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Performance analyses of oxy-fuel power generation systems including CO_2 capture: comparison of two cycles using different recirculation fluids †

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Abstract

With increasing concerns on global warming, reduction of CO_2 emission has become a hot issue and studies of CO_2 capture and storage (CCS) technology in power plant applications are in progress. Oxy-fuel combustion is one of the several available technologies that intend to capture CO_2. Since the combustion gas consists mainly of CO_2 and H_2O in oxy-fuel combustion systems, it is easy to separate CO_2 from the flue gas using a simple mechanical method instead of complex chemical processes. There have been suggested a couple of power cycles using different recirculation fluids for combustion dilution purpose. This study aimed to investigate the influence of CO_2 capture on the performance of two promising oxy-fuel combustion power cycles adopting H_2O and CO_2 as the recirculation fluid. Optimal integration between the carbon capture process and the power cycle was examined and the influences of carbon capture on the entire system performance were compared for the two cycles.

Keywords: Carbon capture and storage (CCS); Oxy-fuel combustion; Recirculation fluid; Condensing pressure; Gross performance; Net performance

1. Introduction

There has been growing interest in the CO_2 capture and storage (CCS) technology as a way to reduce greenhouse gas emission. Studies to propose new or revised power generation systems are actively going on. The purpose of CO_2 capture is to produce a concentrated stream of CO_2 at a high pressure ready for storage or transport. Up to now, three CO_2 capture technologies have been suggested for application in power generation systems: pre-combustion capture, post-combustion capture, and oxy-fuel combustion [1, 2]. In the pre-combustion capture, CO_2 is removed from a pretreated fuel (e.g., syngas produced from coal) prior to combustion. In the post-combustion capture technology, CO_2 is separated from the flue gas using a chemical process. The oxy-fuel combustion technology uses oxygen instead of air to burn the fuel, resulting in a high CO_2 concentration in the flue gas. The post-combustion capture is in concept the simplest because the CCS process can be added at the end of power plants. The pre-combustion capture technology is suitable for gasification power plants where the syngas production process is modified to accommodate an additional CO_2 capture process. On the other hand, the oxy-combustion technology requires heavier revisions of conventional power generation systems or even new thermodynamic cycles because of several unique features such as oxygen generation and combustion dilution.

Oxy-fuel combustion is becoming attractive due to a couple of major advantages. Since combustion takes place in low-nitrogen environment, it produces a flue gas that consists mainly of CO_2 and H_2O. Therefore, a rather simple mechanical process can be used to capture CO_2 instead of more complicated and energy consuming processes such as the chemical absorption/desorption process that is usually adopted in the post-combustion technology [3]. In addition, by removing nitrogen from the oxidant stream, NO_x formation is prevented. However, some technical barriers should also be solved. If fossil fuels are burnt with pure oxygen, flame temperature is excessively high and thus a dilution fluid, which plays the same role as the nitrogen in conventional air-combustors, is needed. As a solution to this problem, oxy-combustion systems usually adopt a closed cycle with a recirculation fluid as the diluting medium. The recirculation fluid is none other than one of the combustion gas components: H_2O or CO_2.

Several unique cycles have been suggested [4-8]. In H_2O-recirculation cycles, CO_2 is usually designed to be removed at

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the condenser. The gas and liquid phases are CO_2-rich and highly H_2O-rich, respectively. Thus, CO_2 can be removed from the power cycle by extracting the gaseous phase. The cycle suggested by Clean Energy Systems [4, 5] is a typical oxy-fuel power cycle adopting H_2O recirculation. On the other hand, the SCOC-CC (Semi Closed Oxy-fuel Combustion Combined Cycle) [6] adopts CO_2 as the recirculation fluid. The liquid phase containing much more H_2O than CO_2 is extracted at the condenser. The gas phase containing CO_2 is recirculated and redundant CO_2 is captured from the recirculated fluid. The GRAZ cycle [7, 8] has two versions and adopt both the H_2O and CO_2 (or flue gas) recirculations. Even though none of the proposed cycles were fully demonstrated, some key technologies such as combustion system and turbomachinery have been demonstrated [4, 5, 9]. Fundamental studies on waste heat recovery type oxy-fuel combustion systems have also been suggested [10, 11].

