Oxy Combustion of Coal - Needs, Opportunities, and Challenges

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Results of basic study on Oxy-fuel Combustion System for CO_2 Capture

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1. Introduction

One of the main topics at Hokkaido Toyako summit held in Japan, July, 2008, was "Environment and Climate Change". As the long-tern Goal, the G8 leaders agreed to seek to share and adopt it with all Parties to the United Nations Framework Convention on Climate Change, with respect to the goal of achieving at least 50% reduction of global emissions by 2050. Concerning the global warming, Kyoto Protocol entered into force in February 2005, and the intension of Japanese government towards a low-carbon society, that means CO_2 emission reduction of 60 – 80 % as compared with the present amount of CO_2 emission by 2050, was expressed in the Fukuda vision. From a global viewpoint, however, thermal power plants are still releasing CO_2 in large quantity at present, which indicates the necessity for a power generation system with Carbon Dioxide Capture and Storage (CCS) in more effective and economical manner.

Among all the fossil fuels used at thermal power plants, coal produces the greatest amount of CO_2 per unit calorific value. Thus, emissions from power plants using coal seem to be one of the significant sources in capturing CO_2 effectively.

Recently many CO_2 capturing process are under development. They are generally divided into three types. Oxy-fuel combustion is one of the types. The others are pre-combustion and post-combustion. The comparison between the three types and the outline of oxy-fuel combustion system are shown in the next section.

After that some basic study results toward realization of oxy-fuel combustion system are introduced and then the progress report of the oxy-fuel demonstration project, the Callide Oxyfuel Project, is also introduced.

2. Outline of the oxy-fuel combustion system

In the flue gas of typical coal fired power plant CO_2 concentration is only about 13%. The main ingredient of the flue gas is nitrogen. This nitrogen originates in combustion air which has about 80% of nitrogen. Removing nitrogen from combustion air makes the flue gas composition theoretically no nitrogen and over 90 percents of CO_2 [1][2]. This higher CO_2 flue gas makes it possible to easily separate CO_2 from other gas components with compression and cooling. This is a concept of oxy-fuel combustion.

As mentioned above, there are other types of CO_2 capturing system. Fig. 1 shows three types of CO2 capturing system. First, numbering (1), is oxy-fuel combustion system. Second, numbering (2), is an example of pre-combustion type applied to coal gasification system. Third, numbering (3), is an example of post-combustion type applied to a conventional boiler system. The second type and the third type are CO_2 capturing system from fuel gas or flue gas containing CO_2. CO_2 is captured with some method such as chemical absorption, physical absorption, adsorption, or membrane permeation. These two types are based on the similar mechanism. As compared with them oxy-fuel combustion system is based on the different mechanism.

