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Process Evaluation of Carbon Dioxide Capture for Coal-Fired Power Plants

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Abstract

Carbon capture is a promising technology for carbon dioxide (CO_2) removal from large stationary CO_2 sources. The effects of carbon dioxide capture process on output efficiency of fossil power plants were investigated. Supercritical pulverized coal and integrated coal gasification combined cycle (IGCC) were assumed as model coal-fired power plants for this investigation. Heat-driven and pressure-driven CO_2 capture processes such as chemical absorption and physical adsorption were assumed for CO_2 capture process. In this study, these technologies were evaluated and compared under the unified basis and conditions by using the commercial process simulator. For IGCC plant, the efficiency penalty by installing water-gas shift reaction was also investigated. Gross and net power generation, efficiency and the efficiency penalty by CO_2 capture process were calculated. Heat duty for CO_2 capture process and CO_2 compression conditions were varied, and those effects on the efficiency penalty were obtained. The results provide a guideline for development of CO_2 capture process of power plants.

Keywords: carbon dioxide capture, power plant, process simulation

1. Introduction

In working group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), it is reported that "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia" (IPCC, 2013). Several scenarios which reduce the carbon dioxide (CO_2) emission and stabilize the global climate change are proposed, such as the 450 scenario and the 550 scenario. The 450 scenario can control the average temperature rise within 2 °C by stabilizing the CO_2 concentration in the atmosphere for 450 ppm. In the scenario, 14 GT/y of CO_2 emission must be reduced in 2030. To reduce the CO_2 emission, it is suggested to use renewable energy, biofuels, nuclear power and carbon capture and storage (CCS), as well as energy saving. CCS is expected to remove 2 GT/yr of CO_2 emission (IEA, 2009). CO_2 is generated by various human activities, such as electricity and heat producing, manufacturing, transport etc. The CO_2 from electricity and heat generation and manufacturing are typically emitted from large exhaust stacks, and they can be described as large stationary sources. The large stationary sources represent potential opportunities for the addition of CO_2 capture plants. The properties of each CO_2-containing gas is different, while the CO_2 partial pressure is important for CO_2 capture. Coal for power generation is primarily burnt in pulverized-coal (PC) boilers producing an atmospheric pressure flue gas stream with a CO_2 partial pressure of up to 0.014 MPa. The newer and potentially more efficient integrated coal gasification combined cycle (IGCC) technology has been developed, and CO_2 partial pressure of CO_2 capture target gas is up to 0.014 MPa (post combustion) or 1.4 MPa (pre combustion) (IPCC, 2005).

There are several CO_2 captuure technologies, which use sorbent, solvent or membranes etc. The technologies are also classified as heat and/or pressure driven process. For example, absorption by chemical solvents and temperature swing adsorption are a heat driven process. On the other hand, the physical absorption of physical solvents, pressure swing adsorption and membrane separation are a pressure driven process. Generally, heat-driven CO_2 capture is used for low CO_2 partial pressure on target gas, while pressure-driven process is used for higher CO_2 partial pressure. The combination of heat and pressure-driven CO_2 capture process such as MDEA process is also evaluated. From the point of view of development of CO_2 capture process, it is important to estimate the efficiency penalty of power plants. There are many studies which analyze the effect of operating conditions of CO_2 capture process on power plant efficiency (Abu Zhara, 2011; Cifre, 2009; Goto, 2013; Strube, 2011). However, the relationship between heat and energy duty of CO_2 capture process and compressors on the efficiency of the power plants is not cleared yet.

In this study, PC and IGCC power plants were modelled by using a process simulator. The effect of properties of CO_2 capture process on power plant efficiency was investigated under the unified basis and conditions, such as coal property, efficiency of compressors or pumps etc. For IGCC plant, the efficiency penalty by installing water-gas shift reaction was also investigated. Gross and net power generation, efficiency and the efficiency penalty by CO_2 capture process were calculated. Heat duty for CO_2 capture process and CO_2 compression conditions were varied, and those effects on the efficiency penalty were obtained.

2. Development of Process Simulation Models

A commercial process simulator Aspen Plus 7.3 was used for the process modelling of power plants. The design basis of PC and IGCC power plant was referred from literature (NETL, 2007). The design coal was bituminous (Illinois No. 6) as shown in the reference. The high heat value (HHV) and low heat value (LHV) of the coal is 27,113 KJ/kg and 26,151 KJ/kg, respectively.

2.1 PC Power Plant

For the development of PC power plant with CO_2 removal, "Case12 PC with supercritical case" in the NETL report was referred (NETL, 2007). Process flow diagram of the PC power plant is shown in Figure 1. Pulverized coal was supplied to the burner. In this burner, steam was generated and was supplied to steam turbines. The steam turbines consist of high-pressure (HP), intermediate-pressure (IP) and low-pressure (LP) turbines as shown in Figure 2. The steam temperature generated by the heater was 593 °C and the pressure of superheated steam was 24.1 MPa. The flue gas from the burner was treated by selective catalytic reduction (SCR), bag filter and flue gas desulfurization (FGD). Finally, CO_2 was removed from the gas and treated flue gas was released from the stack. The separated CO_2 was compressed and liquefied by compressors to sequestration-ready pressure, 15.2 MPa. The details of CO_2 compression process and steam turbines are described in 2.3 and 2.4.