Since power cycles based on oxy-fuel combustion have diverse configurations as briefly named above, various fundamental thermodynamic studies with regard to every aspect of system designs including optimal parameter selection and integration with a CCS process is needed. In particular, the integration of the power cycle and the carbon capture process depends strongly on the configuration of power cycle, i.e., the selection of recirculation fluid. Also, the influence of carbon capture on cycle performance, which needs to be as low as possible, is an important issue. In this regard, this study aimed to investigate the influence of CO_2 capture on the performance of two promising oxy-fuel power cycles adopting different recirculation fluids. The cycle proposed by Clean Energy Systems [4] was selected as the representative H_2O recirculation cycle because it is on the forefront of system development. The SCOC-CC [6] is selected as the representative CO_2 recirculation cycle because its layout is similar to the conventional combined cycle, and thus modifications to the proposed cycle from existing systems are expected to be minimized. Optimal integration between the carbon capture process and the power cycle was examined and the influences of carbon capture on the entire system performance were compared for the two cycles.

2. Analysis

Two different cycles were selected: the cycle proposed by Clean Energy Systems with H_2O recirculation and the SCOC-CC with CO_2 recirculation. The power cycle layouts were taken from the literature [4, 6], and cycle parameters were either taken from the literature or assumed to yield similar performance to the literature (especially, the power output and system efficiency at nominal design condition). In both cycles, combustion gas, thus the main working fluid, was composed only of CO_2 and H_2O because methane and oxygen were used for fuel and oxidant, respectively, and no excess oxygen was assumed. The amount of recirculation fluid was decided to meet the turbine inlet temperature of each cycle. All the analyses were modeled and performed with HYSYS [12].

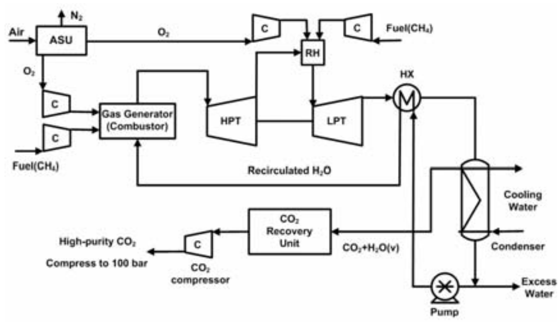

Fig. 1. Schematic diagram of the cycle with H_2O recirculation.

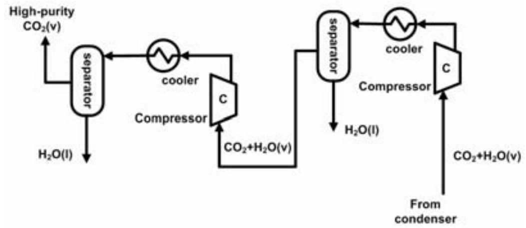

Fig. 2. A two-stage CO_2 recovery unit.

2.1 Cycle with H_2O recirculation

A schematic diagram of the cycle with H_2O recirculation is shown in Fig. 1 [4]. The entire system includes a power cycle, an oxygen production unit and a carbon capture process. Oxygen is produced from the usual air separation unit (ASU). It was assumed that pure oxygen is generated at ambient pressure from the ASU. Oxygen and natural gas which is assumed to be methane (LHV=50,030 kJ/kg) are compressed and then supplied to the combustor. The exhaust gas from the combustor drives the high pressure turbine (HPT), and then is reheated with additional fuel and oxygen at the reheat combustor. After driving the low pressure turbine (LPT), the working fluid is cooled at the regenerative heat exchanger and then flows to the condenser. The condenser inlet fluid contains much more H_2O than CO_2 because H_2O recirculates: H_2O mole fraction is about 90%. Because the condensing temperature of CO_2 is very low, the working fluid does not condense completely and thus a certain amount of vapor phase exists at the condenser outlet. This vapor is extracted to capture CO_2 in it. The liquid phase at the condenser exit is highly H_2O-rich and recirculated to the oxy-combustor side. The excess H_2O, the amount of which is equal to that of H_2O generated at the two combustors, is extracted to the outside of the system.

