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100 MWe 순산소 석탄연소 발전시스템의 개념설계-영동 프로젝트

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Conceptual Design of 100 MWe Oxy-coal Power Plant-Youngdong Project

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ABSTRACT

An existing unit of power plant is considered to refurbish it for possible application of carbon capture and storage(CCS). Conceptual design of the plant includes basic considerations on the national and international situation of energy use, environmental concerns, required budget, and time schedule as well as the engineering concept of the plant. While major equipment of the recently upgraded power plant is going to be reused, a new boiler for air-oxy fired dual mode operation is to be designed. Cryogenic air separation unit is considered for optimized capacity, and combustion system accommodates flue gas recirculation with multiple cleaning and humidity removal units. The flue gas is purified for carbon dioxide separation and treatment. This paper presents the background of the project, participants, and industrial background. Proposed concept of the plant operation is discussed for the possible considerations on the engineering designs.

Key Words : Oxy-coal power generation(순산소 석탄연소 발전), CO_2 capture(이산화탄소 포집), Youngdong project(영동 프로젝트), Conceptual design(개념설계)

1. Background

1.1. Global reduction of CO_2 emission

United Nations Framework Convention on Climate Change(UNFCCC) is an international environmental treaty with the goal of achieving stabilization of greenhouse gas(GHG) concentrations in the atmosphere at a level that would minimize dangerous atmospheric interference with the climate system. Under the Kyoto Protocol, industrialized countries(called 'Annex 1 countries') commit themselves to a reduction of GHG, and agree to reduce their collective emissions. The other countries in the world (called 'Non-annex 1 countries') have also voluntarily participated in establishing authority to manage Kyoto obligations, concentrating on providing national statistics, but have shown interest on interaction with Annex 1 countries in terms of emission trading, clean development mechanism and joint implementation, the so-called flexible mechanisms[1].

It has been agreed to act now to solidify stabilizing atmospheric concentration of GHG. However, members also agreed to recognize the differences among members, mainly based on the level of development of individual member country. 'The common but differentiated responsibilities' among countries are accepted, as categories into newly industrialized, rapidly industrializing, other developing and least developed countries in points of responsibilities, capabilities and potential. A different set of rules has been applied to each group.

Korea is in unique situation; has been classified as one of Non-annex 1 countries in UNFCCC 1992, as a newly developed country with notable economic growth and rapid increase in GHG emissions. Although Korea could have been free from the obligatory commitment, being one of the fast growing economies in transition, and becoming one of the major participants in global emission. Korea has started proactive measures in all the issues related with climate change. Kyoto protocol, which is grounds for mandatory reductions on GHG emissions of Annex 1 countries, is scheduled to expire

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at the end of 2012. Establishment of regime to succeed Kyoto protocol is an urgent issue for a sustainability of mankind. Vigorous efforts are continued as inter-governmental cooperation to cope with uncertainty on reducing GHG emissions. Copenhagen conference of December 2009 has revealed limitation, which just drew less specific political accord because of conflicts between developed and developing countries in a different view on fairness. Nevertheless, it is expected that there would be advanced agreements on policy to adjust global climate change considering tremendous expense in a worst case that we miss the time to be able to deal with minimized efforts[2].

1.2. National goal and corporate strategy for power industry

Based on the national strategy of the Korean government, CO_2 reduction target is set below 30 percent from its 2020 business-as-usual(BAU) level to convert its economy from highly energy dependent and large pollutant emitting base to eco-friendly and sustainable base. Minimizing CO_2 and other emissions cultivating green energy technology is one of Korea's 'Green growth' strategies. There are many action plans including development of renewable energy, enhancement of clean energy development, and development of low carbon/eco-friendly infrastructure. Also, setting international environmental standards, regulations, introduction, and permit of emission trading system will be followed[3].

One of viable ways of reducing CO_2 is to replace electricity market by conventional fossil fuel generation with that by renewable energy technologies. The big challenge for renewable energy industry is to make the cost of clean energy competitive with conventional energy suppliers. Feed in tariff(FIT) is legal obligation on utilities and energy companies to purchase electricity from renewable energy producers at favorable price per unit cost. FIT allows producers to keep the surplus created by technical development and generate excessive profits, unless there is a way to adjust the tariff accordingly. One the other hand, renewable portfolio standards(RPS) mandate utilities to provide renewable electricity to their customers as a percentage of their overall electricity generation mix. RPS aims to develop a set percentage of renewable energy sources at least cost, and does not provide any incentives to develop renewable energy source exceeding the quota, which may lead to limited technological development and technological variety[4].

Another approach to reduce CO_2 emissions is to put economical commitments on emission of CO_2 itself; carbon tax, and cap and trade. A carbon tax is a price-based instrument; it fixes the price of carbon-based energy and allows emissions levels to vary according to economic activity[5]. A cap and trade system is a quantity-based instrument; it fixes the total quantity of emissions and allows the price of energy and energy-related products to fluctuate according to market forces. Carbon tax, and cap and trade have its attributes in terms of emissions certainty, price predictability, environmental effectiveness and simplicity, and transparency. While carbon tax assures price predictability to encourage investment in alternative fuels and energy-efficient technologies, desired environmental emission level can be met in cap and trade system.

Korean National Assembly has passed the RPS program in 2010. It requires utility companies which have over than 500 MWe capacity, to accept the mandatory percent base quota from 2% by 2012 to 10% by 2022. FIT has supported renewable energy industries since 2001. Although it is still controversial, increasing burden of finance to subsidy and quite low renewable energy portion in national energy market make introduce RPS. RPS became effective in 2012, replacing FIT. It is speculated that CO_2 capture ready plants may qualify as a substitute for meeting the requirement of RPS.

1.3. Youngdong oxy-coal project

Youngdong oxy-coal project was launched on October 2007 as one of the national R&D program of Korea. The project, led by Korea Electric Power Research Institute(KEPRI) under Korea Electric Power Corporation(KEPCO), aims at tentative demonstration of CO_2 capture and storage readiness with an existing 125 MWe Youngdong power station unit 1, which is run by Korea South-east Electric Power Company(KOSEP). The research has been planned with multiple stages spanning from 2007 till 2018. The first stage is laying ground for conceptual design of oxy-pulverized coal(PC) combustion system of 100 MWe class oxy-coal power plant, which includes optimization of power trains of boiler, steam turbine, air separation unit(ASU), CO_2 purification (or processing) unit(CPU) as an integrated system. Also, it includes drawing of key technology of oxy-PC combustor and gas cleaning control facilities. In the second phase, basic design of oxy-PC power plant will be conducted, and test of pilot plant and preparation of construction will be performed. In the third stage, detailed design and construction of demonstration plant will be performed by 2015. Finally, demonstration of the plant is expected to be carried out for 3 years from 2016 to 2018.