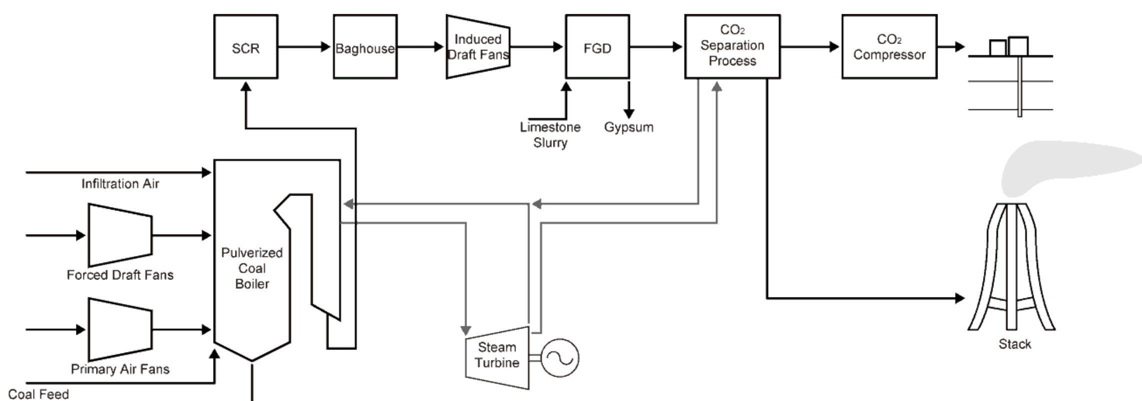

Figure 1. Process flow diagram of PC power plant with CO_2 post-combustion capture (Case12 in the literature (NETL, 2007))

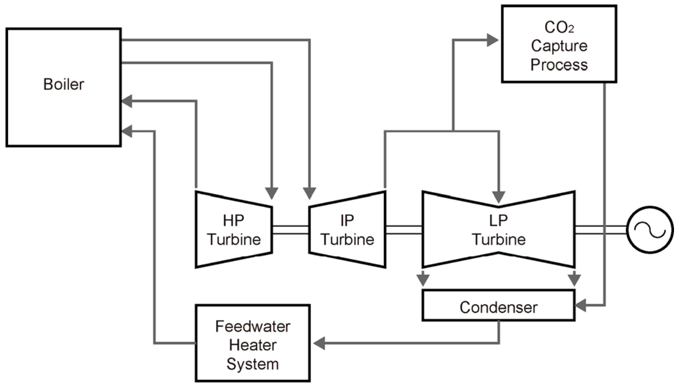

Figure 2. Steam extraction from steam turbines to CO_2 capture process

2.2 IGCC Power Plant

2.2.1 IGCC Without CO_2 Capture

Process flow diagram of the IGCC power plant is shown in Figure 3. Coal was supplied to gasifier and transferred to CO and H_2. The gas was treated by de-SOx reactor and burned in gas turbine engine. The gas turbine engine drove electric generator. The flue gas from the gas turbine was sent to heat recovery steam generator (HRSG) and generate steam which drove steam turbines. The steam temperature from the heater was 538 °C and the pressure of superheated steam was 12.4 MPa. The steam turbines drove electric generators. The fluegas was then sent to stack and emitted to the air.

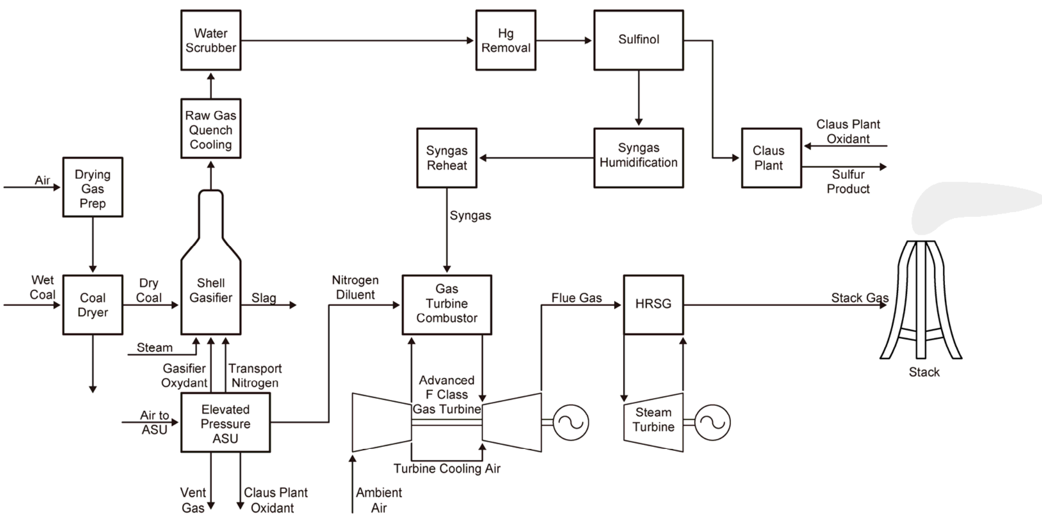

Figure 3. Process flow diagram of IGCC power plant without CO_2 capture (Case5 in the literature (NETL, 2007))