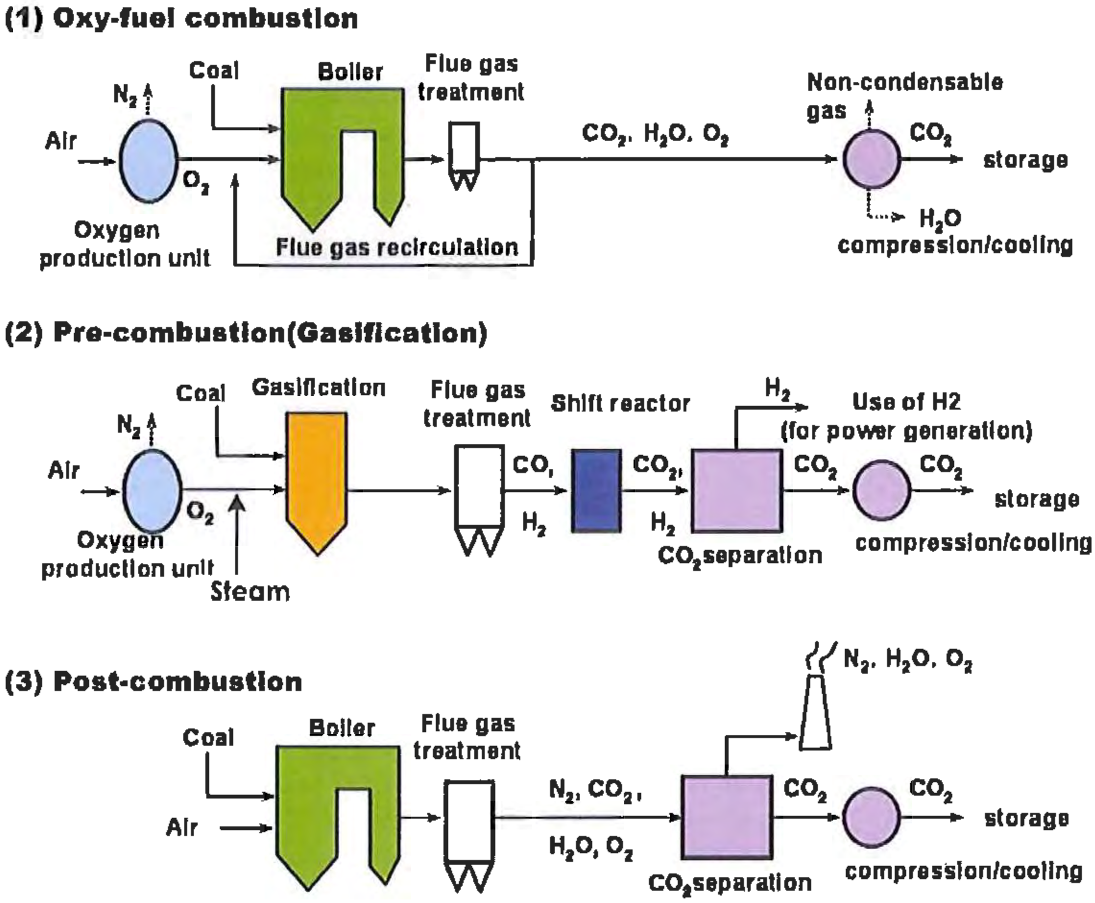


Fig. 1 Typical CO_2 Capturing systems

3. System flow and the subjects to be solved

In the actual oxy-fuel combustion system oxygen is diluted with recycled flue gas because of controlling combustion temperature. Fig. 2 shows simplified oxy-fuel combustion system flow on Callide Oxyfuel Project. Oxygen is separated from air and supplied toward boiler. Oxygen is mixed with recycled flue gas on the way of the boiler combustor inlet, marking as "Mixing point".

Boiler outlet flue gas is filtered with the fabric filter, marking as "FF" in fig. 2. The greater part of flue gas is recycled to the air heater, marking as "AH" in fig. 2. Then the recycled flue gas is heated up, mixed with oxygen, and supplied to the burners. A part of flue gas is conducted with the CO_2 purification unit, marking as "CPU", in fig. 2, and sent to storage system. In the air combustion mode, for example in startup and shutdown operation, flue gas is not recycled and air from atmosphere, marking "Air" in fig. 2, is used for combustion gas.

The fly ash passed through the filter comes to the air heater, marking as "AH" with recycled flue gas. Then the fly ash accumulates at the horizontal duct at the outlet of air heater. Here is the oxygen mixing point and accumulated fly ash is contacted with high concentration oxygen. Generally fly ash from coal combustion system includes several percents of carbon on weight. There is some risk as possibility of ignition of fly ash at the high temperature and high oxygen concentration.

Concerned with oxygen mixing there is another risk. Oxygen and recycled flue gas are mixed in the flow during the mixing point and burner inlet. In order to control all the burner of boiler furnace stably oxygen concentration has to be uniform at the inlet of burner wind box. In the limited area during the mixing point and burner wind box optimization of flow pattern is needed for good mixing of oxygen and recycled flue gas.

Mentioned above there are many subjects toward the realization of oxy-fuel combustion system. We will solve these subjects step by step.

