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Current Status of MHI's CO_2 Recovery Technology and Optimization of CO_2 Recovery Plant with a PC Fired Power Plant

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Abstract

It is the opinion of the authors that CO_2 Capture and Storage (CCS) technology can significantly contribute as an effective countermeasure against climate change, allowing us to continue the utilization of fossil fuels for primary energy production. However for this technology to be widely deployed on a commercial basis there are three key issues that need to be addressed; (1) Reduction in energy consumption, (2) Efficient integration with other environmental control equipment of a PC power plant and (3) Reduction in the decrease of net electrical output.

MHI has delivered multiple commercial CO_2 recovery plants in the chemical and fertilizer industries, which recover CO_2 from natural gas fired flue gas, with four commercial plants in operation and another four under construction, all utilizing the proprietary KM-CDR process.

In order to gain experience with CO_2 recovery from a coal fired flue gas stream, Mitsubishi Heavy Industries (MHI), together with a subsidy from RITE and cooperation from J-POWER, constructed a 10 metric ton per day (T/D) CO_2 recovery demonstration plant at the 2 x 500MW Matsushima power station in southern Japan. This demonstration plant has subsequently achieved more than 4,000 hours of successful test operation during 2006 - 2007 with a further 1,000 hours during 2008, and testing continues today. The demonstration testing confirmed that the KM-CDR process is applicable to coal fired flue gas streams. Future research priorities include the improved integration of the CO_2 recovery process with the flue gas pre-treatment components and the additional optimization of removal and separation methods for coal based impurities accumulating in the absorbent.

An issue of concern for power plant operators is the reduction of the net electrical output due to the demands of CO_2 recovery process. MHI has made significant improvements in this area and in the efficiency of absorbents. However, it is necessary to further reduce the adverse impact on the net electrical output of the power plant via astute integration of the energy transferred between the power plant and the Post Combustion CO_2 Capture (PCC) plant. MHI is investigating the following concepts; (1) Utilizing the waste heat of the PCC plant for the power plant, (2) Utilizing heat recovery from the flue gas for the CO_2 recovery process and (3) Utilizing the compression heat of the CO_2 compressor for the CO_2 recovery process.

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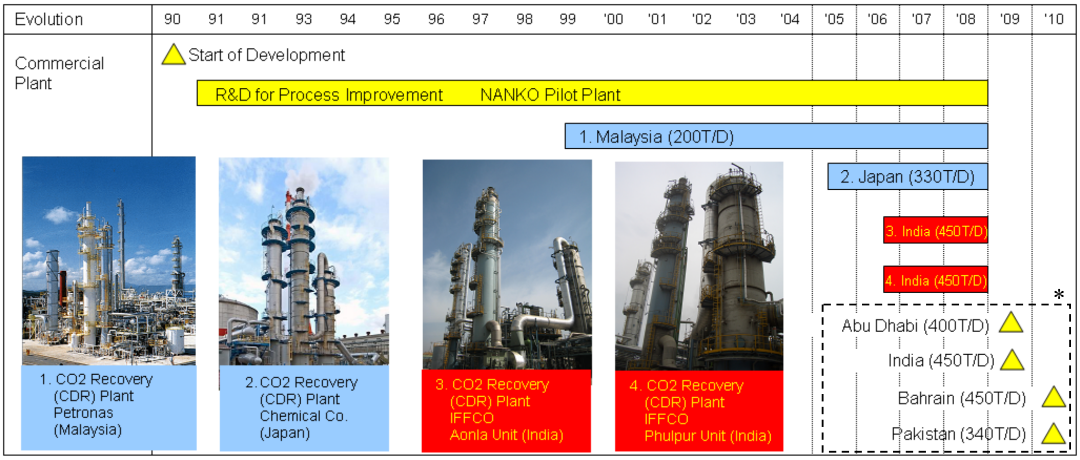
1. Introduction

It is now widely accepted that capturing CO_2 from flue gases and the subsequent injection into geological formations can significantly contribute to reducing emissions of atmospheric CO_2, the principal greenhouse gas. Apart from having obvious benefits in terms of reducing the emission of CO_2 into the atmosphere, CCS will also allow nations around the world to continue using important domestic fossil fuels such as coal in an economic and environmentally sustainable way. MHI is a world leader in the field of PCC technology which stems from more than 18 years of R&D. MHI has been awarded an increasing number of commercial CO_2 capture plant contracts and currently has in excess of 16 years of cumulative commercial operating experience. However, all commercial experience to date has been of flue gas from firing of natural gas. Before wide scale commercial deployment of CCS for application to coal fired flue gas can occur the Net Loss to a power station must be reduced. In this paper, MHI introduces a number of concepts which seek to achieve this aim.