2.2.2 IGCC With CO_2 Capture

Process flow diagram of the IGCC power plant with CO_2 capture is shown in Figure 4. For CO_2 capture case, gasified coal (CO and H_2) was treated by water-gas shift reactor, in which CO reacted with H_2O and yielded CO_2 and H_2. Then CO_2 was removed in CO_2 capture process (shown as Selexol Unit in Figure 4) and liquefied by compressors. The treated gas was burnt in gas turbine engine, yielding hot flue gas. The flue gas was sent to HRSG. The steam temperature from the heater was 566 °C and the pressure of superheated steam was 12.5 MPa.

Generally CO_2 capture from IGCC power plant is performed from the water-shifted gas, and it is called pre-combustion capture. On the other hand, IGCC power plant without CO_2 capture process does not contain water-shift reactor. In this study, post-combustion capture from such process was also estimated. CO_2 partial pressure before CO_2 capture is 1.2 MPa for pre-combustion process and 0.0076 MPa for post-combustion process.

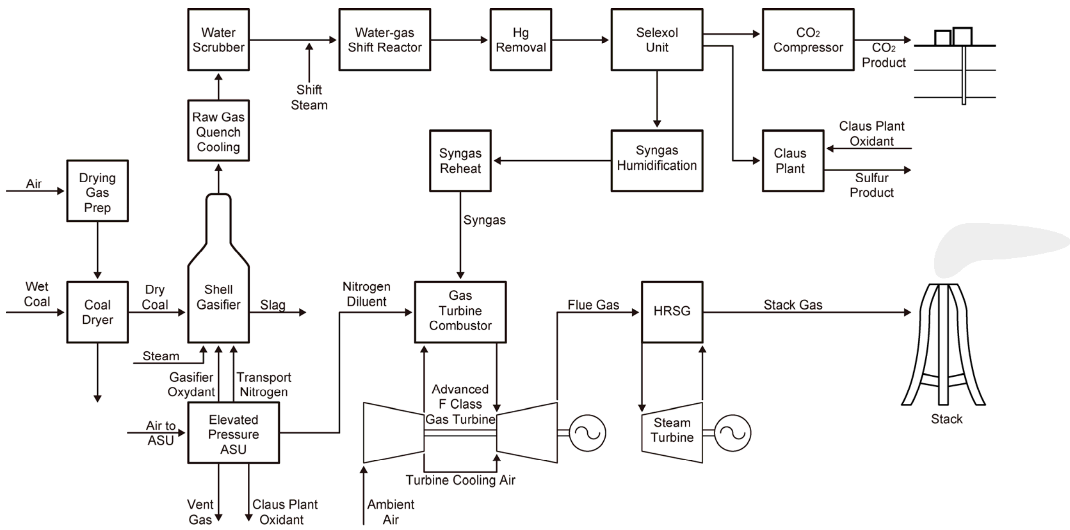

Figure 4. Process flow diagram of IGCC power plant with CO_2 capture (Case6 in the literature (NETL, 2007))

2.3 CO_2 Capture Process

2.3.1 Heat-Driven CO_2 Capture Process

Chemical absorption solvent or temperature swing adsorption (TSA) process was estimated for the CO_2 capture process and was driven by applying heat to the sorbents. In this study, the detailed reaction in CO_2 capture process such as the reaction of CO_2 with chemical solvents or adsorbents was not considered. It was estimated that CO_2 was separated by applying some amount of heat. The provided heat is consumed for reactions, temperature increase, steam generation, and so on. In this study, such a breakdown was not considered and a total heat requirement was considered for sensitivity analysis. The heat required for CO_2 capture was supplied by bypassing steam from the inlet of LP turbine. The steam was estimated to be cooled to 110 °C in the CO_2 capture process. 90% (for PC) or 95% (for IGCC) of CO_2 from the flue gas was captured. CO_2 was flashed in 0.16 MPa from CO_2 capture process and sent to CO_2 compressor.

2.3.2 Pressure-Driven CO_2 Capture Process

Physical absorption solvent, pressure swing adsorption (PSA) and membrane separation process are CO_2 capture process driven by pressure difference. In this process, detailed separation mechanism in CO_2 capture process such as CO_2 absorption, adsorption or membrane transparent was not considered and the outlet pressure of CO_2 capture process was considered as well as that of heat-driven CO_2 capture system. The pressure difference was generated by a pump or compressor driven by electricity generated at the power plant, and was combined with CO_2 compression process.

2.3.3 Heat and Pressure-Driven CO_2 Capture Process

In heat-driven CO_2 capture process, CO_2 was released under higher partial pressure than that of CO_2 source. It is expected that combination of CO_2 capture process operated by heat and pressure may reduce the efficiency penalty. Parametric study of heat required to separate CO_2 and inlet pressure on CO_2 compressor on efficiency penalty of the power plant was carried out from the results obtained in 2.3.1 and 2.3.2.