Under the leadership of KEPRI, several industrial and academic research groups have joined the project. Research tasks are accounted to working groups according to specific development scope; plant conceptual design, boiler and combustion, environmental control, and CO_2 transport and storage. The plant conceptual design has been conducted by KEPRI and Daesung industrial gases company. They focus on development of process analysis method to be applied to pilot and demonstration scale and deduction of optimum concept design. Especially, Daesung industrial gases company gives an idea of 2,000 tons/day ASU and CPU. KEPRI and Korea Institute of Industrial Technology(KITECH) carry out the development of concept design for oxy-PC boiler and combustor, respectively. Combustion characteristics, heat transfer, and flame stability in oxy-firing combustion environment are identified based on experimental and numerical analysis. Burner type and arrangement, furnace configuration, and tube heat exchanger arrangement are being considered with regard to flue gas recirculation(FGR) ratio and oxidant conditions. Korea Institute of Machinery and Materials(KIMM) takes charge of development of in-furnace DeSOx, and hybrid hot and wet electrostatic precipitator(ESP). Basic experiments for sorbent behavior and desulfurization/decomposition characteristics are conducted to draw key design factors. Particulate removal performance in oxy-coal combustion is also examined. Korea Institute of Geoscience and Mineral resources(KIGAM) has worked to secure technologies for transport and injection of CO_2 and to monitor the behavior of injected CO_2 in storage site.

1.4. Ongoing reference cases

Several projects are being conducted with oxy-fuel based on carbon capture and storage(CCS) technology. Callide oxy-fuel project by CS energy of Australia was launched in 2004, which is basically retrofit project of 30 MWe existing coal fired power plant unit #4 in Queensland-based Callide A power station to oxy-coal combustion (Steam condition 123 tons/h, at 4.1 MPa and 460℃). Site selection comes from suitability of its 30 MWe size for demonstration of CO_2 sequestration and geological access to CO_2 storage site[6]. Refurbishment of the Callide A unit #4 commenced in 2009, and will be followed by electricity generation from the oxy-coal combustion in 2011 and geological sequestration in 2012.

Vattenfall has conducted feasibility study on 250 MWe demonstration plant in Jänschwalde, Germany. Operating experiences from their 30 MWth pilot plant in Schwatz Pumpe are employed to new project. Jänschwalde power plant has six power block which generate 500 MWe per a block. Each of the unit blocks has two boilers. Two different CCS projects are applied to one power block. One would be accounted for post-combustion capture based on amine capture technology and other is planned to replace with oxy-fuel boiler. The construction is scheduled to begin in 2011[7].

2. Conceptual design proposal

2.1. Youngdong power plant

Youngdong power plant is located in Gangneung-si, Gangwon-do, on the east coast of South Korea. Fig. 1

Fig. 1. Birds-eye view of Youngdong Power Station.

shows a panoramic view of Youngdong power station. The site was strategically chosen to accommodate the local coal supply when the energy from the domestically originated resource was highly valued in the early 1970's. Large scale utilization of high ash anthracite, virtually the only energy material available in South Korea, was also intended to promote the coal mining industry. The unit 1 with 125 MWe capacity was commissioned in 1973 and unit 2 with 200 MWe capacity was subsequently completed in 1979. The plant has been in service as planned since then, except that socioeconomic changes during the past 3-4 decades have influenced significantly. Now, imported coals replaced local anthracite coal, for which the boiler was originally designed.

Youngdong unit 1 is operating at subcritical boiler pressure for gross power of 125 MWe. Originally, plant was designed to fire the mixture of 90% local anthracite and 10% heavy oil. The local anthracite has characteristics of high ash contents (nearly 32%) and lower heating value. The Downshot-firing furnace was designed to burn local anthracite effectively by increasing the residence time of coal. Storage system for feeding of coal was accordingly designed. Coal pulverized at tube mill is collected in storage bin and is fed into the burner by primary air. Balanced draft system is applied using each of two primary air fans, forced drought fans (FDF) and induced draught fans(IDF) to overcome system resistance. After Ljungstrom type air preheater, the flue gas is introduced to ESP and finally emitted to atmosphere though the stack. The steam turbine has 6 steps of boiler feed water heating process and exhausted steam is condensed at 5.1 kPa with sea water cooling.

2.2. Economics of generating plants

As of 2013, the unit 1 will have reached the 40 years book-life. Plant has been kept serviceable with continuous maintenance and upgrade. To accommodate the newly enacted regulation on emission of SOx, wet flue gas desulfurization(FGD) was added upstream of the stack in 1993. The main transformer and control facilities were exchanged in 2003. Rotors of high pressure (HP) and intermediate pressure(IP) in the steam turbine and of the generator were replaced for improving efficiency in 2003. Feeding system was converted to direct fired system to accommodate imported bituminous coal. KOSEP which owns Youngdong power station has considered various options for decommissioning or retrofitting of the plant. Repowering of unit 1 by accommodating oxy-coal combustion has emerged as a strong candidate from this background.

KOSEP, as one of the independent electric utility companies, considers economics of the generating plants. The national grid is connected and real-time decisions are made on the market, coordinated by Korea Power Exchange. Environment cost is important as well as capital investment and fuel price, but provisions of rates for stand-by and on-demand operation are also arranged. Recently, RPS has also become one of the key issues, which will replace the FIT for the selected sources of energy. Emission of carbon dioxide is not yet directly controlled, for example as in the form of carbon tax, but, without surprise, mandatory regulation is expected in the future.

2.3. Project concept

2.3.1. Demonstration of oxy-coal for CCS

Youngdong oxy-coal project foresees the full scale operation of CCS. Demonstration of 100 MWe class is potentially one of the large scales of its kind in the world at the planning stage of 2010. Commercial operation of full capacity would be required on line in the commercial electricity grid system. KOSEP is considering the feasibility for demonstration of full capacity as a commitment to the environmental issues. Youngdong unit 1 with 125 MWe capacity is considered to be adequate to provide a platform for the planned demonstration.

The plant will be completely operable with CCS capability, but at the same time, the plant will be able to continue to service as a commercially operating plant. This is in-line with the 'capture readiness', where economics and timing as related to the national and international regulations and available technology would limit the immediate operation[8]. It is expected that the plant will demonstrate CCS capability for the designated period(life time of the project), but continuous operation would be allowed while the economics of situations is warranted. It is expected that the plant demonstration will be accepted as a success when the plant shows capability for the extended demonstration period, which is expected to last for 2~5 years.

2.3.2. Repowering plant by installing a new boiler

Demonstration of oxy-coal CCS plant should require rebuilding significant portion of the power plant. Yo-

Table 1. New design coal as compared to the old coal

Coal		Korean Anthracite	Imported Sub-bituminous
HHV(As Received, kcal/kg)		4,791	5,800
Proximate Analysis (As Received, wt%)	Moisture	9.6	18
	Fixed Carbon	54.803	44.51
	Volatile Matter	3.648	34.62
	Ash	31.949	2.87
Ultimate Analysis (As Received, wt%)	Moisture	9.6	18
	C	54.927	58.22
	H	0.741	4.10
	O	2.179	15.58
	N	0.389	0.82
	S	0.217	0.41
	Ash	31.947	2.87

ungdong project calls for installing a boiler, while maintaining the rest of the plant including the water and steam power cycle. New boiler is necessary and reasonable because the plant now has to accommodate the fuel change. New design coal is sub-bituminous coal with higher in-moisture and volatile matter(lower ash) than previous Korean anthracite. Table 1 represents the analysis data of the coals.

Although the plant is generally outdated as a modern power station, major parts of facilities are affordable to keep its own functionality after recent replacement and upgrade in addition to the maintenance. It is possible to cut the expenses by minimizing the modification and maximizing the benefit of the existing plant. Steam turbines and its related facilities will be decided to continue mechanical life, which means the operation conditions of steam cycle should be unchanged on new oxy-coal combustion plant. Selected part of the flue gas cleaning system such as wet FGD will remain after careful evaluation. One of the major concerns in evaluating the concept of retrofit is the availability of site. The space of the Youngdong power station where 125 MWe unit 1 and 200 MWe unit 2 are placed is obviously limited for additional facility, therefore preliminary evaluation of spaces for construction process was found to be acceptable.