2. MHI's commercial CO_2 Capture Achievement

MHI has been involved in R&D relating to CO_2 capture from flue-gas streams of fossil fuel-fired power stations since 1990, undertaken jointly with Kansai Electric Power CO., the second largest electric utility in Japan. These efforts led to the development of advanced PCC proprietary equipment and processes and the successful commercial deployment of four (4) CO_2 capture plants, currently operating in Malaysia, Japan and 2 locations in India as highlighted in Table 2-1. MHI has also been awarded a further four (4) commercial license contracts for CO_2 capture plants expected to be under operation within the next few years as shown in Table 2-2.

Table 2-1 MHI's commercial CO_2 capture plant operation experience



Note * Please see Table 2-2 for more detail

Table 2-2 MHI's commercial CO_2 capture plant awarded

OTHER PROJECTS	Abu Dhabi	India	Bahrain	Pakistan
Project Status	Under Construction	Under Construction	Under Construction	Under Construction
Flue Gas Source	Nat. Gas. Reformer	Nat. Gas. Reformer	Nat. Gas. Reformer	Nat. Gas. Reformer
Expected on stream	2009	2009	2010	2010
CO_2 Capture Capacity(T/D)	400	450	450	340

Figure 2-3 Large Scale Multi Pollutant Test Plant

MHI has already gained considerable commercial experience in CO_2 capture from natural gas-fired boilers. Combined with extensive experiences from large scale commercial FGD deployment and the flow dynamic data obtained from our large scale multi pollutant test plant (Fig 2-3), MHI is ready to provide large scale, single train commercial CCS plants for natural gas fired installations, and intends to leverage this experience for application to large scale CO_2 capture from coal fired flue gas streams.

3. CO_2 Capture from a Coal Fired Boiler

As identified by several global organizations, including the IPCC and IEA, one of the most urgent challenges is to address CO_2 emissions from coal fired power plants, the largest single source of global GHG emissions. MHI has responded to this challenge by constructing and testing a CO_2 capture pilot plant in 2002, with a capacity of 1 T/D, using coal-fired flue gas at its Hiroshima R&D Center [3]. Based on this result as the next step, MHI has completed several test programs capturing 10 T/D CO_2 via a slip stream from a 500MW unit, J-POWER coal fired power station in Matsushima, Japan, with grant funding (50% of project costs) from the Research Institute of Innovative Technology for Earth (RITE) and cooperation from the Electric Power Development Co., Ltd.

Long term operation of this plant has enabled MHI to observe the influences of coal fired flue gas impurities and develop countermeasures for these items. It is only through actual "in-situ" demonstration testing that some of these influences were identified and subsequently resolved through the deployment of specific countermeasures. MHI has over 5,000 hours of near-continuous operation of this facility and has gained significant know how with regards to the impact of specific impurities and the countermeasures necessary to abate these impacts.

3.1. Demonstration Results

3.2.1 Outline of the demonstration plant

Table 3-1, Figure 3-1 and Figure 3-2 show the plant specifications and a flow diagram.

Table 3-1 Specifications of CO_2 Recovery Demonstration Plant

Items	Parameters (planned values)
Installation location	Within Matsushima Thermal Power Station owned and operated by J-POWER
Flue gas source	Flue gas coal-fired boiler
Amount of flue gas to be treated	1750 $m^3{}_N$/h
CO_2 recovery efficiency	90 %
CO_2 recovery capacity	Planned value: 9.5 ton/day (Max. 10 ton/day)
CO_2 concentration	14.1 v %
Other impurities	Dust, SOx, NOx, etc.
Solvent	KS-1 solvent