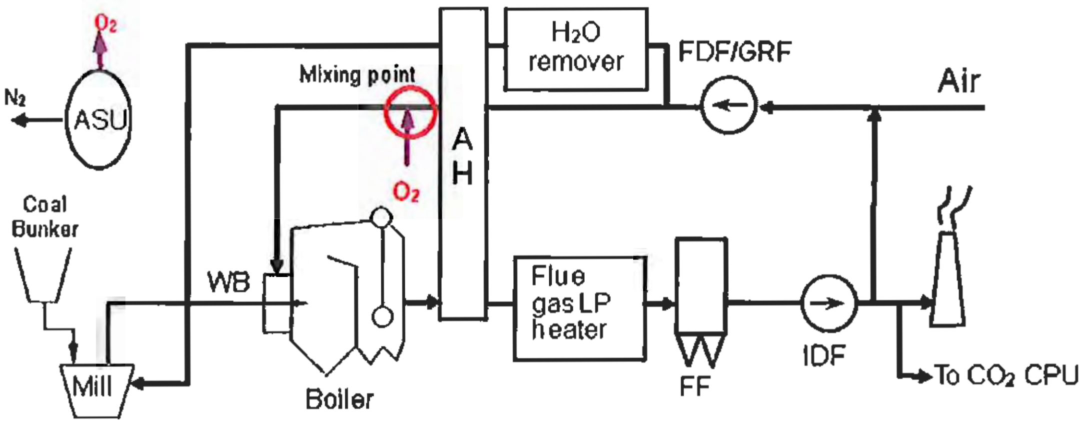


Fig. 2 Oxy-fuel combustion system flow on Callide Oxyfuel Project

4. Results of basic study towards the realization of oxy-fuel combustion technology

As mentioned above, there are some subjects on handling of pure oxygen. Oxygen is mixed with recycled flue gas to control oxygen concentration in the combustion gas. This operation is very important to keep combustion condition steady and safe. The mixing operation is carried out by a simple line mixing because of making the pressure drop at the flue gas recycle line minimize. Pure oxygen is put into the flue gas recycle duct with an injection nozzle therefore near by the injection nozzle oxygen concentration is locally very high. When the recycling flue gas flow is not uniform, there is every possibility of oxygen accumulation at the local area. Accumulation of oxygen is very hazardous, but that does not always lead to failure. It is necessary to confirm the safety condition on flammability of fly ash and material of duct. And it is also necessary to study the mixing performance. In this paper some basic study results are introduced. The first is behaviour of fly ash in the high oxygen condition, and the second is the results of gas mixing simulations. In addition to the previous two items, the test results on performance of flame detector that is a important sensor to control the combustion condition.

4.1 Behaviour of fly ash in the high oxygen concentration atmosphere

In this section we introduce the test results which are concerned with behaviour of fly ash under high oxygen concentration and high temperature. The tests were carried out using the small tube reactor with electric heater. System configuration of test apparatus is shown in Fig. 3. In the test, O_2 concentration in the supply gas to the furnace is controlled by the mass flow meter for O_2 and N_2 gas, and N_2 is used as the balanced gas in the test. Gas temperatures around the sample cell are monitored and gas temperature is increased controlling the rate of 3 degree C per a minute up to the setting temperature. Carbon content in the sample based on fly ash is adjusted by mixing the activated carbon and is set in the cell which is approximately $1cm^3$. In the gold furnace, supply gas is heated at the lower section of the furnace filled with the ceramic balls by electrical heater.

Pattern diagrams of the test results are summarized in Fig. 4. Test results show the characteristics of ignition and weight loss depending on the O_2 concentration and carbon content in the sample and are classified into 3 types of results. First is the area of ignition in the left diagram of Fig. 4. This means that the temperature of the sample is rapidly increased at red heat at a certain temperature. Second is the area of no ignition with weight loss shown in the both diagram of Fig. 4. Temperature increasing was not detected however weight loss is measured after the test. This is because the carbon content in the sample was oxidized in the high temperature. Third is the un-reacted area shown in the right diagram of Fig. 4. Temperature increase was not detected and weight loss was not measured.

From now, many tests would be performed to evaluate the safety condition during mixing of O_2 with recycled flue gas. From these results, we can review the safety atmosphere and select the appropriate mixing point with O_2.