2.4 CO_2 Compression

CO_2 separated in the CO_2 capture process was pressurized to 15.2 MPa, so that it could be transferred to the sequestration site by pipeline. CO_2 compressors were connected in series as shown in Figure 5. The compression conditions are listed in Table 1, which were also referred from a literature (NETL, 2007). The compressed CO_2 was cooled to 52 °C (125 °F) between each compressor except the first and second stage (32 °C or 90 °F). The power consumption of the first stage was smaller than the other compressors because it worked as a liquid pump. For the conditions that the inlet pressure was lower than 0.16 MPa, additional compressors were added so that the pressure difference of inlet and outlet would be less than 2.2 times.

Table 1. Outlet pressure for each stage of CO_2 compression process

Stage	Outlet pressure (MPa)
1	15.3
2	8.27
3	3.76
4	1.71
5	0.78
6	0.36

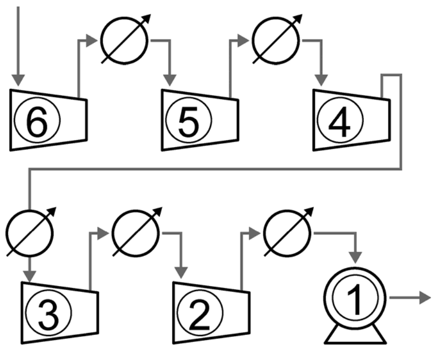

Figure 5. Configuration of CO_2 compression process

The relation between CO_2 inlet pressure P_{CO2} [MPa] and compression energy per CO_2 mass w_{CO2} [kW/t-CO_2] is shown in Figure 6. It shows good relation to semi-log plot and the fitting result is shown in Equation (1).

$$w_{CO2} = -26.37 \ln(P_{CO2}) + 58.16 \tag{1}$$

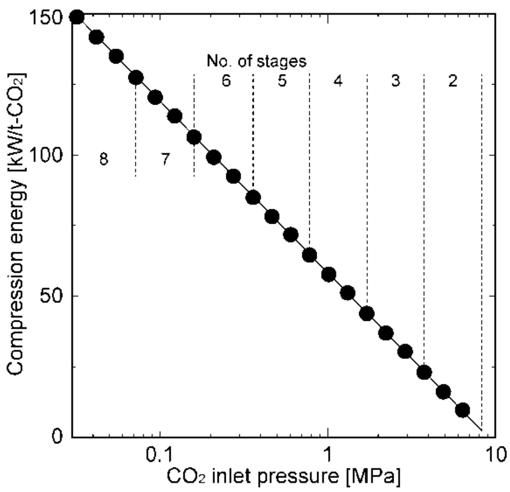

Figure 6. Relation between CO_2 inlet pressure (P_{CO2}) and compression energy (w_{CO2}), outlet pressure = 15.2 [MPa]

2.5 Variations of Process Model Calculation

Power generation and efficiency of the power plants were calculated and verified with reference data. Generated power $\dot{W}$[kW] and efficiency η (net, gross) [%] are calculated by following equations:

$$\dot{W}_{net} = \dot{W}_{gross} - \dot{W}_{aux} \tag{2}$$

$$\eta_{gross} = (\dot{W}_{gross} \times 3.6) / \dot{Q}_{coal} \times 100 \quad (3)$$

$$\eta_{net} = (\dot{W}_{net} \times 3.6) / \dot{Q}_{coal} \times 100 \quad (4)$$

Where $\dot{Q}_{coal}$ is thermal input to the plant by coal combustion [GJ/h], 3.6 is a conversion factor from kW to GJ/h. CO_2 recovery ratio was 90% for PC case and 95% for IGCC cases, therefore

$$\dot{m}_{CO2\text{-}sep} = 0.90\ \dot{m}_{CO2\text{-}gen} \text{ (for PC)},\ \dot{m}_{CO2\text{-}sep} = 0.95\ \dot{m}_{CO2\text{-}gen} \text{ (for IGCC)} \quad (5)$$

The data are shown in Tables 2–4. It was confirmed that the calculated data show good agreement with those reference data (NETL, 2007).

Table 2. Reference conditions and calculation results for PC with post-combustion CO_2 capture case

	Reference (Case 12)	This study	w/o CCS
Coal feed [t/h] ($\dot{m}_{coal}$)	266.090	266.090	266.090
Thermal input, LHV [GJ/h] ($\dot{Q}_{coal}$)	6,958,520	6,958,520	6,958,520
Gross power [kW] ($\dot{W}_{gross}$)	663,445	673,181	797,924
Aux power [kW] ($\dot{W}_{aux}$)	117,450	114,212	63,860
Net power [kW] ($\dot{W}_{net}$)	545,995	558,969	734,064
Gross efficiency [%] (η_{gross})	34.3	34.8	41.3
Net efficiency [%] (η_{net})	28.2	28.9	38.0
CO_2 generated [t/h] ($\dot{m}_{CO2\text{-}gen}$)	631.1	622.7	622.7
CO_2 separated [t/h] ($\dot{m}_{CO2\text{-}sep}$)	568.1	560.4	–
Heat duty for CO_2 capture [GJ/h] ($\dot{Q}_{cap}$)	2,067	2,067	–
Heat duty for CO_2 capture per CO_2 mass [GJ/t] (q_{cap})	3.64	3.64	–