2.3.3. Boiler concept by PC combustion vs. Circulating fluidized bed(CFB) combustion

At the early stage of the project, there was consideration on combustion method of the new boiler; PC combustion or circulating fluidized bed(CFB) combustion. PC combustion technology is generally favored in the common application for coal-fired power plant worldwide and its size is approaching 1GWe. On the other hand, CFB combustion technology has advantages of high fuel flexibility and low emissions of SOx and NOx compared to the PC combustion. However, operation is more complex than PC boiler and scaling up to larger units may not be common[9]. Current state of art of CFB combustion, in terms of the largest available plant size, is 460 MWe of Largisza power station in Poland. Most Korean coal-fired power stations employ PC combustion. There are only two CFB boilers in Korea, which are 200 MWe in commercial operation and 340 MWe in construction. After the retrofitting of the plant for oxy-fuel combustion, comparative evaluation of PC over CFB should be further evaluated in terms of adaptability of air and oxygen combustion modes. The topics will be discussed in more detail separately[10]. However, the conceptual design process will proceed with the assumption that PC firing concept will be adopted.

2.3.4. Air-oxy dual mode

Air-oxy dual mode means that the boiler is allowed to operate either in conventional air-firing mode or also in oxy-firing mode. This gives operational flexibility, thereby oxy-fuel combustion becomes more affordable. The test operation duration is expected to be 2~5 years. Concept of dual mode can be further classified into a) start-up by air-firing mode and change over to oxy-firing mode, and b) complete dual operation. The guide line on operation is suggested that air-firing mode be run for the half of test period and other half be at oxy-firing mode for facilities test and data acquisition.

2.3.5. Down-rating for oxy-fired mode 125 MWe → 100 MWe

Existing steam turbine of Youngdong power station unit 1 is capable of generating 125 MWe. Air-firing mode takes full load capacity of 125 MWe as designed. As partial load of 100 MWe is applied to the oxy-firing mode, however, down-rating was determined. Decision for this down-rating was partly economical but also partly strategic. The main retrofit should be the introduction of ASU, whose capacity is well over the current practice. Capital cost and site requirement for the newly introduced ASU was estimated and compromise was reached on the capacity of 2,000 tons/day (roughly 60,000 Nm^3/h based on oxygen production). The plant electricity generating capacity is then adjusted to the nominal 100 MWe. The quantity of oxygen required for 100 MWe power generation is determined from the quantity of coal. The fuel coal of 10.7 kg/s is fed into the boiler for 100 MWe power generation. The quantity of oxygen required was theoretically calculated to in accordance with flow rate of air introduced into FD fans. Youngdong power station unit 1 is located right next to unit 2 and the power station is bordered with private houses. Therefore, the repowering work has to be conducted in restricted area. Site requirement for ASU was given as the critical consideration. Obviously, capital investment on new installation of ASU and CPU is of immediate concern. Additionally, operating cost of oxygen plant is critical in oxy-coal power plant, which would also limit the contribution of oxygen plant in the total capital investment.

3. Design considerations for the major systems

The power plant is composed of complex processes with many units. Therefore, the processes need to be separated with considerations of characteristics of the unit system. In this study, oxy-coal power generation system is divided into five blocks, water-steam system (generation of electricity using steam), combustion system(injection of coal and generation of steam by combustion), flue gas control system, air separation system, and CO_2 processing system.

3.1. Water-steam system

In Youngdong oxy-fuel project, existing water-steam system including steam turbines and a condenser is going to be reused without change in the reheating/regenerative Rankine cycle. Fig. 2 shows a schematic diagram of the water-steam system.

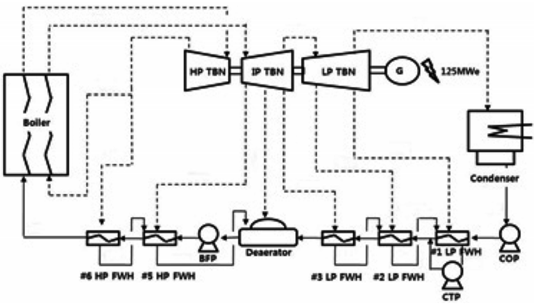

Fig. 2. Schematic diagram of the water-steam system.

Temperature of steam at the boiler exit is 814 K. Main and reheat steam conditions at turbine inlet are 12.9 MPa/811 K and 3.1 MPa/811 K because of heat loss. Although overall steam generating capacity will change, retrofitted system for dual mode has to keep the conditions. Table 2 indicates operating conditions between air-firing mode and oxy-firing mode in water-steam system. Efficiency of the existing boiler is 83.4% because of using high ash coal and deterioration of the boiler. After new boiler for dual mode is built, however, it is expected that efficiency of the boiler is 88% or higher. As rotors of HP and IP turbines were replaced for maintenance, it contributed to improvement of internal isentropic efficiency(HP: 80.7 → 82%, IP: 85.2 → 86.5%, LP: 88.2 → 92.2%) and thermal efficiency (42.9 → 43.5%) of the turbines.

3.2. Combustion system

3.2.1. Oxy-PC with FGR

Combustion system in a coal-fired power plant is composed of a pulverizer, pulverized coal transport lines, burners, and furnace. Coal is usually transported to

Table 2. Operating conditions of water-steam system for dual mode

	Variables	Unit	Existing Air	Retrofitted Air	Retrofitted Oxy
	Fuel Type		Anthracite + Heavy oil	Sub-bituminous	Sub-bituminous
Boiler	Evaporation rate	tons/h	372	372	290
	Main steam P / T	MPa / K	12.9 / 814	12.9 / 814	12.9 / 814
	Reheat steam P / T	MPa / K	3.1 / 814	3.1 / 814	3.1 / 814
	Efficiency	%	83.4	88 (expected)	88 (expected)
Turbine	Generating Power	MWe	125	125	100
	Thermal efficiency	%	43.5	43.5	43.5
	Condenser pressure	kPa	5.1	5.1	5.1

the burner with primary oxidizer, and main oxidizer is supplied as secondary oxidizer, and tertiary air could augment the combustion.

One of the important concepts in oxy-firing is FGR. FGR has been used for conventional air-firing system, for example, to reduce NOx emission by lowering the peak flame temperature. In typical application of conventional air-firing system, flue gas up to 25% is extracted from the boiler outlet duct and is then returned through a separate duct and hot gas fan to the combustion air duct that feeds the wind box. The role of recirculated flue gas applied to oxy-firing system is the same as reducing the flame temperature. The flue gas which mainly consists of CO_2 and H_2O is supplemented to make flame temperature and heat transfer profile compatible to air-firing level. It has been reported that appropriate O_2/FGR ratio (vol.%) is at range of 70~75%[11-17].

The extraction location is one of the focuses. If the flue gas is recirculated at downstream of air preheater or ESP bearing relatively high temperature, it is called wet FGR. While wet FGR has advantages in minimizing boiler loss and the size of flue gas treatment devices, the combustion environment is likely to be corrosive due to highly concentrated SO_2 and SO_3. Wet FGR used as primary air would be partially condensed at cold surface of coal particles and agglomerate, and then the facilities can be clogged by agglomerate of mixture. Dry FGR is that the moisture in the flue gas is removed in the flue gas condenser(FGC) to saturation points, 30~40℃, and recycled to the combustor. Dry FGR has opposite attributes compared with wet FGR. Therefore, it is suggested that 20 w% of total FGR is dry FGR for primary oxidizer and remaining 80 w% is wet FGR for secondary and/or tertiary oxidizer. Fig. 3 represents a schematic diagram for calculation of O_2/FGR ratio.