The condenser pressure determines not only the power output of the turbine but also the CO_2 purity of the extracted vapor. Thus, it is the major design parameter in this study. If a sufficiently high CO_2 purity is guaranteed, the extracted CO_2 can be directly compressed up to the storage pressure (e.g. 100 bar). This happens when the condensing pressure is sufficiently high. However, if the CO_2 purity does not meet the required standard (as high as 95%), a CO_2 recovery unit

(CRU) is needed. The highly pure CO_2 gas after the CRU is compressed for storage. This happens when the condensing pressure is as low as that of conventional steam turbines. A CRU is a multi-stage unit [13, 14] in which a stage consists of compression, cooling and liquid removal. The liquid is highly H_2O-rich. Repetition of the stage yields highly pure CO_2. Studies on optimal design of the entire CRU process have also been performed [11, 14-17]. According to a recent study [11], two-stage compression up to 30 bar provides a sufficiently high CO_2 purity. Thus, such a CRU was adopted in this study as shown in Fig. 2. Then, the captured CO_2 was compressed to 100bar for the purpose of storage. The condenser outlet temperature was set at 25 °C, which was also the temperature of the CRU inlet vapor.

The gross system power output is defined as follows.

$$\dot{W}_{Gross} = \dot{W}_T - \dot{W}_{Aux} \tag{1}$$

The auxiliary power consumption includes the power required to produce oxygen at the ASU, and other powers to drive the oxygen compressor, the fuel compressor and various pumps.

$$\dot{W}_{Aux} = \dot{W}_{ASU} + \dot{W}_{Comp,O_2} + \dot{W}_{Comp,CH_4} + \dot{W}_{Pump} \tag{2}$$

The usual ASU energy consumption is known as 200 kWh per ton of pure O_2 [18]. Therefore, the ASU power consumption of this study was calculated by multiplying this specific power consumption by the required oxygen flow rate. The other three auxiliary power consumptions were directly calculated. Then, the gross system efficiency is defined by

$$\eta_{Gross} = \frac{\dot{W}_{Gross}}{\left(\dot{m} \cdot LHV\right)_{fuel}} \tag{3}$$

Table 1 shows major parameters used in simulating the power cycle. The power consumption required for the entire CCS process consists of two parts: the CRU and the subsequent gas compression.

$$\dot{W}_{CCS} = \dot{W}_{CRU} + \dot{W}_{Comp,CO_2} \tag{4}$$

The net system power output and efficiency including this CCS power consumption is represented by

$$\dot{W}_{Net} = \dot{W}_{Gross} - \dot{W}_{CCS} \tag{5}$$

$$\eta_{Net} = \frac{\dot{W}_{Net}}{\left(\dot{m} \cdot LHV\right)_{fuel}} \tag{6}$$

Table 2 lists the main parameters for the CCS process. Variations in the net system performance and the purity of the separated CO_2 from the condenser with the condenser pressure were analyzed, and the net system performance in case of using CRU was also predicted. Both results were compared to select the recommended design condition.

Table 1. Main parameters of the H_2O recirculation cycle.

Combustor pressure	100 bar
Reheater pressure	20 bar
High pressure turbine inlet temperature	815 °C
Low pressure turbine inlet temperature	1400 °C
Condenser pressure	Variable
Condenser exit temperature	25 °C
Turbine efficiency	90 %
Compressor efficiency	87 %

Table 2. CRU parameters.

Inlet gas pressure	variable
Inlet gas temperature	25 °C
Compressor efficiency	87 %
Intercooling temperature	25 °C
Outlet gas pressure	30 bar

2.2 Cycle with CO_2 recirculation

Fig. 3 shows the schematic diagram of the cycle with CO_2 recirculation (SCOC-CC). This cycle is a kind of combined cycle which is a combination of a gas turbine cycle (Brayton cycle) and a steam turbine cycle (Rankine cycle). The oxygen generation process is the same as in the previous cycle. Also, compressed oxygen and natural gas are supplied to the combustor as in the previous cycle. However, compressed CO_2 gas instead of H_2O is provided to the combustor as a diluting medium. The combustion gas drives the turbine and flows to the heat recovery steam generator (HRSG), which produces a high pressure steam to drive the bottoming steam cycle. After the HRSG, the working fluid is further cooled to a sufficiently low temperature which enables condensation of H_2O. At the end of the condenser, the H_2O-rich liquid phase is removed and the remaining CO_2-rich gas phase is recirculated, thereby forming a semiclosed Brayton cycle. A certain amount of the recirculating flow is extracted for CO_2 capture. Since the CO_2 purity of the recirculating CO_2 is sufficiently high, the CRU is not required when the condenser operates around ambient pressure. The bottoming cycle is quite similar to the steam