Table 3. Reference conditions and calculation results for IGCC case without CO_2 capture

	Reference (Case 5)	This study
Coal feed [t/h] ($\dot{m}_{coal}$)	205.305	205.305
Thermal input, LHV [GJ/h] ($\dot{Q}_{coal}$)	5,368,931	5,368,930
Gross power [kW] ($\dot{W}_{gross}$)	748,020	730,640
Aux load [kW] ($\dot{W}_{aux}$)	112,170	102,012
Net power [kW] ($\dot{W}_{net}$)	635,850	628,628
Gross efficiency [%] (η_{gross})	50.2	49.0
Net efficiency [%] (η_{net})	42.6	42.2
CO_2 generated [t/h] ($\dot{m}_{CO2\text{-}gen}$)	455.2	459.1
CO_2 captured [t/h] ($\dot{m}_{CO2}$)	0	0
Heat duty for CO_2 capture [GJ/h] ($\dot{Q}_{cap}$)	0	0
Heat duty for CO_2 capture per CO_2 mass [GJ/t] (q_{cap})	0	0

Table 4. Reference conditions and calculation results for IGCC case with pre-combustion CO_2 capture

	Reference (Case 6)	This study	w/o CCS
Coal feed [t/h] ($\dot{m}_{coal}$)	214.629	214.606	214,606
Thermal input, LHV [GJ/h] ($\dot{Q}_{coal}$)	5,612,763	5,612,170	5,612,170
Gross power [kW] ($\dot{W}_{gross}$)	693,555	675,845	675,845
Aux load [kW] ($\dot{W}_{aux}$)	176,420	166,359	142,071
Net power [kW] ($\dot{W}_{net}$)	517,135	509,486	533,774
Gross efficiency [%] (η_{gross})	44.5	43.4	43.4
Net efficiency [%] (η_{net})	33.2	32.7	34.2
CO_2 generated [t/h] ($\dot{m}_{CO2\text{-}gen}$)	477.0	479.2	479.2
CO_2 captured [t/h] ($\dot{m}_{CO2}$)	453.3	455.3	0
Heat duty for CO_2 capture [GJ/h] ($\dot{Q}_{cap}$)	0	0	0
Heat duty for CO_2 capture per CO_2 mass [GJ/t] (q_{cap})	0	0	0

3. Results

3.1 CO_2 Capture Energy (Heat)

3.1.1 PC Power Plant

The effect of steam extraction on efficiency of PC power plant was estimated. The steam conditions which entered to LP turbine was 414.9 °C, 0.949 MPa, 1,980,000 kg/h and its enthalpy $\dot{H}_{LP\text{-}in}$ was −25,003 GJ/h. The enthalpy will be −30,631 GJ/h when it was supplied to CO_2 capture process and cooled to 110 °C ($\dot{H}_{110}$). Thus the maximum CO_2 capture energy to the CO_2 capture process ($\dot{Q}_{cap\text{-}max}$) was calculated as;

$$\dot{Q}_{cap\text{-}max} = \dot{H}_{LP\text{-}in} - \dot{H}_{110} = 5{,}628 \text{ GJ/h} \quad (6)$$

CO_2 recovered amount ($\dot{m}_{CO2}$) of this condition was 568.6t/h, from Table 2. Therefore, maximum CO_2 capture energy per CO_2 weight $q_{cap\text{-}max}$ [GJ/t-CO_2] is;

$$q_{cap\text{-}max} = \dot{Q}_{cap\text{-}max} / \dot{m}_{CO2\text{-}sep} = 9.90 \text{ GJ/t-}CO_2 \quad (7)$$

Power generation by an LP turbine ($\dot{W}_{gen}$) was 339,160 kW, and it was 17.5% of total thermal input to this process ($\dot{Q}_{coal}$ = 6,958,520 [GJ/h] =1,932,922 [kW], LHV).

Efficiency penalty $\Delta\eta$ [%-point] was defined as the difference between the net efficiency with ($\eta_{net\text{-}w/\,CO2cap}$) and without CO_2 capture process ($\eta_{net\text{-}w/o\,CO2cap}$). In this condition, $\Delta\eta$ was 17.5% when heat duty for CO_2 capture was 9.90 GJ/t-CO_2. The calculations are summarized in Table 5. From the calculation results obtained above, the relation between CO_2 capture energy per CO_2 mass (q_{cap}) and efficiency penalty ($\Delta\eta$ [%]) was calculated as following equation;

$$\Delta\eta = (\Delta\eta_{max} / q_{cap\text{-}max}) \cdot q_{cap} = 1.75\, q_{cap} \quad (8)$$