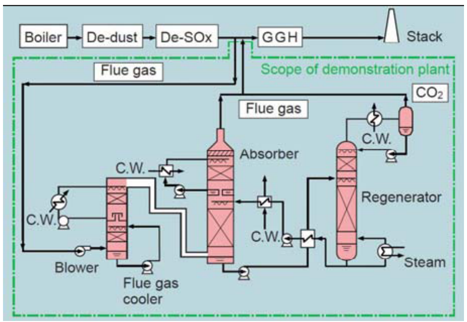


Figure 3-1 Flow Diagram of CO_2 Recovery Demonstration Plant

Figure 3-2 Matsushima Demonstration Plant Photograph

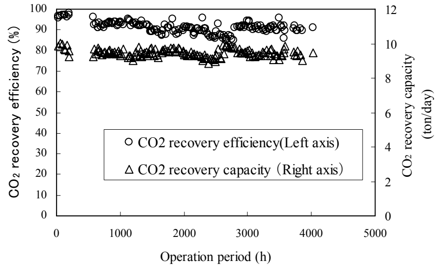


Figure 3-3 Stability of the CO_2 recovery efficiency and capacity

3.2.2 Demonstration Test Results

(1) Monitoring plant operations

Installing the pre-treatment equipment allowed the CO_2 recovery plant to operate stably for a period of 5,000 hours. The performance assessment is as follows:

a. CO_2 recovery efficiency and recovered CO_2 quantity

Figure 3-3 illustrates time-sequence data of CO_2 recovery efficiencies. Following 5,000 hours of demonstration operation, both CO_2 recovery efficiency and recovered CO_2 quantities indicated equivalent or higher performance than our baseline prediction.

b. Heat consumption required for CO_2 recovery

Performance of heat consumption required for CO_2 recovery: 730 to 820kcal/kg- CO_2, which exceeded our original baseline forecast. If the energy saving process (explained in 4.1 of this paper) is applied, the heat consumption is expected to decrease by approximately an additional 15% to 630~700kcal/kg CO_2, which is better performance than that recorded for natural gas fired flue gas due to the high CO_2 concentration in coal fired flue gas.

c. Purity of recovered CO_2

The results for CO_2 product purity shows that the KM-CDR process can achieve a purity of CO_2 recovered (>99.9%), similar to our results for a natural gas-fired boiler.

(2) Identifying the influence of dust

- ✧ The capture efficiency of dust in the flue gas ranges from 40 - 50% in the flue gas cooler, and 40 - 60% in the absorber. With a filter added to remove dust from the solvent, the dust concentration in the solvent does not increase thus the dust concentration of approximately 10mg/kg can be maintained.
- ✧ Our examination of the dust concentration in the solvent, and the foaming tendency of the solvent, indicated no interrelation with either the absorber pressure loss or the regenerator pressure loss. A dust concentration of 10mg/kg, or lower accumulated in the solvent, does not cause flooding.
- ✧ Figures 3-4 and 3-5 illustrate trend data of the pressure losses recorded in the flue gas cooler and absorber. After 4,000 hours of operation, no tendency was observed for increased pressure loss. The results revealed that the plugging of packing material and demisters can be prevented through dust removal utilising pre-treatment facilities and filter systems in the solvent line.

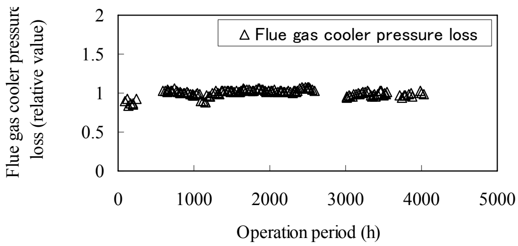


Figure 3-4 Stability of pressure loss of the flue gas cooler

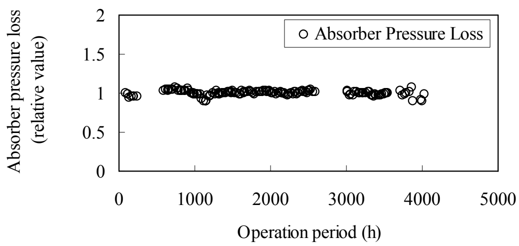


Figure 3-5 Stability of the pressure loss of the absorber

✧ The heat transfer coefficient decreased in the heat exchanger using cooling water after the lapse of many hours of operation. This was explained by the adhering of material in the cooling water to the heat transfer surface. This problem can be solved by implementing appropriate water treatment. No significant decreases in the heat transfer coefficient were observed in the heat exchanger without using cooling water.