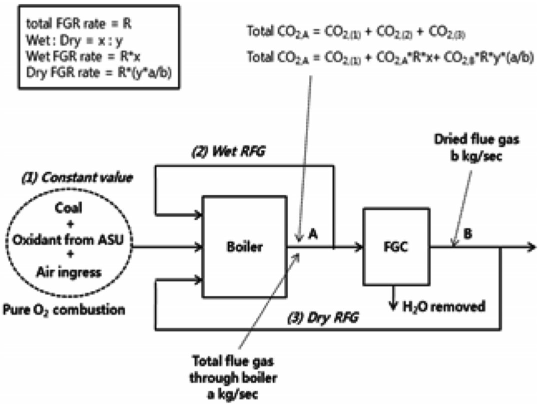

Fig. 3. Schematic diagram for O_2/FGR ratio.

3.2.2. Design concept for oxy-coal combustion characteristics

Investigation of combustion characteristics in oxy-firing mode and comparing them with those of air-firing mode is a crucial process for design and operation of an oxy-fuel boiler. Many researchers have reported that combustion characteristics in an oxy-firing mode can be significantly different compared with an air-firing mode because of the difference of gas properties(especially, heat capacity) between N_2 and CO_2[16,18-20]. The difference can affect the flame characteristics such as temperature, length, and heat fluxes to the wall of the boiler. In oxy-firing case, flame may not be able to maintain the well-attached condition and length of the flame is extended because of the ignition delay. Temperature of the flame can be decreased due to larger heat capacity of CO_2 than N_2. Oxygen lancing may become necessary for preventing the unnecessary ignition delay.

Important consideration for determining configuration of a unit burner is that the burner is for dual firing, which means that the burner design is based on a conventional PC burner. It is difficult to operate the dual mode with one burner type because combustion characteristics would effectively change as mentioned above. It is important that air-firing environment should be described in oxy-firing operation, because water-steam system is going to be reused. Lancing oxygen or controlling flow rate of oxidizer, and separate burners for an oxy-firing are being evaluated.

3.2.3. Burner and furnace design

For the burner and furnace design in oxy-firing mode, many results from fundamental combustion studies have been reported recently[16,18].

The first step is to define design parameters. Table 3 shows the items of the conceptual design for dual-firing system.

First parameter is oxygen concentration in the oxidizer, which is related to FGR ratio. That is related to the thermal matching in a radiative part of the boiler. Concentrations of CO_2 and H_2O are higher than other gas species in combustion gas, and gaseous radiation in oxy-firing mode may be stronger than in air-firing

Table 3. Items of the conceptual design for dual-firing system

Category	Items of the conceptual design	
	Dependent on thermal load (BMCR*, VWO**, NR***)	Independent on thermal load
Total combustion system	• Total heat input • Stoichiometric ratio	
Furnace	• Volumetric heat release rate • Heat release rate • Heat absorption rate	• Volume • Area Furnace projected area Exit area • Geometry(Dimensions and Angles)
Burner arrangement	Number of burners and pulverizers used for various thermal loads	• Firing method: Wall(Front, Opposite), Tangential, Arch • Vertical/Horizontal spacing • Number of levels • Number of burners for level
Unit burner	• Primary air/oxidizer Flow rate Temperature Composition for oxy-mode Oxygen, H_2O(related to dehumidification) • Secondary air/oxidizer Flow rate Temperature Composition for oxy-mode Oxygen, H_2O(related to dehumidification)	• Geometry Primary coal(+air/oxidizer) nozzle Secondary air/oxidizer Tertiary air/oxidizer Swirler(Number of vane, Angle, Location, Width., etc.) • Oxygen lancing for oxy-mode • Oxygen lancing • Flow rate of the pure oxygen • Number and diameter of the nozzles for lancing
Overfire air/oxygen	Stoichiometry in the fuel-rich zone and fuel-lean zone	
NOx control method	• Staging • Reburning	Stoichiometry in each stage

*Boiler Maximum Continuous Rating, **Valve Wide Open, ***Normal Rating

mode[18]. As a result, flame temperature in oxy-firing case is measured to be lower than in air-firing mode. Design coal is a sub-bituminous and it contains larger amount of volatile matter than anthracite. Therefore, prevention of firing in ducts for transporting the coal is a very important issue. Even if oxygen concentration in the oxidizer can be theoretically up to 21%, the oxygen concentration in the primary oxidizer is not to exceed 10%(wet base). In that case, however, flame can become seriously unstable due to the ignition delay[21].

Table 4. Number of pulverizers and burners in use, and load for a unit burner for various thermal loads

	BMCR	VWO	NR	75% NR	50% NR	30% NR
Number of pulverizers in use	3	3	3	2	2	1
Number of burners in use	12	12	12	8	8	4
Load for a unit burner (MWth)	31.9	31.9	28.6	32.6	22.7	29.5

A set of 8~16 burners are typically used for ~100 MW scale power boiler in air-firing conditions[22]. In that case, three pulverizers are required for the operation and another one is needed for stand-by. Table 4 represents the number of pulverizers and burners in use, and load for a unit burner for various thermal loads. Design has been performed for 6 cases(BMCR, VWO, NR, 75% NR, 50% NR, and 30% NR). For all cases, the number of burners in use is designed to be controlled to maintain thermal load of ~30 MWth for the unit burner.

Each swirl burner in wall firing system can be operated in dual mode when it is appropriately designed. However, some difficulties are expected for a T-firing combustion system in optimization for dual mode, because optimum operation condition for forming favorable fireball in the furnace is usually made at an operating point, not in a range. Therefore, a wall firing system is adopted for the demonstration in this project. Considering the scale of the current boiler, front firing concept is favored to the opposite firing arrangement. Meanwhile, T-firing operation in dual-firing is believed to be also possible, as seen through the combustion study in a T-firing furnace of 15 MWth scale[23].

Design of furnace configuration should be differently considered as heat transfer profile is varied in oxy-firing environment compared to air-firing environment. The dominating factor that affects the dimensioning of an oxy-coal fired furnace is higher radiative heat transfer due to the high concentrations of CO_2 and H_2O in the flue gas. For example, radiation intensity increases to approximately 25~30% at 67.3% FGR ratio[24]. It explicitly affects the thermal performance of the boiler.

There will be a drop in furnace exit gas temperature due to the difference in radiative heat transfer from CO_2 and H_2O. It is expected that residence time of gas is longer due to the density difference in oxy-firing. The higher CO_2 content increases the density of flue gas, which results in a longer gas residence time in the furnace(for matched furnace heat transfer, oxy-fuel has 20% longer furnace residence time). The convection pass typically contains the heating surface for the superheater, reheater, and economizer. When calculating the performance for the boiler convection pass, enough gas recycle is used to avoid changes to the heating surface. It is expected to be practical since the flue gas has a higher density so that gas velocities will actually be less than with air-firing.

The oxy-coal fired boiler with the same heat input has a furnace cross section slightly smaller compared to the air fired case while the height is larger and the total heat exchange surface is smaller. That means more compact design is possible because of less heat loss. Fig. 4 shows the different shape in existing Downshot-firing 125 MWe air-firing furnace and new 100 MWe oxy-firing furnace.

