems with CO_2 recovery. Cases 1, 2, 3 and 4 stand for a base IGCC system without CO_2 recovery, DC-IGCC system with mixed H_2/O_2 cycle and CO_2 recovery, IGCC system with steam-injected H_2/O_2 cycle and CO_2 recovery, IGCC system with fuel cell and CO_2 recovery, respectively. Compared with the other IGCC systems with CO_2 recovery, the thermal efficiency of case 4 is the highest. The thermal efficiency of case 3 is higher than that of case 2 due to the application of a steam-injected H_2/O_2 system. In addition, compared with the base IGCC system without CO_2 recovery, after recovering CO_2, the system efficiencies of both cases 2 and 3 are lower. However the thermal efficiency of case 4 does not decrease, but increases by 7 percentage points. So by integrating a fuel cell combined cycle system with the traditional IGCC system, the system efficiency is remarkably improved. To sum up, syngas-oriented separation and integration with the advanced cycle system is a feasible way to improve the system efficiency of the IGCC system with CO_2 recovery.

6. Conclusions

Different IGCC systems with CO_2 recovery have been studied in this paper. The key parameters affecting IGCC system performance have been analyzed and compared. The thermodynamic characteristics have been investigated based on comparison of different IGCC systems. The research results show the overall IGCC system performance is markedly improved by integrating with an advanced thermal cycle system. The performance of IGCC with O_2/CO_2 cycle and syngas separation is better than that with simple semi-closed O_2/CO_2 cycle. The comparative result also shows that the performance of the one with fuel cell and CO_2 recovery is the best. The promising results obtained in this paper will provide valuable information and a new method for further study on the IGCC system with high efficiency and zero-CO_2 emissions.

Acknowledgments

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Nomenclature

b	fuel consumption ratio, kg/kWh
C_E	fuel price, \$/kg
C_P	CO_2 penalty price, \$/kg
G_{CO2}	CO_2 specific emission, kg/kWh
G_{CO20}	CO_2 specific emission from system without CO_2 recovery, kg/kWh
Gcl	mass flow of fuel consumption, kg/s
GH2	mass flow of H_2 consumption of fuel cell, kg/s
G_S	mass flow of steam injected to the combustor of H_2/O_2 system, kg/s
G_W	mass flow of feed water injected to the combustor of H_2/O_2 system, kg/s
Hu	lower heating value of coal, kJ/kg
HuH2	lower heating value of hydrogen, kJ/kg
I_{EP}	comprehensive performance index, \$/kWh
Nfc	fuel cell power, kW
Nfcgt	gas turbine power of fuel cell combined cycle system, kW
Nfcst	steam turbine power of fuel cell combined cycle system, kW
Ngt	semi-closed gas turbine power, kW
Nho	H_2/O_2 system power, kW
Nst	steam turbine power of semi-closed gas-steam combined cycle system, kW
N_{tot}	total output power of IGCC system, kW
P	pressure, bar
P_{fc}	operating pressure of fuel cell system, bar
R_S	steam injection coefficient, $R_S=G_S / (G_S+G_W)$
T	temperature, °C
T_{fc}	operating temperature of fuel cell, °C
T_3	Inlet temperature of semi-closed gas turbine, °C
T_4	outlet temperature of semi-closed gas turbine, °C
X_{CO2}	CO_2 recovery ratio, $X_{CO2}= (G_{CO20}- G_{CO2})/ G_{CO20}$
ΔG	standard Gibbs free energy in the condition of fuel cell reaction, kJ/mol
ΔH_{298}	standard enthalpy of formation at 298K in the condition of fuel cell reaction, kJ/mol.

Greek symbols

π	pressure ratio of semi-closed gas turbine;
π_{fc}	pressure ratio of small gas turbine of SOFC combined cycle system;
π_{opt}	optimized pressure ratio of semi-closed gas turbine;
η_0	the thermal efficiency of fuel cell at a given operating temperature and operating pressure of 1atm, % (LHV)
η_e	overall system auxiliary power ratio, %
η_{ig}	net IGCC system efficiency, % (LHV);
η_{fc}	the actual thermal efficiency of H_2/O_2 fuel cell system, % (LHV)
η_{th}	the theoretical efficiency of H_2/O_2 fuel cell system, % (LHV)

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