Operational results of oxyfuel power plant (Callide Oxyfuel Project)

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Abstract

In 2013, CO₂ levels surpassed 400 ppm for the first time in recorded history. So, we are facing global warming due to the increase levels of atmospheric carbon dioxide (CO₂). As a method of reducing CO₂ emissions from the thermal power plants, there are carbon dioxide capture and storage (CCS) technologies. Oxyfuel combustion is one of the CO₂ Capture technologies and IHI have developed it since 1989. Then, Callide Oxyfuel Project commenced to apply oxyfiring technology in an existing coal fired power plant and to demonstrate an oxyfuel power plant in March, 2008. Demonstration began in 2012 after existing boiler was retrofitted. During the demonstration for approximately three years, many tests were conducted and many data were collected for commercial use. As a result, we confirmed characteristics of oxyfiring such as total heat absorption, combustion characteristics, emissions of NO_x, SO_x, carbon-in-ash, operational flexibility from 15MWe (50%L) to 30MWe (100%L) and behavior of injected CO₂ at the injection site. Total heat absorption of the boiler under oxyfiring was 2 to 3MW higher because of decreasing heat loss in flue gas and rising temperature of boiler feed water by a flue gas cooler. NO was decomposed in the furnace under oxyfiring because flue gas was recirculated. On the other hand, reaction between SO₂ and absorbent such as Ca, Mg in ash was not so active regardless of high concentrated SO₂ under oxyfiring. Carbon-in-ash was almost 40%~70% in oxyfiring compared with in airfiring because of longer residence time in the furnace. Operational flexibility is important to control oxyfiring operation and it was confirmed that oxyfiring can be operated as well as airfiring. In this paper, operational results are presented in Callide Oxyfuel Project.

Key words : Coal, CCS, Oxyfuel, Oxyfiring, CO₂, Power plant, Oxy-combustion, Callide, Australia

1. Introduction

In 2013, CO₂ levels surpassed 400 ppm for the first time in recorded history. Coal fired power plants are considered one of the resources to emit the large amount of CO₂. According to “World Energy Outlook 2014” (IEA), coal use in Non-OECD countries will increase up to about three times in 2040 as compared with 1990. Therefore, reducing CO₂ concentration in the atmosphere is an important and urgent issue, so the world is focusing on countermeasures. Coal fired power plants still discharge more CO₂ emissions during the combustion process than any other fossil fuel power generation plants. Coal is a stable primary energy resource for power generation and will remain as a key energy resource in the future. Therefore, CO₂ emissions from coal-fired power plants must be reduced.

Recently, many CO₂ capturing processes’ which are applied to coal-fired power plants have been developed, such as post-combustion capture and pre-combustion capture. Oxyfuel combustion is also a potential candidate for capturing CO₂ from coal-fired power plants. IHI have developed oxyfuel combustion technology since 1989, and a feasibility study on the demonstration project between Australia and Japan started in 2004, followed by the Callide Oxyfuel Project which commenced to demonstrate oxyfuel power plant in 2008.

During the demonstration, many tests were conducted and many data were collected. Through this project, we confirmed the operational flexibility, improved plant efficiency, CO₂ concentration in flue gas, flame stability, and combustion characteristics such as decrease of carbon-in-ash and NO in flue gas etc., under oxyfiring.

In this paper, the operational results of the 30MWe oxyfuel power plant after approximately three years demonstration at the Callide Oxyfuel Project are introduced.

2. Outline of the oxyfiring system

In oxyfiring system, O₂ is separated from the air by Air Separation Unit (ASU) and supplied to the boiler for coal combustion. Moreover, the flue gas from the boiler is recirculated and mixed with O₂ in order to use conventional airfiring technology. Accordingly, the oxyfiring flue gas is emitted mainly comprises of CO₂ and H₂O, and will theoretically enhance the CO₂ concentration in flue gas up to more than 90 dry%. The overall CCS concept using an oxyfiring system is shown in Fig.1.

The method for capturing almost pure CO₂ involves removing H₂O and separating non-condensable gases from the oxyfuel gas via a CO₂ compression and purification unit (CPU).

The characteristics of oxyfiring technology are as follows :

- Highly-concentrated CO₂ can be captured directly from flue gas, because N₂ is removed before combustion.
- Efficiency of oxyfuel boiler is far higher than that of an airfiring boiler under the same conditions, because the amount of flue gas is decreased (by approximately one-fifth). The feed-water system can also be integrated with the flue gas system for heat recovery, making it even more efficient.
- NO_x emissions are reduced, because recirculation gas is supplied to a furnace and the NO_x in the recirculation gas is decomposed. Moreover, NO_x can be removed at the CPU.
- Enriched O₂ and increasing residence time in the coal combustion process can reduce carbon-in-ash.
- The system can be applied to existing power plants as well as new construction power plants.