It is reported that, compared with an air fired furnace, an oxy fired furnace with a flue gas recycle flow rate of 56% requires only 65% of the surface area and 45% of the volume[25]. Oxy-coal combustion is adaptable to a new boiler or a retrofit of an existing boiler. The boiler modifications that are needed are the addition of a low pressure economizer, gas recirculation duct and fans, oxygen feeding duct, and dampers for oxygen and recirculation flow control.

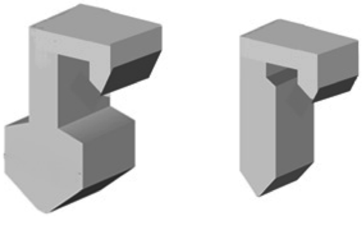
(a) (b)

Fig. 4. Furnace appearance (a) Existing Downshot-firing furnace for 125 MWe air-firing (b) New furnace for 100 MWe oxy-firing.

Such a high radiant heat flux about 85 kW/m^2(at 30% concentration of O_2 in the $CO_2 + O_2$ oxidizer), to the wall for oxy-firing case, could very likely cause severe slagging problems in the furnace[26]. Due to the high content of CO_2 in the flue gas, a change in deposit chemistry is assumed, and the formation of carbonates in the deposit could be possible. As carbonate deposits are very corrosive, the metal wastage rate could increase[27]. In oxy-fuel combustion, the slagging grade increases with decreasing flue gas recirculation volume flow with increasing oxygen content.

In the oxy-firing mode, it is expected that requirement of NOx emission can be met by employing the existing technology; low-NOx burner technology, staging, reburning, selective non-catalytic reactor(SNCR) and FGR, even if regulation of NOx concentration in CO_2 to be sequestrated has not been fixed yet. However, NOx emission can be important in air-firing mode because the boiler to be designed should be operated in both air-firing and oxy-firing mode.

3.3. Flue gas control system

3.3.1. Different strategy

Dual mode system is required to satisfy the current flue gas emission standards(SO_2 80 ppm, NO_2 80 ppm, and dust 30 mg/Sm^3). Because emission characteristics in oxy-firing combustion are different from those in the conventional air-firing combustion[28,29], different strategies for cleaning flue gas are to be applied to air-firing and oxy-firing modes. Fig. 5 indicates flue gas control process in dual mode. Emissions from the air-firing mode are generally controlled with proven technology; the low NOx burner or staging combustion with SNCR for DeNOx, dry(or hot) ESP for collecting dust,

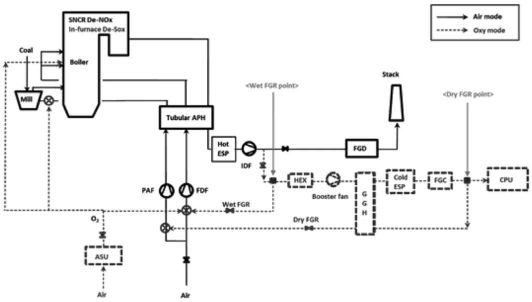

Fig. 5. Flue gas control process in dual mode.

and wet FGD system for DeSOx. Then, flue gas is emitted to the atmosphere through a stack. Existing wet FGD facilities with desulfurizing efficiency of 85% will be reused and existing ESP with particulate control level less than 20 mg/Sm^3 is also going to be reused.

In oxy-firing system, flue gas passes through in-furnace dry DeSOx and hot ESP. In-furnace DeSOx is selected considering its improved efficiency in oxy-firing. Even though the conversion of coal-S to SO_2 in oxy-firing mode is lowered, the SO_2 is enriched because of flue gas recirculated. Further, longer residence time and inhibition of decomposition of $CaSO_4$ are favorable to in-furnace DeSOx. The injection location of lime stone and grid system for injection will be considered. Particulate will be captured by hybrid hot and cold ESP systems. To prevent damage of flue gas compressors in CPU, the dust should be removed to the lowest level. Wet(or cold) ESP system has merit of removing fine particulate to sub-micron level as well as acid gases and mercury. In operating dual mode, hot ESP is shared, which is run at different operating temperature and flue gas of oxy-firing mode is introduced into cold ESP once again. There is no NOx control device for oxy-firing mode. NOx reduction to one fourth of that in air-firing is achievable in oxy-fuel combustion because of decrease in conversion of fuel-N and increase reduction of NO to N_2[28]. The benefits of NOx reduction in oxy-firing is accepted in the project.

3.3.2. Heat recovery and flue gas condensing

In flue gas system in oxy-firing mode, additional units for heat recovery and flue gas condensing are considered[30]. The flue gas flowing out the air preheater has relatively higher temperature in oxy-firing than air-firing, because the heat which is required to increase the temperature of N_2 in air-firing is not necessary. It is related to heat integration of the system and thereby there is opportunity for increase of the boiler efficiency. Recovered heat can be used for heating feed water in steam cycle instead of extraction of steam from the LP turbine, and for drying coal in fuel feeding system. The recovered heat will be useful to generate electricity.

Flue gas should be cooled to near room temperature in FGC to satisfy input condition of CO_2 introduced into CPU. As the flue gas is condensed, part of the flue gas is used to dry FGR and the others are introduced into CPU. Flue gas is cooled by direct contact water and moisture in flue gas is condensed until moisture concentration reaches saturation point at designed temperature. Therefore, latent heat of condensing water is significant. Even though a relatively small amount of heat is recovered in the condensing process, performance of the heat exchanger and economic feasibility should be comprehensively considered.

3.3.3. Effect of change of flue gas properties on duct and fan systems

As dominant gas species is changed from N_2 to CO_2, the flue gas density increases. Change of flue gas properties induces change of volume flow rate and velocity. The difference of pressure drop is also expected because the flue gas of each mode experiences the distinct train of flue gas system. Besides, different operating temperatures for both modes influence the volume flow rate and pressure drop. Although current IDF is typically designed to operate at about 150℃, for example, the IDF may have to treat the volume flow rate at around 250℃ in oxy-firing mode. Accordingly, if the same balanced draft system is used, fans have to satisfy the different volume flow and pressure increase for each mode. It should be interpreted whether it is possible to handle the change of combustion mode with fan flow control or not. Fig. 6 represents the pressure draft curve in dual mode. (O) and (A) apply

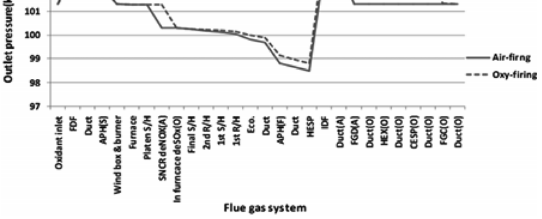

Fig. 6. Pressure draft curve in dual mode.

only to oxy-firing mode and air-firing mode, respectively.

Comparing to pressure draft in the convective pass, pressure loss in oxy-firing mode is lower than air-firing mode through SNCR DeNOx and in-furnace DeSOx systems because of lower gas volume flow rate in oxy-firing mode. The flue gas at the outlet of air preheater has similar gas volume because the flue gas in oxy-firing mode leaves at higher temperature than air-firing mode. The volume flow rate and pressure between two modes are different in FDF and IDF. Because fan has its own characteristics curves which represents static pressure and power consumption as a function of volume flow rate, several cases on fan locations and installation separate fan for each mode can be considered. Some alternatives using variable speed control, inlet damper control, and outlet damper control are being discussed[30].