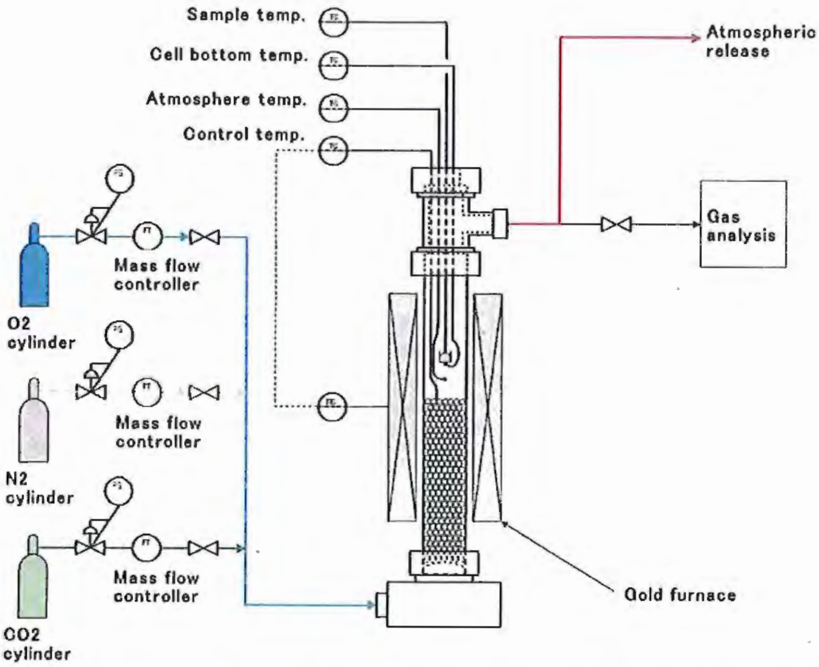


Fig.3 System configuration of confirmation test of the behaviour of fly ash under the high temperature and high O_2 concentration atmosphere

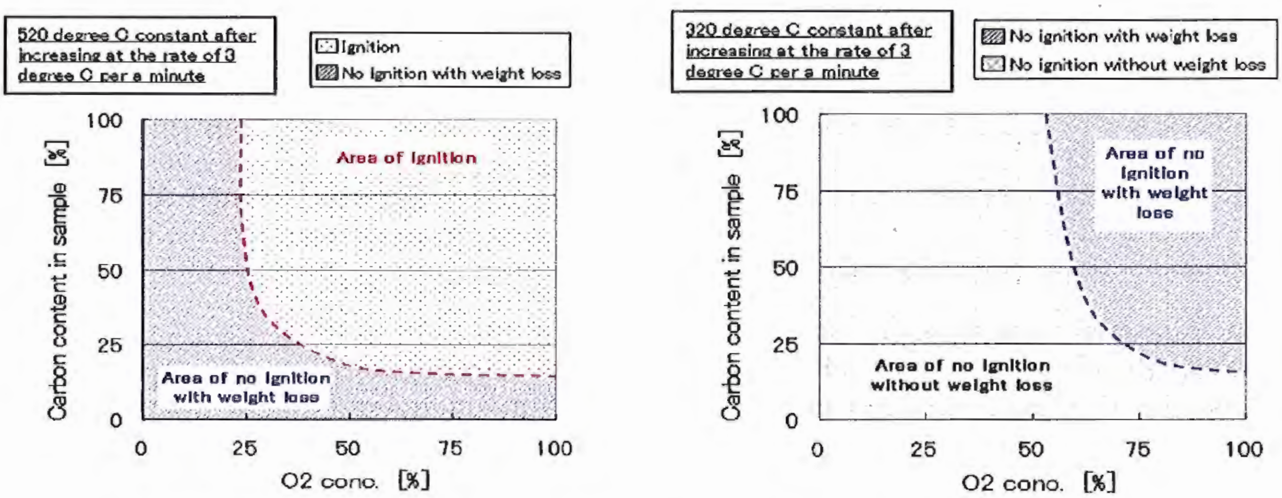


Fig. 4 Pattern diagrams of the behaviour of fly ash under high temperature and high O_2 concentration atmosphere

4.2 Mixing of O_2 with recycled flue gas

In the oxy-fuel combustion system, oxygen is mixed with recycled flue gas in order to keep the flame temperature before the combustion in the furnace. In the normal oxy-fuel process, oxygen is mixed with recycled flue gas at the outlet of air-heater which is upstream of burner wind-box with considering of avoidance the oxygen leakage at the air-heater. This means that mixing area is only duct to the burner after the mixing point. If there is the higher distribution gradient of O_2 concentration at the burner wind-box, flame temperature and combustion characteristics are different among the burners. This higher distribution gradient like this should be avoided in order to maintain the safety condition and the stable operation of the boiler. In addition, considering the lifetime and the safety for the duct, the O_2 concentration with higher temperature region should be as low as possible on the duct wall, as described in section 4.1. Therefore, mixing simulation study was performed to confirm the distribution gradient of O_2 concentration at the burner inlet.