Table 5. Steam and CO_2 capture conditions for PC power plant

Stream	LP inlet
Enthalpy [GJ/h] ($\dot{H}_{LP\text{-}in}$)	−25,003
Enthalpy at 110 °C [GJ/h] ($\dot{H}_{110}$)	−30,631
Maximum heat duty for CO_2 capture [GJ/h] ($\dot{Q}_{cap\text{-}max}$)	5,628
Maximum heat duty for CO_2 capture per CO_2 mass [GJ/t-CO_2] ($q_{cap\text{-}max}$)	10.0
Power generation by steam turbine [kW] ($\dot{W}_{gen}$)	339,160
Maximum efficiency penalty [%] ($\Delta\eta_{max}$)	17.5%
Constant of proportionality	1.75

3.1.2 IGCC Power Plant (Post-Combustion)

The effect of steam extraction on efficiency for post-combustion CO_2 capture for IGCC power plant (i.e., without water-gas shift reactor) was also examined, and the results are shown in Table 6. As shown in the table, the maximum CO_2 capture energy was 1,833 GJ/h under this condition. The CO_2 generation was 453.3 t/h from Table 3, therefore maximum CO_2 capture energy per CO_2 mass was 4.12 GJ/t-CO_2. If the heat duty exeed the value, steam should be supplied from the inlet of IP turbine. When steam is supplied from the inlet of IP turbine, maximum CO_2 capture energy per CO_2 mass is 4.95 GJ/t-CO_2.

Table 6. Steam and CO_2 capture conditions for IGCC power plant with post-combustion CO_2 capture process

Stream	IP inlet	LP inlet
Enthalpy [GJ/h] ($\dot{H}$)	−7,327	−7,649
Enthalpy at 110 °C [GJ/h] ($\dot{H}_{110}$)	−9,481	−9,482
Maximum heat duty for CO_2 capture [GJ/h] ($\dot{Q}_{cap\text{-}max}$)	2,154	1,833
Maximum heat duty for CO_2 capture per CO_2 mass ($q_{cap\text{-}max}$)	4.94	4.20
Power generation by steam turbine [kW] ($\dot{W}_{gen}$)	202,025	112,884
Efficiency penalty [%] ($\Delta\eta$)	13.5	7.57
Constant of proportionality	2.74	1.80

In this condition, the relation between CO_2 capture energy per CO_2 mass (q_{cap} [GJ/t-CO_2]) and efficiency penalty ($\Delta\eta$ [%]) is given by following equations.

$$\Delta\eta = 1.80\ q_{cap} \qquad (0 \le q_{cap} \le 4.20) \tag{9}$$

$$\Delta\eta = 2.74\ q_{cap} \qquad (4.20 < q_{cap} \le 4.94) \tag{10}$$

3.1.3 IGCC Power Plant (Pre-Combustion)

CO_2 capture from pre-combustion CO_2 capture from IGCC (i.e., with water-gas shift reactor) was considered. Calculation results are shown in Table 7. The power generated in steam turbines was smaller than that of the post-combustion case because water-gas shift reactor consumes energy.

Table 7. Steam and CO_2 capture conditions for IGCC power plant with pre-combustion CO_2 capture process

Stream	IP inlet	LP inlet
Enthalpy [GJ/h] ($\dot{H}$)	−5,880	−6,128
Enthalpy at 110 °C [GJ/h] ($\dot{H}_{110}$)	−7,287	−7,287
Maximum heat duty for CO_2 capture [GJ/h] ($\dot{Q}_{cap\text{-}max}$)	1,406	1,159
Maximum heat duty for CO_2 capture per CO_2 mass ($q_{cap\text{-}max}$)	2.93	2.41
Power generation by steam turbine [kW] ($\dot{W}_{gen}$)	156,528	87,852
Efficiency penalty [%] ($\Delta\eta$)	10.0	5.64
Constant of proportionality	3.42	2.33

In this condition, the relation between CO_2 capture energy per CO_2 mass (q_{cap} [GJ/t-CO_2]) and efficiency penalty ($\Delta\eta$ [%-point]) is given by following equations.

$$\Delta\eta = 2.33\ q_{cap}\ (0 \le q_{cap} \le 2.41) \tag{11}$$

$$\Delta\eta = 3.42\ q_{cap}\ (2.41 < q_{cap} \le 2.93) \tag{12}$$

3.2 CO_2 Capture Energy (Pressure)

As discussed in 2.4, there is a linear semi-log relation between CO_2 compression energy and CO_2 inlet pressure to the compression process. The CO_2 compression energy w_{CO2} can be converted to efficiency penalty $\Delta\eta$ for PC and IGCC (post and pre-combustion CO_2 capture) processes by following equation.

$$\Delta\eta = w_{CO2} \times (\dot{m}_{CO2} / \dot{Q}_{coal}) \times 100 \quad (13)$$

The y-axis intercept and constant of proportionality of Equation (1) are converted as shown in Table 8.