3.4. ASU, Oxygen plant

Oxygen has been used in many industrial processes. There are three main methods to air separation commercially available; cryogenic separation, adsorption separation using the pressure swing adsorption(PSA), or membrane separation[31-34]. Cryogenic separation is considered to be practical for ASU in oxy-coal combustion systems because of high efficiency, production in large quantity, and production of high purity. In addition, it can extract gas species in liquid form, which is more convenient for transportation and storage as back-up for flexible combustion mode.

For a 100 MWe oxy-coal power generation, capacity producing oxygen, 1,914 tons/day, is theoretically calculated in accordance with air flow rate introduced into FDF(380,500 kg/h × 0.2096). Surplus capacity for backup, 2,000 tons/day (60,000 Nm^3/h) capacity was proposed[35]. For comparison with reference cases, Table 5 represents the capacity of power generation and ASU in representative oxy-fuel projects.

Table 5. Capacity of ASU in reference oxy-fuel projects

	Schwartz Pumpe (Vattenfall)	Callide (CS Energy)	Youngdong (KOSEP)
Power generation (MWe)	10	30	100
ASU capacity (tons/day)	240	660	2,000
Oxygen purity (%)	95	95	95

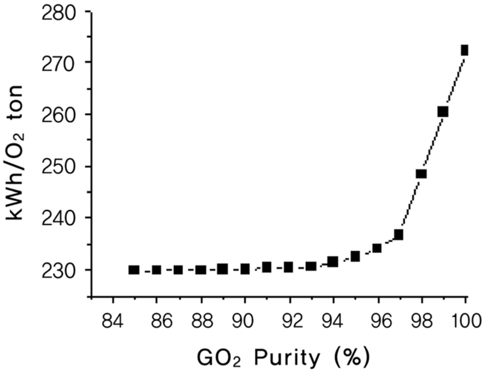

Fig. 7. Power consumption on O_2 purity[35].

In oxy-coal power plant, oxygen is used as oxidizer for coal combustion. Produced oxygen for combustion has relatively low purity such as 90~98%, whereas purity 99.5% or higher is required in usual process. Power consumption in ASU is strongly related with oxygen purity. As the purity of produced oxygen increases, air flow rate and compressor power increases, respectively.

Fig. 7 shows power consumption according to purity of oxygen produced (kWh/ton O_2) in ASU. This is evaluated with consideration of GO_2(gaseous oxygen) production (Nm^3/h), GO_2 purity produced (%), oxygen density (ton/m^3), and compressor power consumed (kW). Power cost increases rapidly at purity 97.5%, because purity 97.5% is crossover point of O_2-N_2 and O_2-Ar separation, which means O_2-Ar separation is more difficult than O_2-N_2[8]. Appropriate range of O_2 purity is related to power consumption, effect on combustible stability, and power consumption to compress flue gas at CPU. In this study, O_2 purity 95% is proposed to be the most efficient in view of the efficiency of the overall power cycle through process analysis as shown in Table 5.

Required power for ASU is one of the issues for design of ASU, a major power consumer in the plant, which is dependent on oxygen recovery ratio and main air compressor. Discharge pressure is mainly dependent on pressure drop at LP column and main condenser Δ T. Researches have focused on reducing power consumption in the rectification process, such as using tray to packing(pressure drop at LP column) and reducing the effect of the LO_2(Liquid O_2) head using multiple main condensers with low height[33].

Air separation by rectification is based on air liquefaction principle. The systems are classified according to type of rectification column, such as double column cycle(DC), side column cycle(SC), and heat integrated distillation column(HIDIC). In this conceptual design of the project, DC and SC cycles have been carefully evaluated, while HIDIC is excluded from the early stage because of its immaturity in technology[35]. Oxygen of variable purity, nitrogen, and argon are produced in DC, whereas only oxygen of purity 95% is produced in SC. SC approximately spends 10% less power than that of the DC, because compressors in the SC were optimized to produce oxygen of purity 95%. However, it has higher investment costs than those of the DC. Low operating pressure of the SC makes a plumbing system larger, which leads to higher costs. It needs additional units such as a warm part unit and another column. Warm part unit means a pre-purification unit of air to remove the carbon dioxide and moisture. As a result of assessment of the ASU process for 100 MWe oxy-coal power plant[35], SC is the best unit in terms of power consumption. However, DC type producing GO_2 of purity 95% was selected with consideration of both investment costs and stability. Table 6 indicates cases considered for evaluation and Fig. 8 shows a schematic diagram of proposed ASU system based on DC.

Table 6. Case study for ASU design

	Case 1	Case 2-1	Case 2-2	Case 3
Column type	Double	Double	Double	Side
GO_2 production (%)	99.5	95	95	95
Main air compressor	1	1	2	2
Warm part	1 set	1 set	2 sets	2 sets

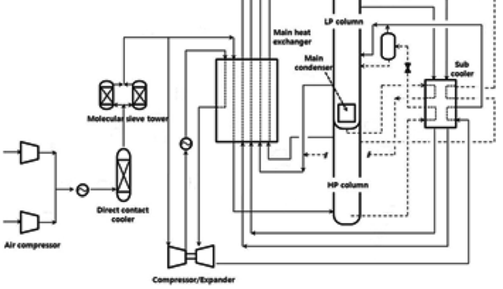

Fig. 8. Schematic diagram of proposed ASU.

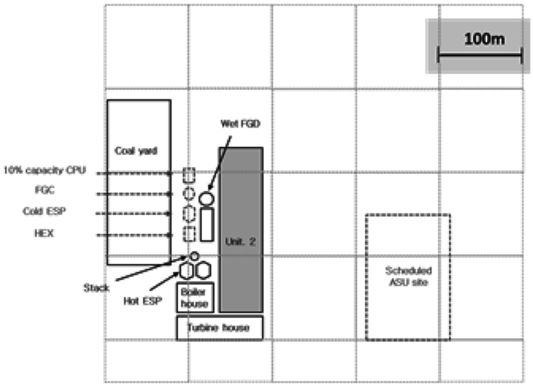

Fig. 9. Layout and site requirement of ASU.

ASU of 2,000 tons/day capacity occupies sufficiently large area more than 10,000 m^2. Fig. 9 shows layout of Youngdong power plant and a proposed site to build the ASU. ASU will occupy the biggest footprint in the overall system. The units that occupy the largest area are air compressors and storage tanks, so the required area is variable according to the quantity of liquid oxygen for storage. For instance, about 1,000 m^2 area per a compressor is required based on 50,000 Nm^3/h scale. Additional units, such as roads, support, and piping lines, occupy most of the area. If the site on which the ASU is to be built is limited, the scale of the facilities needs to be reduced. The cold-box and tanks can be separated and built, or height of the units can be controlled. After the ASU is demonstrated in oxy-coal project, it may be difficult to manage and maintain the ASU for operation. If the ASU does not operate continuously after oxy-coal combustion and carbon capture technologies are verified, it can be treated with other purpose[35].

3.5. CPU, CO_2 capture

Currently available technologies for CO_2 capture include amine absorption, membrane separation, or cryogenic separation. Amine absorption is based on a classical amine loop technology using monoethanolamine (MEA) as a sorbent. Amine absorption has been used to capture 90%(mole basis) of the CO_2 at the power plant for post-combustion[36]. Cryogenic separation is a similar approach to technology in ASU process. Gas including high concentration of CO_2 is compressed and separated. It was commercialized and proposed for CO_2 capture in oxy-coal power plant to readily capture and compress CO_2 for pipeline transportation and storage.