Temperature of recycled flue gas and O_2 are approximately 300 degree C and normal temperature for each. Flow rate of O_2 is a quarter of flow rate of recycled flue gas.

Fig. 5 shows the mesh structure of the model that has 600,000 points from the air-heater to burner inlet (wind-box). STAR-CD is used as the program for thermo-fluid analysis in this study.

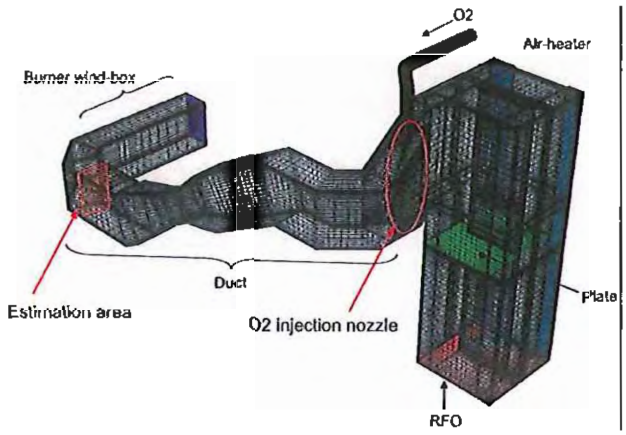


Fig. 5 Simulation model

Results of 2 types of the O_2 injection nozzle are introduced in this study. The first is the normal (non optimized structure and direction) injection nozzle type (Case 1) and the second is the final improved (optimum) injection nozzle type (Case 2) obtained by evaluating the results of any types of nozzles. Results of mixing for 2 types of nozzle are shown in Fig. 6 and Fig. 7.

From the results of case 1 in Fig. 6 and Fig. 7, O_2 flow more than 50% O_2 concentration pass along the bottom on the duct wall, because the direction and the distribution of O_2 injection nozzle is not optimum, it can be seen that there is the unbalance of O_2 concentration in the range of ±3%.

On the other hand, from the results of case 2, it is found that the area of higher O_2 concentration on the duct wall around the mixing point such like case 1 is improved and the distribution gradient of O_2 concentration at the inlet of burner wind-box is also improved to be in the range of less than ±1% as shown in Fig. 7.

These results obtained in this study will be reflected with the design of the demonstration plant and the mixing simulation like this will also be put into practical use at the commercialization stage of oxyfuel combustion system.

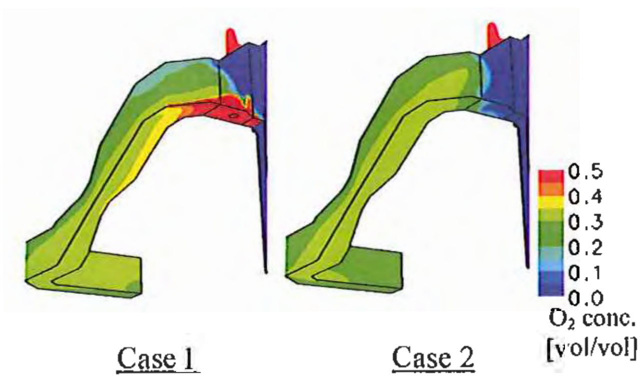


Fig. 6 Simulation results of oxygen concentration on the duct wall after the mixing

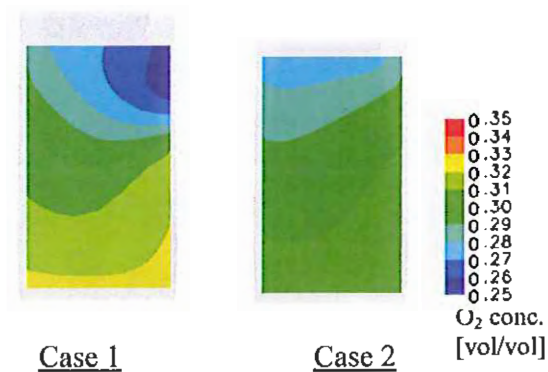


Fig. 7 Simulation results of oxygen concentration at the inlet of burner wind-box