Table 8. Slopes and y-intercepts of the relation between CO_2 inlet pressure P_{CO2} and compression energy w_{CO2} for PC and IGCCpower plants

	Slope	y-intercept
PC with post-combustion CO_2 capture	−0.765	1.69
IGCC with post-combustion CO_2 capture	−0.771	1.70
IGCC with pre-combustion CO_2 capture	−0.770	1.70

4. Discussion

4.1 CO_2 Capture Energy (Combination of Heat and Pressure)

The results obtained in 3.1 and 3.2 were combined and the efficiency penalty ($\Delta\eta$) was obtained as a function of CO_2 capture energy (q_{cap}) and CO_2 inlet pressure for compressors (P_{CO2}). For PC with post-combustion CO_2 capture, the relation was obtained from Equation (8) and Table 8, and is expressed as Equation (14)

$$\Delta \eta = 1.75\ q_{cap} - 0.765 \ln(P_{CO2}) + 1.69 \quad (14)$$

The relation is plotted in three-dimensional graph shown in Figure 7.

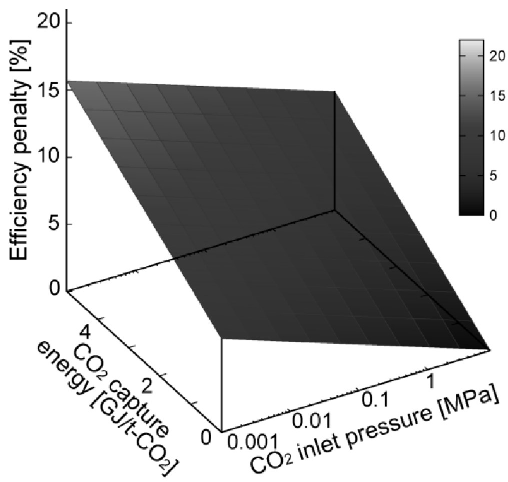

Figure 7. Relation between CO_2 capture energy (q_{cap}), CO_2 inlet pressure for compressors (P_{CO2}) and efficiency penalty ($\Delta\eta$) for PC with post-combustion CO_2 capture

For IGCC with post-combustion CO_2 capture case, the efficiency penalty ($\Delta\eta$) was obtained from Equation (9), (10) and Table 8, and is expressed as Equations (15), (16) and Figure 8.

$$\Delta \eta = 1.80\ q_{cap} - 0.771 \ln(P_{CO2}) + 1.70 \quad (0 \le q_{cap} \le 4.21) \quad (15)$$

$$\Delta \eta = 2.74\ q_{cap} - 0.771 \ln(P_{CO2}) + 1.70 \quad (4.21 < q_{cap} \le 4.95) \quad (16)$$

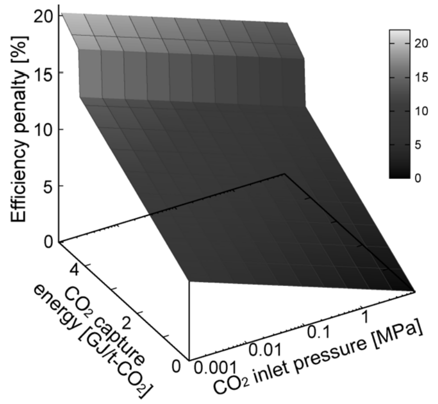

Figure 8. Relation between CO_2 capture energy (q_{cap}), CO_2 inlet pressure for compressors (P_{CO2}) and efficiency penalty ($\Delta\eta$) for IGCC with post-combustion CO_2 capture

For IGCC with pre-combustion CO_2 capture case, the efficiency penalty ($\Delta\eta$) was obtained from Equations (11), (12) and Table 8, and is expressed as Equations (17), (18) and Figure 9.

$$\Delta \eta = 2.33\, q_{cap} - 0.770 \ln(P_{CO2}) + 1.70 \quad (0 \le q_{cap} \le 2.41) \tag{17}$$

$$\Delta \eta = 3.42\, q_{cap} - 0.770 \ln(P_{CO2}) + 1.70 \quad (2.41 < q_{cap} \le 2.93) \tag{18}$$

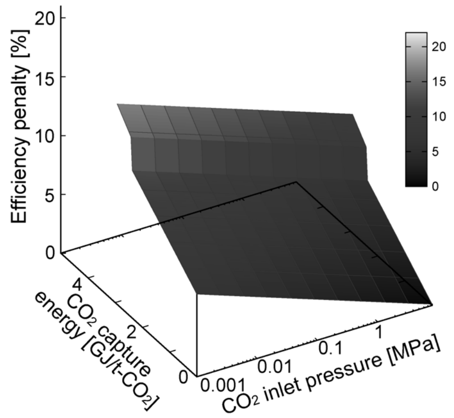

Figure 9. Relation between CO_2 capture energy (q_{cap}), CO_2 inlet pressure for compressors (P_{CO2}) and efficiency penalty ($\Delta\eta$) for IGCC with pre-combustion CO_2 capture

4.2 Comparison With Other Studies

The comparison of efficiency penalty reported in other studies with calculation by this study is summarized in Table 9. The calculated results show a good agreement with the reference data.