It is expected that the quantity of flue gas to be pro-

Table 7. Case study proposed for CO_2 recovery

	Case A	Case B
CO_2 phase	Compressed gaseous CO_2	Liquefied CO_2
CO_2 purity (%)	97.5	99.5
CO_2 recovery (%)	93.2	88.5
Power cost (kWh/CO_2 ton)	143	161

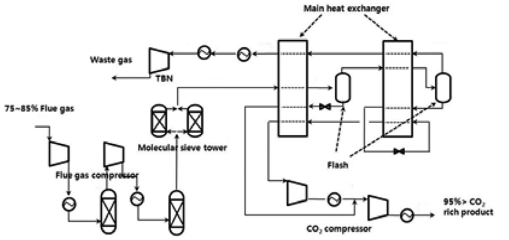

Fig. 10. Schematic diagram of proposed CPU.

cessed is 55,000 Nm^3/h in 100 MWe oxy-coal power generation system. The flue gas from the boiler will contain generally up to approximately 80% by CO_2 vol.%(on dry basis). In the present, the CO_2 purity required for sequestration is generally more than 95% and recovery more than 90% for the CPU design[37].

As a result of assessment of the CPU process for 100 MWe oxy-coal power plant[35], two possible cases are being considered depending on the phase of produced CO_2. Table 7 represents two cases proposed for CO_2 recovery. In view of the power cost and CO_2 recovery, case A looks appropriate, but case B can be considered in view of the easy storage and transport of liquefied CO_2. Fig. 10 shows a schematic diagram of proposed CPU system. Flue gas at 40℃ and 1 bar conditions enters the CPU, flue gas compression, separation of SOx and NOx, and dryer. Dried flue gas is separated into CO_2 and inert gas in a cold-box using cryogenic separation.

Full capacity operation of CPU for CO_2 capture in the demo plants based on oxy-coal combustion is not being considered e.g., Vattenall or CS Energy[38,39]. In the Callide project, for reference, 12 vol.% of the total flue gas (18,000 Nm^3/h) is being introduced into the CPU and, in the Schwartz Pumpe project, 60 vol.% of the total flue gas (6,600 Nm^3/h) is being introduced into the CPU. In the current conceptual design of the Youngdong project, partial CO_2 capture is also being considered, such as 10 vol.% of the total flue gas (55,000 Nm^3/h). That is because CCS technology has been not prepared to support the oxy-firing combustion, such as appropriate storage geometry, economic assessment of CO_2 transport, and technology for injection or monitoring. Since conceptual design proposal of CPU is naturally connected to transport and storage of CO_2, it should be considered with various CO_2 flow rates and distances corresponding to conceptual storage sites[39]. Although all gaseous CO_2 can be captured, they can be emitted again to the atmosphere. It means that it can show the possibility for CO_2 capture as demonstrated concept.

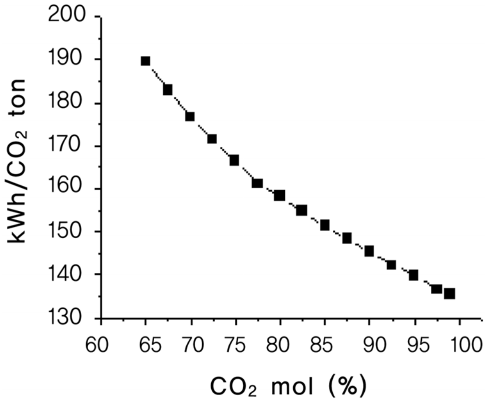

Fig. 11. Power consumption of CO_2 purity[35].

As CO_2 purity of flue gas is high, power cost become low. Fig. 11 shows relative power consumption for the CO_2 processing system as a function of CO_2 purity. It is evaluated with consideration of CO_2 production (Nm^3/h), CO_2 purity produced (%), carbon dioxide density (ton/m^3), flue gas compressor power consumed (kW), CO_2 compressor power consumed (kW), and flue gas expander power generated (kW). Variables in power costs are excess oxygen, air leak in the boiler, and oxygen purity in ASU. As excess oxygen and air leak are much, power consumption of CPU is higher. Provided that oxygen of high purity is introduced into the boiler, power consumption for the CPU will be low. The variables are closely related to performance of each unit and overall plant. The premise of oxy-coal combustion to obtain flue gas that contains only CO_2 and water vapor so that pure CO_2 can be obtained by condensing. Due to excess oxygen required for combustion and air leak into the boiler, the flue gas will contain significant amount of inerts. The stream contains impurities comprising of small amounts of SOx and NOx. Because impurities affect water solubility and consequently corrosion, it should be considered[40].

4. Conclusion and prospect for the future

Conceptual design for the Youngdong oxy-fuel project was presented for demonstration of 100 MWe oxy-coal power plant. Considerations for conceptual design of the major systems, such as water-steam, combustion, flue gas control, air separation, and CO_2 processing systems, were discussed to provide the design parameters for the proposed oxy-coal technology demonstration with the background to promote the project.

The various development stages from planning to implementation of the demonstration plant for CO_2 capture are in progress. In this project, a demonstration plant of air/oxy-coal combustion will be completed by the end of 2015 and it is finally expected to be carried out for 2016~2018. For stable operation, reducing cost, and enhancing efficiency of a CCS based power generation system, sustainable research is necessary with the efforts toward commercialization.

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The Korean oxy-coal project has moved further since this paper was written. Some of the project details, therefore, have changed accordingly. Readers who are interested in the final details of engineering designs should be careful and are requested to check the current status.

Reference

[1] Winkler H., Brouns B., and Kartha S., “Future mitigation commitments: differentiating among non-Annex I countries”, Climate Policy, Vol. 5, 2006, pp. 469-489.

[2] Pennell, N., Fowler, R., Fayad, W., and Sayed, T. E., “Climate change after the Kyoto protocol, A new architecture for global policy”, Booz and Company Inc., 2009.

[3] Gwak, D., “Green growth: a Korean version of sustainable development”, KIET Industrial Economic Review, Vol. 14, No. 2, 2009.

[4] Cory, K., Couture, T., and Kreycik, C., “Feed-in tariff policy: Design, implementation, and RPS policy interactions”, National Renewable Energy Laboratory, Technical report, NREL/TP-6A-45549, 2009.

[5] Revelle, E., “Cap-and-trade versus carbon tax; Two approaches to curbing greenhouse gas emissions”, League of women voters of the United States: Climate change task force, 2009.

[6] Spero, C., “Callide oxyfuel Project-Status and development”, Proceedings of the 1st oxyfuel combustion conference, 2009, Cottbus, Germany.

[7] Strömberg, L., Lindgren, G., Jacoby, J., Giering, R., Anheden, M., Burchhardt, U., Altmann, H., Kluger, F., and Stamatelopoulos, G., “First test results from Vattenfall’s 30 MWth oxyfuel pilot plant in Schwartz Pumpe”, Proceedings of the 34th Int. technical conference on clean coal and fuel systems, 2009, Clearwater, FL, USA.

[8] Irons, R., Sekkapan, G., Panesar, R., Gibbins, J., and Lucquiaud, M., “CO_2 capture ready plants”, Technical report of IEA Greenhouse gas R&D programme, Report number: 2007/4, 2007.