Fig.1 Concept of the oxyfiring system

The oxyfiring system plays a significant role as an optional technology for capturing CO₂ from coal-fired power plants. This technology is a focus in many countries and they have conducted research and development to realize the commercial oxyfuel power plants.

3. Callide Oxyfuel Project

Callide Oxyfuel Project in central Queensland, Australia, was established in 2008. Callide-A, which was a retrofit of an existing power plant with a capacity of 30MWe, was the largest operating oxyfuel power plant in the world that sold electricity to Australia. This was achieved with funding from the Australian and Japanese governments, the Queensland state Government, and was followed by research results from 1989 in Japan. Before Callide Oxyfuel Project commenced, various evaluations were conducted regarding oxyfiring for realizing demonstration at Callide-A such as combustion characteristics, heat transfer, ignition and safety and so on. These results are shown in the other paper (Yamada et al., 2010).

The project milestones to date are shown in Table 1. The overview of Callide-A power plant is shown in Fig.2 and the oxyfiring process in Callide-A is shown in Fig.3. The specification of Callide-A boiler was written in the paper (Komaki et al., 2013).

This project was composed of three stages. In stage 1, the existing boiler was retrofitted to an oxyfuel boiler. The ASU and the CPU were installed. In stage 2, the CO₂ captured by oxyfiring system was transported by truck and stored underground. In stage 3, the project outcomes have been summarized including the data which had been acquired through the operation. The objectives of stage 1 involved analyzing the design and cost data so that it could be applied to existing plants, and accumulating operational experience, as well as demonstrating the oxyfuel boiler system and CPU.

The oxyfuel power plant was demonstrated and the various tests were performed from March 2012 to March 2015. The CO₂ captured from the oxyfuel power plant was transported and injected into the storage layer.

Table 1 Milestones of the Callide Oxyfuel Project

Month, Year	Course
2004	Feasibility study of the Callide oxyfuel Project commenced.
March, 2006	MoU (Memorandum of Understanding) signed
October, 2006	Australian Government's Low-emission Technology Demonstration Fund funding announcement
March, 2008	Callide Oxyfuel Project Joint Venture agreements finalized
August, 2008	Refurbishment of Unit A4 at Callide-A Power Station commenced
October, 2008	Official launch of the Callide Oxyfuel Project
January, 2009	Refurbishment of Unit A4 at Callide A Power Station completed
October, 2009	Earthworks commenced at Callide A Power Station
January, 2010	Earthworks completed and foundation excavations commenced at Callide A Power Station
March, 2011	Boiler modification completed for oxyfiring at Callide A Power Station
April, 2011	First coal firing in air mode after boiler oxyfiring modifications
March, 2012	First boiler operation in full oxyfiring mode
December, 2012	Demonstration phase began
February, 2015	Oxyfuel operation of 10,000 hours achieved
March, 2015	Demonstration phase completed

Fig.2 Overview of Callide-A power station

Fig.3 Oxyfiring process in Callide-A

4. Operational results of the oxyfuel power plant

The Project team operated the oxyfiring power plant for approximately three years from March 2012 when O₂ was supplied to the boiler. Initial operation results are referred to the other paper (Komaki et al., 2013). Then, various basic characteristics of the oxyfuel boiler were confirmed. This section introduces the major results of the oxyfuel boiler in demonstration. Many tests were conducted in order to confirm the characteristics of oxyfuel boiler by using different mill configuration, loads, O₂ concentration in total gas (inlet O₂ concentration) and so on. The results from the demonstration of the oxyfuel boiler are shown as follows.

- Operational flexibility
 - ✓ Combustion in various coal
 - ✓ Load ramp up & down test
 - ✓ Turn-down test
 - ✓ Optimization of mode transition
- Confirmation of boiler performance
 - ✓ 30MWe operation at both airfiring and oxyfiring
 - ✓ Various boiler inlet- O₂
 - ✓ Direct- O₂ injection to the flame
 - ✓ Bypass operation of dehydration device
 - ✓ Simulated staging combustion
 - ✓ Exposure test of boiler tubes for high temperature and materials for low temperature
- Reliability
 - ✓ Operation hours
 - ✓ Inspection of equipment

As a result of demonstration, Callide-A achieved the strong track records as follows.