4.3 Performance of flame detector

In the oxy-fuel combustion, the atmosphere for the combustion is different from the air combustion and is consist of the gases with higher concentration of CO_2 and H_2O. There is no example to check the performance of flame detector in such atmosphere. Flame loss signal of flame detector can be connected with mill trip or MFT (Master Fuel Trip) in some situations. To detect the flame properly by flame detector is key issue to operate of the power plant in safety. Therefore, performance of flame detector during oxy-fuel combustion was confirmed using the pilot combustion test facilities in Aioi works of IHI

Regarding the test facilities, the furnace is a vertical and cylindrical furnace with a capacity of 1.2 MWt, an inside diameter of 1.3 m, and a length of 7.5 m. In the oxy-fuel combustion, the flue gas taken out after the bag filter is supplied to the burner by the GRF (Gas Recirculation Fan) and is also used as gases for transporting pulverized coal as well as for combustion. The combustion gas is mixed with O_2 for adjusting the O_2 concentration at the inlet of the furnace. Combustion test under both air and oxy-fuel conditions combustion was performed monitoring the detection level of flame detector. Forney-IDD flame detector was used in this test.

Test condition is simulated with the operation condition at demonstration plant as shown in Table 1 and flow diagram of test facilities is also shown in Fig. 8. In the oxy-fuel combustion test, the concentration of flue gas CO_2 was about 77dry% as compared with 16dry% in air combustion.

Table 1 Test operation condition

Items	Air combustion	Oxy-fuel combustion
PC feed rate [kg/h]	100	100
Burner wind-box O_2 [wet%]	21(Air)	36
Total O_2 to the furnace [wet%, calc.]	21(Air)	27
Flue gas O_2 [dry%]	3.5	3.5
Flue gas CO_2 [dry%]	16	77

Fig. 9 shows the photos of the flame at air and oxy-fuel combustion. Both flame is almost same shape, however flame temperature of oxy-fuel combustion measured by radiation thermometer is lower than that of air combustion. This is because CO_2 and H_2O have higher emissivity at oxy-fuel combustion and the flame temperature is adjusted by recirculation gas flow to obtain the same heat flux on the furnace wall. In such situation, Fig. 10 shows the result of flame detection signal after the adjustment by Forney-IDD in the test. Signal output is in the range between -5V and +5V, and more than 0V of signal output means "Flame on". Both air and oxy-fuel combustion is performed with the continuous operation during one day. At the gain adjustment, gain level is decreased in order to check the behaviour of signal level at both combustions. From the result, it can be found of the slightly lower level of signal output in oxy-fuel combustion as compared with the level in air combustion, however it is confirmed that the signal level is high enough to detect the flame and adjustable signal level by gain in order to detect the flame signal stably.

Based on the test results, flame detector will be considered to be adjusted at the demonstration and commercial stage.

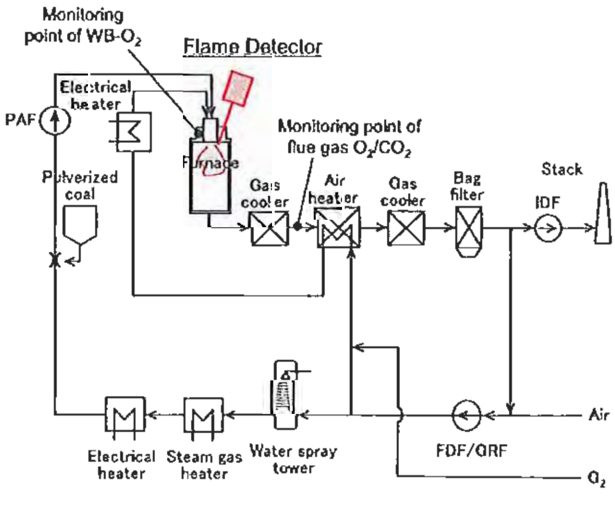
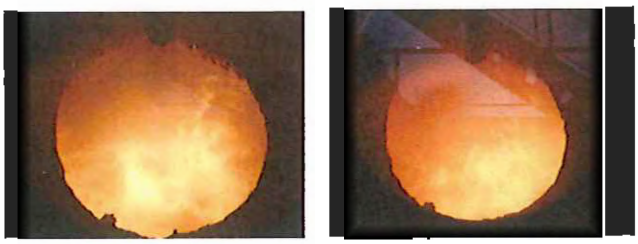