[9] Oskarsson, K., Berglund, A., Deling, R., Stenack, O., and Fritz, J., “A planner’s guide for selecting clean-coal technologies for power plants”, The world bank, Washington D. C., 1997, Chapter 3, pp. 17-40.

[10] Lee, K., Kim, S., Choi, S., and Kim, T., "Performance evaluation of an oxy-coal-fired power plant", Journal of Thermal Science and Technology, Vol. 4, No. 3, 2009, pp. 400-407.

[11] Arias, B., Pevida, C., Rubiera, F., and Pis, J., "Effect of biomass blending on coal ignition and burnout during oxy-fuel combustion", Fuel, Vol. 87, No. 12, 2008, pp. 2753-2759.

[12] Bejarano, P. and Levendis, Y., "Combustion of coal chars in oxygen-enriched atmospheres", Combustion Science and Technology, Vol. 179, No. 8, 2007, pp. 1569-1587.

[13] Naredi, P. and Pisupati, S., "Comparison of char structural and reactivity parameters for air-coal and O_2/CO_2 coal combustion", Proceedings of the Int. conference on coal science and technology, 2007, Nottingham, UK.

[14] Scheffknecht, G. and Maier, J., "Firing issues related to the oxyfuel process", VGB PowerTech, Vol. 88, No. 11, 2008, pp. 91-97.

[15] Rathnam, R., Elliott, L., Wall, T., Liu, Y., and Moghtaderi, B., "Difference in reactivity of pulverized coal in air(O_2/N_2) and oxy-fuel(O_2/CO_2) conditions", Fuel Processing Technology, Vol. 90, No. 6, 2009, pp. 797-802.

[16] Khare, S., Wall, T., Gupta, R., Elliott, L., and Buhre, B., "Retrofitting of air-fired PF plant to oxy-fuel: heat transfer impacts for the furnace and convective pass, and associated oxygen production requirements", Proceedings of the 5th Asia-Pacific conference on combustion, 2005, Adelaide, Australia.

[17] Uchida, T., Yamada, T., Hashimoto, K., and Watanabe, S., "Recent test results on oxy-fuel combustion using the pilot scale test facilities", 3rd meeting of the oxy-combustion network, 2008, Yokohama, Japan.

[18] Buhre, B., Elliott, L., Sheng, C., Gupta, R., and Wall, T., "Oxy-fuel combustion technology for coal-fired power generation", Progress in Energy and Combustion Science, Vol. 31, 2005, pp. 283-307.

[19] Andersson, K. and Johnsson, F., "Flame and radiation characteristics of gas-fired O_2/CO_2 combustion", Fuel, Vol. 86, 2007, pp. 656-668.

[20] Hjärtstam, S., Andersson, K., Johnsson, F., and Leckner, B., "Combustion characteristics of lignite-fired oxy-fuel flames", Fuel, Vol. 88, 2009, pp. 2216-2224.

[21] Choi, C., Chae, T., and Yang, W., "Considerations on design with combustion system of oxy-pulverized coal power plants", Proceedings of the 40th Korean society of combustion symposium, 2010, Mokpo, Korea.

[22] Basu, P., Kefa, C., and Jestin, L., "Boilers and burners: design and theory", Springer, New York, 2000.

[23] Levasseur, A., Chapman, P., Nsakala, N., and Kluger, F., "Alstom's oxy-firing technology development and demonstration-Near term CO_2 solutions", Proceedings of the 34th Int. technical conference on clean coal and fuel systems, 2009, Clearwater, FL, USA.

[24] Kakaras, E., Koumanakos, A., Doukelis, A., Giannakopoulos, D., and Vorrias, I., "Oxyfuel boiler design in a lignite-fired power plant", Fuel, Vol. 86, No. 14, 2007, pp. 2144-2150.

[25] Seltzer, A. and Fan, Z., "Design of a Flexi-Burn-TM pulverized coal power plant for carbon dioxide and sequestration", Proceedings of the 34th Int. technical conference on clean coal and fuel systems, 2009, Clearwater, FL, USA.

[26] Chae, T., Yu, T., Bang, B., Kim, S., and Yang, W., "A numerical study on characteristics of oxy-pulverized coal combustion in a corner-firing boiler of 125 MWth scale", Proceedings of the 34th Int. technical conference on clean coal and fuel systems, 2009, Clearwater, FL, USA.

[27] Bordenet, B., "Influence of novel cycle concepts on the high temperature corrosion of power plants", Materials and Corrosion, Vol. 59, No. 5, 2008, pp. 361-366.

[28] Liu, H. and Okazaki, K., "Simultaneous easy CO_2 recovery and drastic reduction of SOx and NOx in O_2/CO_2 coal combustion with heat recirculation", Fuel, Vol. 82, 2003, pp. 1427-1436.

[29] Liu, H., Zailani, R., and Gibbs, B., "Pulverized coal combustion in air and in O_2/CO_2 mixtures with NOx recycle", Fuel, Vol. 84, 2005, pp. 2109-2115.

[30] Kim, S., Ahn, H., Choi, S., Kim, Y., Kim, T., and Seo, S., "Flue gas system for an air-oxy dual firing power plant", Proceedings of the 40th Korean society of combustion symposium, 2010, Mokpo, Korea.

[31] Ahari, J., Pakseresht, S., Mahdyarfar, M., Shokri, S., Zamani, Y., Nakhaei, A., and Naderi, F., "Pre-

dictive dynamic model of air separation by pressure swing adsorption", Chemical Engineering and Technology, Vol. 29, 2006, pp. 50-58.

[32] Mun, H., Park, D., and Son, M., "Air separation technology and future", Chemical Industry and Technology, Vol. 15, 1997, pp. 211-217.

[33] Smith, A. and Klosek, J., "A review of air separation technologies and their integration with energy conversion processes", Fuel Processing Technology, Vol. 70, 2001, pp. 115-134.

[34] Yong, P., Mun, H., and Yi, S., "Exergy analysis of cryogenic air separation process for generating nitrogen", Journal of Industrial and Engineering Chemistry, Vol. 8, 2002, pp. 499-505.

[35] Lee, H., Choi, S., Mun, H., Choi, H., Park, W., and Seo, S., "Design considerations for ASU and CPU in 100 MWe oxy-coal power generation", Proceedings of the 8th Asia-Pacific conference on combustion, 2010, Hyderabad, India.

[36] Bouillon, P., Hennes, S., and Mahieux, C., "Post-combustion or oxyfuel-A comparison between coal power plants with integrated CO_2 capture", Energy Procedia, Vol. 1, 2009, pp. 4015-4022.

[37] Zanganeh, K., Shafeen, A., and Salvador, C., "On the performance of an advanced pilot-scale CO_2 capture and compression unit(CO_2CCU)", Proceedings of the 1st oxyfuel combustion conference, 2009, Cottbus, Germany.

[38] Wall, T. and Yu, J., "Coal-fired oxyfuel technology status and progress to deployment", Proceedings of the 34th Int. technical conference on clean coal and fuel systems, 2009, Clearwater, FL, USA.

[39] Yamada, T., Tamura, M., Fujimori, T., and Misawa, N., "Test results of oxy-fuel combustion and oultline of demonstration project in Australia", Proceedings of the Int. conference on power engineering, 2007, Hangzhou, China.

[40] Davidson, R. and Santos, S., "Oxyfuel combustion of pulverised coal", IEA clean coal centre, 2010.

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