Table 9. CO_2 capture conditions and efficiency penalty of literatures and calculation results

Reference	CO_2 capture Technology	CO_2 capture energy [GJ/t-CO_2]	Inlet pressure [MPa]	Efficiency penalty [%-points]	This study [%-point]	Note*
NETL, 2007	selexol	0	1.2	1.6	1.6	(b)
NETL, 2007	Econamine	3.6	0.16	9.1	9.4	(a)
Dave, 2011	MEA	4.0	0.16**	11.1	10.1	(a)
Stöver, 2011	MEA	3.6	0.16**	8.0-9.8	9.4	(a)
Stöver, 2011	H3	2.8	0.16**	9.9-11.2	8.0	(a)

*: (a) PC with post combustion CO_2 capture, (b) IGCC with pre combustion CO_2 capture.

**: Estimated value from the stripper temperature.

4.3 The Effect of Water-Gas Shift Reaction on Efficiency in IGCC

The difference in efficiency of post- and pre-combustion CO_2 capture was considered. The difference in those processes was the existence of water-gas shift reaction. There was 5.6%-points of difference in the gross efficiencies of without CO_2 capture (Table 3) and pre-combustion CO_2 capture (Table 4) case. This was attributed to the loss of water-gas shift reaction. In case 6 or pre-combustion case, the compression energy of CO_2 was 24,288 kW, which corresponds to 0.4%-points of efficiency penalty. Therefore the total efficiency penalty by CO_2 capture and compression will be 6.0%-points. Therefore, Equation (15) will be;

$$q_{cap} \leq 0.428 \ln(P_{CO2}) + 2.39 \quad (0 \leq q_{cap} \leq 4.21 \text{ or } 0.00378 \leq P_{CO2} \leq 70.2) \tag{19}$$

By solving the equation, the condition for the case 5 which would be lower than the efficiency penalty in Case 6 was obtained as Figure 10. Therefore, it can be concluded that the efficiency of IGCC with post-combustion CO_2 capture will be better than that of IGCC pre-combustion process if the CO_2 capture process which satisfies the painted region in Figure 10 of CO_2 capture energy and CO_2 inlet pressures to CO_2 compressor.

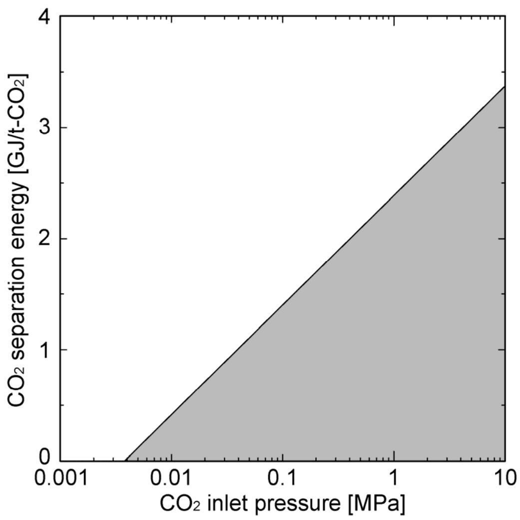

Figure 10. Relation between CO_2 capture energy (q_{cap}), CO_2 inlet pressure for compressors (P_{CO2}) and efficiency penalty ($\Delta\eta$) for IGCC with pre-combustion CO_2 capture

5. Conclusion

The effects of carbon dioxide capture process on output efficiency of fossil power plants were investigated aiming to obtain a performance guideline of CO_2 capture process for coal-fired power plants. The power plant models were developed by using a commercial process simulator Aspen Plus 7.3 and plant data reported from NETL. It was found that the efficiency penalty $\Delta\eta$ [%-point] can be estimated from the CO_2 capture energy (q_{cap} [GJ/t-CO_2]) and CO_2 inlet pressure to the CO_2 compressors (P_{CO2} [MPa]) by the following equations;

for PC power plant,

$\Delta\eta = 1.75\, q_{cap} - 0.765 \ln(P_{CO2}) + 1.69$

for IGCC power plant with pre-combustion CO_2 capture,

$\Delta\eta = 1.80\, q_{cap} - 0.771 \ln(P_{CO2}) + 1.70 \quad (0 \leq q_{cap} \leq 4.21)$ or

$\Delta\eta = 2.74\, q_{cap} - 0.771 \ln(P_{CO2}) + 1.70 \quad (4.21 < q_{cap} \leq 4.95)$

for IGCC power plant with post-combustion CO_2 capture,

$\Delta\eta = 2.33\, q_{cap} - 0.770 \ln(P_{CO2}) + 1.70 \quad (0 \leq q_{cap} \leq 2.41)$ or

$\Delta\eta = 3.42\, q_{cap} - 0.770 \ln(P_{CO2}) + 1.70 \quad (2.41 < q_{cap} \leq 2.93)$.

The calculated results were compared with the reference data, and they showed a good agreement.

For IGCC power plants, the effect of the installation of water-gas shift reactor on the efficiency penalty was investigated. The net efficiency was reduced 5.4 points by installing water-gas shift reactor. It was calculated that the efficiency of IGCC with post-combustion CO_2 capture will be better than that of IGCC pre-combustion process if the CO_2 capture process which satisfies the following condition;

$q_{cap} \leq 0.428 \ln(P_{CO2}) + 2.39 \quad (0 \leq q_{cap} \leq 4.21 \text{ or } 0.00378 \leq P_{CO2} \leq 70.2)$

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