(3) Identifying the influence of SOx
The flue gas cooler provided with a desulfurization by caustic soda, removed 98% or more of the SO_2 entering the system. This resulted in a SO_2 concentration at the CO_2 absorber inlet of less than 0.1 ppm as per our expectation. Almost all the SO_2 at the outlet of the flue gas cooler was absorbed by the solvent and generated heat-stable salts (HSS).

(4) Identifying the influence of NOx
The flue gas cooler absorbed almost none of the NOx in the flue gas. The solvent in the CO_2 absorber absorbed approximately 1 to 3% of the inlet NOx. The HSS amounts produced were also at a low level, even after the 5,000 hours of demonstration operation, and did not cause any operational concerns.

(5) Identifying the influence of chlorine and fluorine
Chlorine or fluorine was below the detection limit in the flue gas or solvent during the demonstration testing period, and we assume these were completely removed upstream of the CO_2 recovery plant.

(6) Identifying solvent loss
The solvent loss recorded was close to our expectation. In this test, we assessed the solvent loss quantitatively from the flue gas of the coal-fired boiler. We will apply the test results to actual projects.

3.2.3 Next Steps

(1) A future research priority is the improved integration of the CO_2 recovery system with the flue gas pre-treatment components and the additional optimization of removal methods for impurities accumulating in the absorbent. We are undertaking the above tests utilizing the same facility in Japan to further integrate the CO_2 recovery process with the environmental control equipment of the power plant.

(2) Concurrently we are applying this technology process to a large-scale CO_2-capture demonstration plant for a coal-fired boiler. In recognition that MHI has completed extensive R&D programs and to address flexibility issues, which will offer further robust incentives for PCC plant, we believe it is important to progress into the medium scale (~500 T/D) demonstration phase for coal fired flue gas according to the scale up map shown in Figure 3-6. This will lead to a greater understanding of the larger-scale effects of coal fired flue gas impurities and the options for cost reduction and a foundation for future wide scale application.

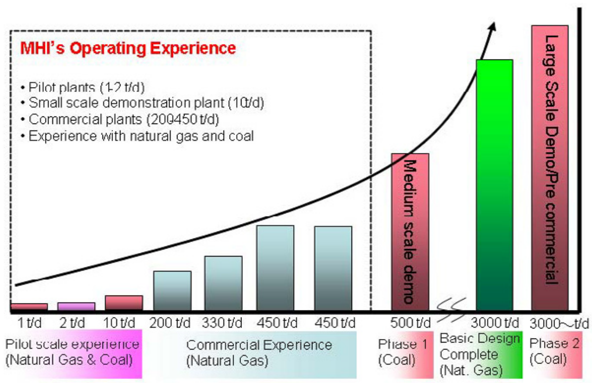


Figure 3-6 Scale up & road map for commercialization of PCC for coal fired boilers

4. Efficient Integration of CO_2 Recovery (PCC) Plant with the Power Plant

4.1. MHI's process improvements to reduce energy requirements

The flue gas blower feeds flue gas to the PCC plant. As the flue gas passes through the absorber after the flue gas cooler, the KS-1 solvent is distributed within the absorber, selectively absorbing the CO_2 from the flue gas and the solvent is then collected in the bottom of the absorber as a "CO_2-rich" solution. It is then heated by the lean solvent from the regenerator described below and pumped into the upper section of the CO_2 regenerator (stripper). Within the CO_2 regenerator, the CO_2-rich solution contacts with an upward stream of low pressure stripping-steam produced by the reboiler, which removes the CO_2 from the CO_2-rich solution, yielding CO_2 gas with a high purity (>99.9%). The stripped lean solution is cooled down by giving up energy to the rich solvent (see Fig.3-1 above) using a water cooled heat exchanger and then reintroduced into the absorber for the base KM-CDR process.