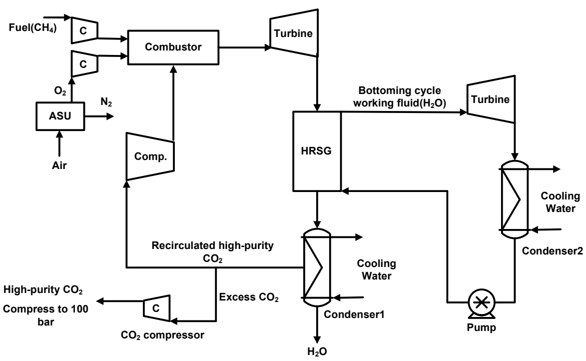

Fig. 3. Schematic diagram of the cycle with CO_2 recirculation.

Table 3. Main parameters of the CO_2 recirculation cycle.

Combustor pressure	40 bar
Turbine inlet temperature of the topping cycle	1400 °C
Turbine inlet temperature of the bottoming cycle	560 °C
Turbine inlet pressure of the bottoming cycle	100 bar
Topping cycle condenser pressure	1 bar
Bottoming cycle condenser pressure	0.05 bar
Turbine efficiency	90 %
Compressor efficiency	87 %

turbine cycle of conventional combined cycle power plants.

The gross system power output is also defined by Eq. (1) and the power of the main compressor to recirculate the CO_2-rich gas is added to the auxiliary power consumption:

$$\dot{W}_{Aux} = \dot{W}_{ASU} + \dot{W}_{Comp} + \dot{W}_{Comp,O_2} + \dot{W}_{Comp,CH_4} + \dot{W}_{Pump} \quad (7)$$

The definition of the gross system efficiency is the same as Eq. (3). The CCS power consumption includes only the power to directly compress the highly CO_2-rich gas extracted from the condenser as follow.

$$\dot{W}_{CCS} = \dot{W}_{Comp,CO_2} \quad (8)$$

The net system performance is calculated by Eqs. (5) and (6). Table 3 lists the main parameters used for the CO_2 recirculation cycle calculation.

3. Results and discussion

3.1 Cycle with H_2O recirculation

The condenser pressure is the main design variable. Given the condenser exit temperature (25 °C), the compositions of the extracted vapor depend on the condensing pressure. Of course, the condenser pressure also affects turbine power. The properties of CO_2/H_2O mixture at the condenser condition can be presented by the vapor-liquid equilibrium chart shown in Fig. 4. The two components have very different vapor pressures. At the condition of Table 1, the mole fractions of CO_2 and H_2O at condenser inlet are about 10 % and 90 %, respectively. Once the working fluid condenses, its temperature decreases. When reaching the exit temperature, the fluid is still in two phases, and the vapor and liquid phases are extracted separated as explained before. The liquid phase is highly H_2O-rich and its compositions do not change effectively with pressure variation. However, the compositions of the vapor phase depend much on pressure. For example, a pressure variation from 10 kPa to 100kPa causes a change of CO_2 composition from 69 % to 96.8 %. Therefore, the purity of the extracted vapor becomes higher as the condensing pressure rises.

Fig. 5 shows the variation in CO_2 mole fraction in the extracted vapor phase. Therefore, from the viewpoint of ease of CO_2 capture, a higher condensing pressure is preferable because direct compression of the extracted vapor at this pressure would yield a high pressure gas with sufficiently high CO_2 purity ready for storage or transport. Assuming a CO_2 purity requirement of 95 %, the condensing pressure should be higher than 65 kPa. Below this pressure, the extracted vapor needs to be processed through the CRU shown in Fig. 2 to meet the requirement. Fig. 5 also presents the CO_2 mole fraction after the full CCS process. It reaches over 99 % for all condensing pressure conditions. Thus, highly pure CO_2 can be captured through the CRU even with a low pressure vapor that contains considerable amount of H_2O.