- ✓ Total generation: 14,800 hours
- ✓ Oxyfuel operation: 10,200 hours
- ✓ CO₂ capture operation: 5,600 hours
- ✓ Coal burned: 320,000 tones

4.1 Total heat absorption of oxyfuel boiler

The amount of flue gas through the burners is approximately 70% under oxyfiring compared with airfiring. Heat absorption is defined as heat transferred from radiation and convection. Total heat absorption of the boiler is included furnace, 1SH, evaporator and 2SH. It was 2 to 3 MW higher under oxyfiring, because heat loss of flue gas was decreased and heat of flue gas was recovered in order to raise temperature of boiler feed water by a flue gas cooler. Therefore, plant efficiency under oxyfiring was enhanced. Then, there was no significant difference regarding convection between the bank and the furnace under both airfiring and oxyfiring. These results were almost the same by combustion test facilities and simulation at the stage of feasibility study before the operation (Yamada et al., 2007).

4.2 Combustion characteristics

Figure 4 and 5 show carbon-in-ash and the combustion characteristics about NO_x, SO_x in both airfiring and oxyfiring respectively. Figure 4 shows the weighted average value of carbon-in-ash of each hopper after burning blended bituminous coal and every ash from 13 hoppers was sampled and analyzed. Regarding “Oxyfiring+direct-O₂” data in Coal B and D was not obtained. In Callide-A, two O₂ lances for each burner were what we call direct-O₂ installed in order to evaluate the effect of supplying pure O₂ near the burners. The maximum capacity was set about 10% of total O₂ which was supplied to the boiler. From the test results of direct-O₂ injection test, carbon-in-ash in oxyfiring with direct-O₂ was further decreased compared with airfiring and oxyfiring, carbon-in-ash was almost 40%~70% in oxyfiring compared with in airfiring because of the longer residence time in the furnace for the small amount of flue gas. In the meantime, in Fig.5, corrective value to 12% CO₂ of NO and SO₂ were used in order to compare on the basis of emissions amount. Conditions of flue gas O₂ concentration at the boiler exit during the tests were the same in oxyfiring as in airfiring. The NO_{corr}, with a 12% CO₂ corrective value, declines around 60% with oxyfiring because NO was decomposed in recirculated flue gas in the furnace. In fact, it was reported in the research paper (Okazaki and Ando, 1997) that the effect of a reduction of recycled NO in the furnace was dominant and more than 50% of recycled NO was reduced to become N₂ through the chemical reaction in the combustion zone. This means NO_{corr} emissions can be reduced in the oxyfiring. In oxyfiring, the source of NO_x is mainly fuel NO_x and thermal NO_x by air leakage into the boiler.

On the other hand, SO₂ in recirculated flue gas was not so different between airfiring and oxyfiring from the Fig.5. This means SO₂ under oxyfiring is much more concentrated than under airfiring. Reaction between SO₂ and absorbent such as Ca, Mg in ash was not so active regardless of high concentrated SO₂ under oxyfiring. From this result, DeSO_x facility needs to be installed if there is trouble regarding SO₂.

Fig.4 Carbon-in-ash in various coal and conditions

Fig.5 Difference of combustion characteristics between airfiring and oxyfiring

4.3 Various boiler inlet O₂ tests

The various boiler inlet O₂ operations were conducted to check operational flexibility. It is important that oxyfiring can be operated as well as airfiring at minimum and maximum load. Boiler inlet O₂ is defined as O₂ concentration in the total amount of boiler inlet flow such as primary flow and secondary flow and so on. Operational range in airfiring and oxyfiring is shown in Fig.6. Through the operation, boiler performance such as steam condition was maintained during the oxyfiring operation as well as the airfiring. However, the boiler outlet gas temperature was decreased in oxyfiring because the heat absorption of the boiler was slightly increased as discussed in section 4.1. It means plant efficiency can be improved by oxyfiring. Then, heat flux on the furnace wall was also increased by increasing inlet-O₂ as expected. This result shows that flame temperature rose as boiler inlet O₂ concentration was increased, and it caused the energy of radiation to increase.

The photos of flame were taken from the observation windows near the burner throat and brightness of flame was different depending on the boiler inlet O₂ as shown in Fig.7. These photos were taken by the same camera and the same setting. Flame location was closer to burner throat due to the reduction of gas volume and higher O₂ concentration in combustion gas, when boiler inlet O₂ was 30%.