Fig. 8 Flow diagram of combustion test facilities in Aioi



(PFT : 1400degree C) Air combustion

(PFT : 1330degree C) Oxy-fuel combustion

*PFT: Peak flame temperature measured by radiation thermometer

Fig. 9 Flame at both air and oxy-fuel combustion

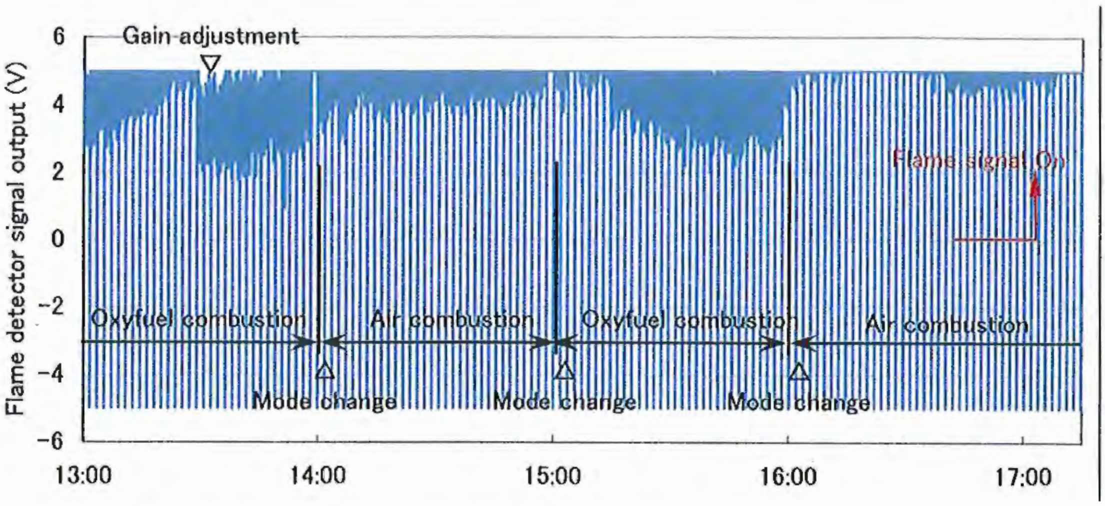


Fig. 10 Result of detection signal of the flame at both air and oxy-fuel combustion

5. Demonstration Project in Australia

On the basis of the study results described above and previous study results[2][3], Joint Venture for the demonstration project of oxy-fuel combustion was established in 2008, that is called "Callide Oxyfuel Project" [4], and the works are now under way for applying oxy-fuel combustion to an existing power plant by way of demonstration. This project aims at recovering and storage CO_2 from an actual existing power plant and also obtaining the economical and technical data or knowledge for the commercialization. The outline of the project is described as follows:

Fig.11 shows the site location of the existing power plant and the CO_2 storage of the demonstration project. Specifically, the project is implemented at the power generation system in Callide-A power plant No.4 unit owned by CS Energy on the east coast of Australia [5]. The capacity of this unit is 30MWe without reheat cycle, main steam flow at 30MWe is approximately 130t/h and coal feed rate is approximately 30t/h.

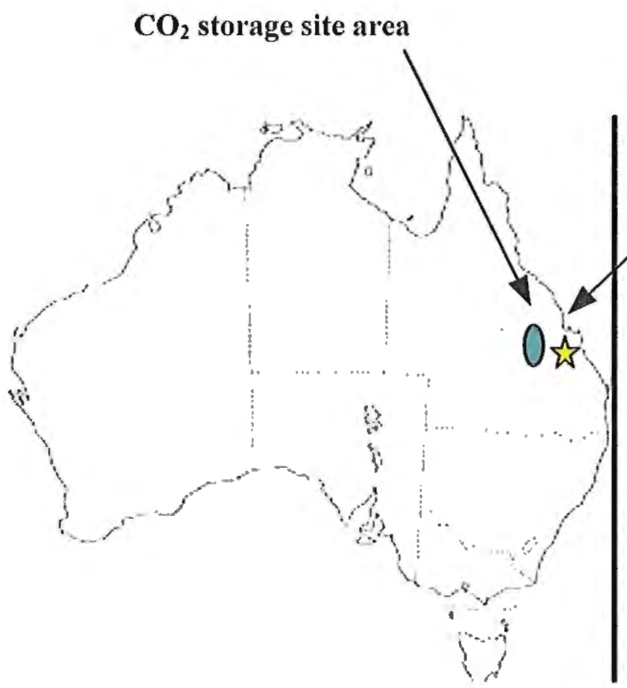
Regarding the application of oxy-fuel combustion to the existing power plant, 2 of air separation units with the capacity of 330t/h and O_2 purity of 98% will be installed near the power plant, air/gas flow system of the boiler will mainly be modified and CO_2 purification unit with the compression and cooling will also installed. It will be expected to have the CO_2 capture rate of 50 - 100 ton per a day at the condition of the liquefied CO_2.