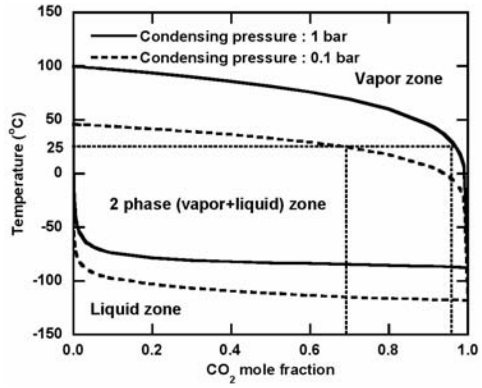

Fig. 4. Vapor-liquid equilibrium chart.

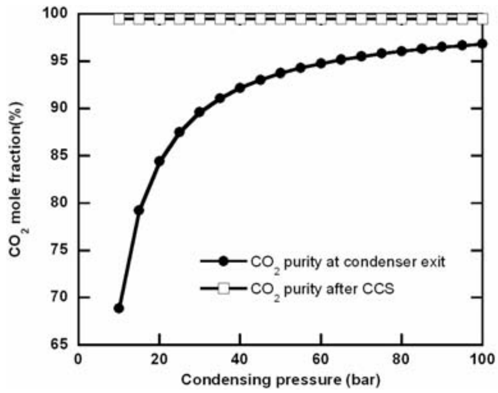

Fig. 5. Variation in CO_2 mole fraction with condensing pressure in the H_2O recirculation cycle.

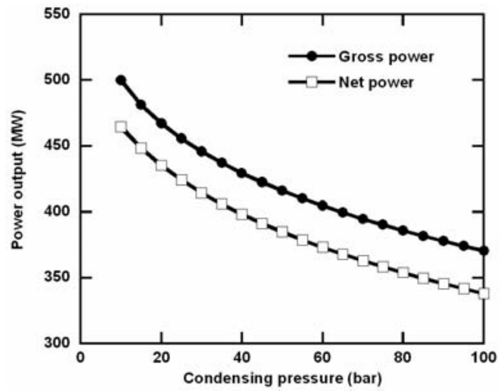

Fig. 6. Variation in power output with condensing pressure in the H_2O recirculation cycle.

Table 4. Performance of the H_2O recirculation cycle with a condensing pressure of 10kPa.

Fuel energy input	949.7 MW
High pressure turbine power	111.5 MW
Low pressure turbine power	508.4 MW
Total turbine power	619.9 MW
ASU power	54.6 MW
Oxygen and methane compression power	63.6 MW
Pump power	1.7 MW
Total auxiliary power consumption	119.9 MW
Gross power output	500.0 MW
Gross system efficiency	52.6 %
CO_2 purity at the condenser exit	68.9 %
CRU power	31.6 MW
CO_2 compression power	3.8 MW
Total CCS power consumption	35.4 MW
Net power output	464.6 MW
Net system efficiency	48.9 %
Capture CO_2 purity	99.8 %

Fig. 6 shows the variations in gross and net system power outputs, defined by Eqs. (1) and (5), respectively. The gross power output increases with decreasing condenser pressure as in usual steam turbine power plants. The power consumption for the entire CCS (CRU + gas compression) also increases with decreasing condenser pressure as shown in Fig. 7. The CRU which compresses the extracted vapor to 30bar consumes a greater power than the remaining compression process up to 100 bar. Despite the increase in CCS power consumption, the net power output increases with decreasing condenser pressure because the increase in the gross power output is much larger. Fig. 8 shows the variations in gross and net system efficiencies.

The present results provide useful design guidelines. If a sufficiently high condenser pressure (> 65 kPa, higher than usual condensing pressures of steam turbine power plants) is selected, the CRU is not necessary and thus the entire system construction may be simplified and capital cost reduced. However, if the fuel economy of the entire system is important, the condensing pressure needs to be as low as possible. For example, the 10 kPa condition yields 20 % higher system efficiency than the 65 kPa condition. Also, using the CRU, a much higher CO_2 purity can be obtained compared with the direct compression of the vapor at 65 kPa. Table 4 summarizes the system performance for the 10 kPa condensing pressure. Gross power output is set at 500 MW. The CCS power consumption is 7.1 % of the gross power output. The system efficiency also decreases by the same rate, yielding a net efficiency of 48.9 %.