Fig.6 Operational range in airfiring and oxyfiring

Fig.7 Photos of the flame in oxyfiring with various inlet-O₂, 24.5%, 27% and 30% at 28MWe

4.4 Turn-down test in oxyfiring

At the design stage, the existing burners were reused, 30MWe operation was required in both airfiring and oxyfiring and the minimum load under oxyfiring was set to be 24MWe with inlet O₂ of between 24 and 30%, because flame stability and heat balance of flue gas were concerned. Through the test, the stability of flame was confirmed at 24MWe and there was a possibility to reduce the load. Therefore, turn-down test of the oxyfuel boiler was conducted by the appropriate operational condition monitoring the flame shape and stability in visual and the level of flame detection.

As a result, operational range down to 15MWe was achieved that was equivalent to airfiring operation as shown in Fig.6. The minimum load was 21MWe (70%L) when the boiler inlet O₂ was controlled at 27%. And also minimum load was 15MWe (50%L) when the boiler inlet O₂ was controlled from 23 to 24%. During turn-down test, burner flames look stable and the boiler operation such as steam condition and flue gas condition were also stable.

4.5 CO₂ purity at CPU and CO₂ injection

The CO₂ concentration in oxyfuel flue gas at the CPU inlet is an important factor for the economics of the CO₂ capture plant. The target value of CO₂ concentration at CPU inlet was 70 dry% and this was generally achieved under the condition of 28 to 30MWe operation as predicted from calculations based on excess combustion O₂ and expected air ingress rates into the boiler. In commercial oxyfuel power plants, it will be very important to strictly minimize the air ingress into the boiler process in order to achieve targeted CO₂ concentration in flue gas. From the lessons of the Callide oxyfuel demonstration, a number of measures to reduce the air ingress and to increase the concentration of CO₂ in the flue gas to values exceeding 85 dry% have been identified.

In the CPU, oxyfuel flue gas was purified to obtain almost pure CO₂ through the following process equipment: low-pressure wet scrubber with caustic soda, compression, high-pressure wet scrubber, drier, cryogenic separation of CO₂ from non-condensable gases such as O₂, N₂ and Ar, and liquefaction. Final product consisted of CO₂ with a purity of over 99.9% which was retained in a storage tank at a condition of -30 degree C, 1500 kPa(A). Figure. 8 shows the sampling of liquefied CO₂ for analysis.

In late 2014, a series of CO₂ injection tests utilizing CO₂ product from Callide-A were undertaken in collaboration with the CO2CRC. The purpose of the injection tests were to evaluate the relative geochemical effects of pure CO₂ and CO₂ with added impurities (NO₂, SO₂ and O₂) on the reservoir rock and formation water within the Paraette Sandstone (at depth of ~1450 m) within the Otway geological basin in Victoria. Figure 9 shows the CO₂ injection site.

Fig.8 Sampling of liquefied CO₂ at Callide-A site

Fig.9 CO₂ injection site (CO2CRC Otway)

5. Business scheme of future oxyfuel power plant

The feasibility study of 500MWe oxyfuel power plant in Australia was performed. Figure.10 shows the image of future oxyfuel power plant which includes ASU, CPU and flue gas desulfurization (FGD) for commercialization. From the study results, the sales of N₂ and CO₂ from the oxyfuel power plants are very important and beneficial. Economic efficiency of oxyfuel power plant by selling CO₂ and N₂ is shown in Fig.11. If CO₂ and N₂ can be sold effectively, the cost of electricity for oxyfuel power plants can be lower than that for conventional airfiring plants and the oxyfuel power plants will be easy to be applied commercially. Figure 12 shows the proposed project scheme for commercialization.

Oxyfuel combustion for CO₂ capture is now ready for scale-up as an outcome of demonstration and learnings of the Callide Oxyfuel Project. In commercial oxyfuel power plants, one of the main problems is the economic efficiency. However, results of the feasibility study, oxyfuel power plant for CO₂ capture can be considered to be economically advantageous as compared with other CO₂ capture systems.

Fig.10 Image of future oxyfuel power plant for commercialization

Fig.11 Result of cost study

Fig.12 Proposed project scheme

6. Conclusion

This report introduced the Callide Oxyfuel Project and operational results of the oxyfuel boiler after demonstration. The data which was accumulated through the many tests will be used towards the commercialization of this technology. To realize this oxyfiring system as a highly-efficient CCS system, we will push forward research and development further. Recently, CO₂ emissions (kg/MWh) from coal fired power plants are restricted less than or equivalent to NGCC (Natural Gas Combined Cycle) level, for example 420 kg/MWh in Canada. To comply with regulation, the oxyfuel power plant with CCUS (Carbon Capture, Utilization and Storage) can be expected.

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