The candidate CO_2 storage site is in the process of the site selection. At this stage, the area of CO_2 storage is planning to be about 250 km to the west of the power plant site. This area was selected because it is not far away from the power plant site, the estimated CO_2 storage capacity is sufficient, and the reservoir characteristics such as permeability and porosity are adequate for CO_2 storage. After the decision of the site and the layer, trial drilling at storage site will be implemented.

The entire schedule of the demonstration project is shown in Table 2. Before the moving to demonstration project, Australia and Japan jointly conducted a feasibility study of oxyfuel combustion technology in FY 2004 [6] and FY 2005 [7]. Based on its results, detailed studies have started in 2006, aiming of the application of this technology to the existing power plant and the integration with CO_2 storage. And simultaneously, the clarification of the project scheme towards the demonstration and the acquirement of the project budget were reviewed in 2006 and 2007. And, in the beginning of 2008, Joint Venture for the demonstration project was established under the supporting of both Australian and Japanese government. Electric Power Development Co., Ltd. (J-POWER), Mitsui & Co., Ltd. (Mitsui) and IHI Corporation (IHI) are participating in Joint Venture and Japan Coal Energy Center (JCOAL) is the supporting collaborator on technical issues from Japanese side. In November 2008, launch was held in the site to celebrate the start of site works [4].

Project mainly consists of stage 1 and 2. In stage 1, demonstration operation of oxy-fuel combustion with CO_2 capture will be performed for four years after the plant completion at the middle of 2011. In stage

2, the injection of captured CO_2 from the power plant will start in 2011 simultaneously, and the demonstration of CO_2 injection into the underground and the monitoring of CO_2 storage will be performed for three years. This demonstration project will be summarized at 2016.



Callide A: 4 x 30 MWe
Evaporation: 123 t/h steam at 4.1 MPa／460°C
Commissioned: 1965 – 69
Refurbished 1997/98
Boiler equipments:
Type / 2-drum type
Burner / 6 burners
Mill / 3 mills
Flue gas treatment / Fabric filter (without DeNOx/DeSOx)

Callide-A Power plant

Fig. 11 Power Plant site and CO_2 storage site

Table 2 Demonstration Project Schedule

Items \ JP-FY	2004	05	06	07	08	09	10	11	12	13	14	15	16
FEED	■	■	■		Feasibility								
Demonstration Project						Commencement of demonstration							
Stage 1 CO_2 capture(ASU, Boiler retrofit, CO_2 compression & purification unit)			■	■	Oxyfuel retrofit / Commissioning			Demonstration					
Stage 2 CO_2 storage(Site selection, Drilling Injection)				Site selection / Drilling / Design			Site work / commissioning	CO_2 injection & monitoring				Conclusion	
Stage 3 Project summary					Commencement of CO_2 storage							■	■

6. Conclusion

These results obtained in this study will be reflected with the design of the demonstration plant for Callide Oxyfuel Project and the mixing simulation like this will also be put into practical use at the commercialization stage of oxy-fuel combustion system.

Oxy-fuel combustion technology has been attracting and increase attention worldwide because it has a potentiality for providing a breakthrough solution that helps reduce CO_2 emissions. In relation to this technology, many countries are conducting research and development towards the realization of this technology which is one candidate of the CO_2 capture from the power plant.

We would like to have much knowledge and information through the studies including above and the demonstration operation at Callide-A, and contribute to reduce CO_2 from the pulverized-coal fired power plant using oxy-fuel technology.

7. Acknowledgments

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