3.2 Cycle with CO_2 recirculation

In the cycle with CO_2 recirculation of Fig. 3, the mole fraction of CO_2 in the turbine exhaust gas is as high as 85 %.

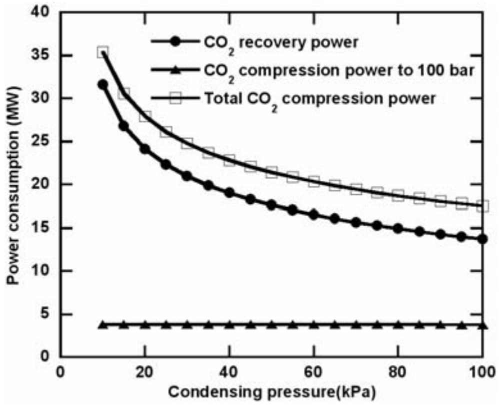

Fig. 7. Variation in compression power consumption with condensing pressure in the H_2O recirculation cycle.

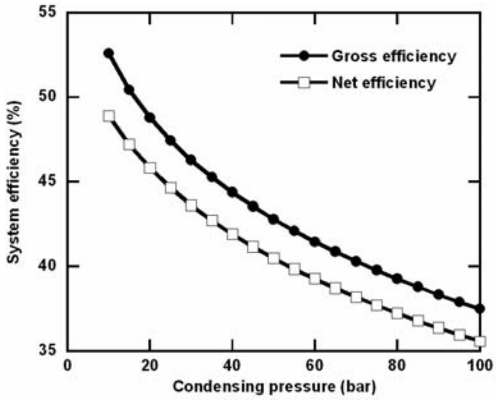

Fig. 8. Variation in system efficiency with condensing pressure in the H_2O recirculation cycle.

Therefore, the topping cycle is more like a gas turbine than a steam turbine. Thus, the turbine exhaust pressure is set at near ambient pressure, thereby allowing for 1 bar at the condenser as shown in Table 3. It is clear from Fig. 4 that the CRU is not necessary because the CO_2 concentration of the vapor phase extracted at 1 bar is sufficiently high. CO_2 concentration depends on the condenser exit temperature, that is, the temperature of the extracted vapor. Fig. 9 shows the variation in CO_2 mole fraction with condensing temperature. At 25 °C, which is the same as the condensing temperature of the cycle with H_2O recirculation, CO_2 mole fraction is 96.8 %. Up to 33 °C, it remains over 95 %. Fig. 10 shows the gas compression power required to compress the extracted vapor from 1 bar to 100 bar. The compression power increases slightly with increasing extraction temperature because of an increase in H_2O fraction. Table 5 summarizes the performance of the cycle with a condenser exit temperature of 25 °C. The same gross power output (500 MW) as in the cycle with H_2O recirculation was assumed. The CCS power consumption is 5% of the gross power output, which is smaller in comparison to the cycle with H_2O recirculation. The main reason for this difference is that the cycle with CO_2 recirculation provides a higher inlet pressure for the carbon capture process than the other cycle.

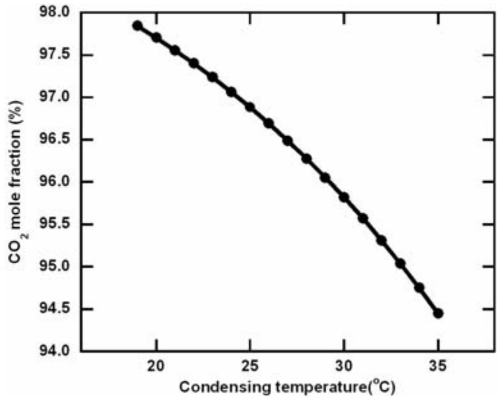

Fig. 9. Variation in CO_2 mole fraction of the extracted vapor with condensing temperature in the CO_2 recirculation cycle.

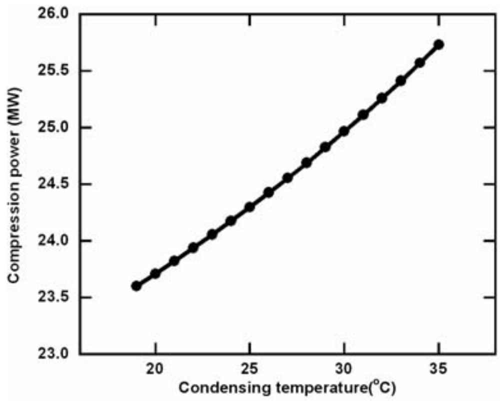

Fig. 10. Variation in CO_2 compression power with condensing temperature in the CO_2 recirculation cycle.

On the whole, the cycle with CO_2 recirculation cycle has two major advantages over the other cycle. First, its layout is almost the same as the conventional combined cycle. The only difference is the presence of the condenser after the HRSG. Thus, a modification from an existing combined cycle plant may be quite practicable. Secondly, the CO_2 capture process can be simpler compared to the cycle with H_2O recirculation as noted above.

Since this study was focused on illustrating integrations of oxy-combustion power cycles and CO_2 capture, and its effect on the entire system performance, we benchmarked two proposed cycles with published performance data. A further detailed feasibility study for the two cycles and other proposed cycles is required as a subsequent research. For example, both the reheat turbine inlet temperature of the H_2O recirculation cycle and the topping cycle turbine inlet temperature of the CO_2 recirculation cycle are quite challenging (1400°C). The analysis in this study was conducted without considering turbine blade cooling and produced similar performance to the published data. Thus, the proposers of the cycles did not seem to consider full hot section cooling of the turbines. In reality, however, turbine cooling at this high temperature would affect cycle performance. Therefore, a subsequent study using practicable component models should be conducted to estimate more reasonable system performance of the cycles.

Table 5. Performance of the CO_2 recirculation cycle with a condenser exit temperature of 25°C.

Fuel energy input	882.0 MW
Topping cycle turbine power	586.9 MW
Bottoming cycle turbine power	226.6 MW
Total turbine power	813.5 MW
ASU power	50.6 MW
Main compressor power	205.2 MW
Oxygen and methane compression power	55.4 MW
Pump power	2.3 MW
Total auxiliary power consumption	313.5 MW
Gross power output	500.0 MW
Gross system efficiency	56.7%
CO_2 compression power	24.3 MW
Net power output	475.7 MW
Net system efficiency	53.9 %
Capture CO_2 purity	96.9 %

4. Conclusions

Integrations of carbon capture process with two oxy-fuel combustion power cycles were investigated, and results are summarized as follows.

The presence of CO_2 affects the condensing characteristics of working fluids. The compositions of the working fluid at the condenser exit depend on condensing pressure and temperature. In particular, CO_2 composition varies considerably with condensing pressure. In the cycle with H_2O recirculation, the variations in CO_2 concentration and power output with condensing pressure were investigated. Above a certain pressure, the CO_2 concentration reaches high enough so that a carbon recovery unit is not necessary, but the system efficiency is not sufficiently high. The net system efficiency increases as condensing pressure decreases because turbine power enhancement is much larger than the increase in CCS power consumption. With condensing temperature and pressure of 25 °C and 10 kPa, the efficiency penalty due to the CCS process is estimated to be 7.1% when the CO_2 delivery pressure of 100bar is assumed. In the cycle with CO_2 recirculation, the carbon recovery unit is not necessary with the condensing pressure around ambient pressure because the CO_2 concentration is sufficiently high (>95 %) in a wide condensing temperature range. The efficiency penalty due to the CO_2 compression is expected to be 5% with the same CO_2 delivery pressure as in the previous cycle. Therefore, in terms of the CCS process, the cycle with CO_2 recirculation seems to be advantageous. A subsequent study using more practical power cycle component models would predict more feasible performance targets of the entire power system including CO_2 capture.

Acknowledgment

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Nomenclature

ASU	:	Air separation unit
CRU	:	Carbon recovery unit
CCS	:	Carbon capture and storage
HPT	:	High pressure turbine
LHV	:	Lower heating value
LPT	:	Low pressure turbine
$\dot{m}$	:	Mass flow rate
RH	:	Reheater
$\dot{W}$	:	Power
η	:	Efficiency

Subscripts

Aux	:	Auxiliary components
comp	:	Compression
Gross	:	Gross performance
Net	:	Net performance
pump	:	Pumping
T	:	Turbine

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