To reduce the steam consumption at the reboiler, we employ a unique concept to utilize lean solvent and steam condensate heat for regeneration inside the stripper heating the semi-lean solution. Figure 4-1 shows the outline of the KM-CDR "improved" process flow (Bold line section).
Through application of this process, the steam consumption is reduced by a further 15% compared with the conventional KM-CDR Process achieving 660kcal/kg CO_2 recovered. [4] Other elements of the improved process are also effective in recovering flue gas heat and the CO_2 compression heat to the CO_2 regenerator to reduce the steam consumption, utilizing the semi-lean solvent heat integration concept shown in Figure 4-2 and explained below.

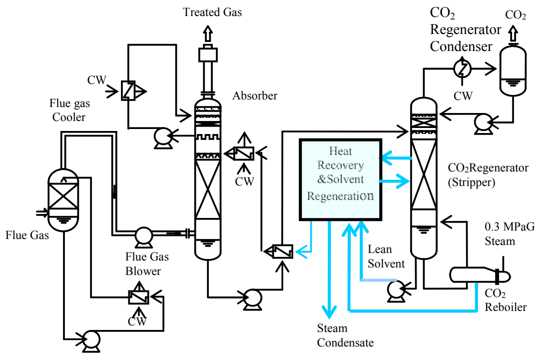


Figure 4-1 Improved Process

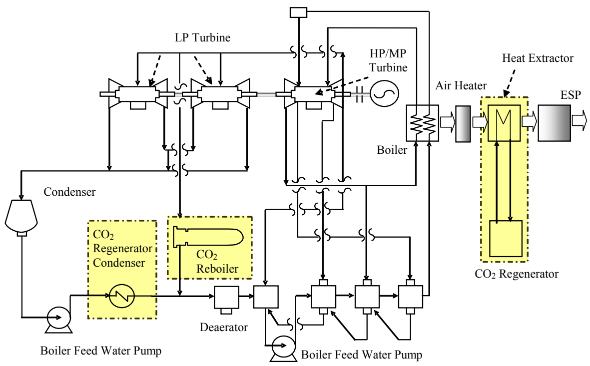


Figure 4-2 Heat Integration in Power Plant

4.2. MHI's Heat Integration Concept to Reduce Energy Penalty

There is further opportunity to reduce the impact on the net output via astute integration of the power plant and PCC plant. MHI has investigated the following concepts which we aim to apply to future projects.

4.2.1 Heat Integration Method

Heat integration between Power Plant and PCC Plant is shown in Figure 4-2.

(1) Utilization of the waste heat of PCC plant for the power plant
The boiler feed water (BFW) is used to cool the regenerator condenser, which raises the temperature of BFW and saves the low pressure steam consumption required to heat up BFW in the power plant, increasing the gross output.

(2) Utilizing the recovery heat of the flue gas for the CO_2 recovery Process

Flue gas heat at the outlet of the air heater is recovered by the semi-lean solvent flowing inside of the heat extractor, which is one of the important components utilized in one advanced MHI concept titled "MHI's High Efficiency System Proven Technology for Multi Pollutant Removal". In this case, the flue gas temperature is the important parameter and the steam consumption in the reboiler is reduced by approximately 9% for the case where the flue gas is cooled from 158degC to 106degC by the heat extractor.

(3) Utilization of the compression heat of the CO_2 for the CO_2 recovery process

Additional intercooler cooled by the semi-lean solvent is added at the outlet of each stage of the compressor where a 4 stage compression system is utilized. The CO_2 compression heat is recovered by the semi-lean solvent to be utilized in the regenerator to reduce the steam consumption in the reboiler by approx 5%.

4.2.2 Study Conditions

(1) Study Conditions are shown below

Plant Type:	Supercritical	
Gross Output:	1,070MW	
Fuel:	Bituminous Coal	
Flue Gas Condition (PCC Plant inlet)		
- Flue gas volume:		$3{,}147{,}000m^3N/h$
- Inlet CO_2 Amount:		18,670 T/D
- Inlet Flue Gas Temperature:		45degC at FGD outlet (158degC at Air Heater outlet)
PCC Plant Performance		
- CO_2 Recovery Efficiency:		90%
- Product CO_2 Pressure:		2,000psig ($140kg/cm^2G$)

(2) Study Cases are shown below

Case	Explanation
Original	Without PCC Plant in the above condition.
Base (Original with PCC Plant)	Installation of PCC Plant
Heat Integration	Installation of PCC Plant with Heat Integration of (1), (2) and (3) in 4.2.1

4.3. Study Result

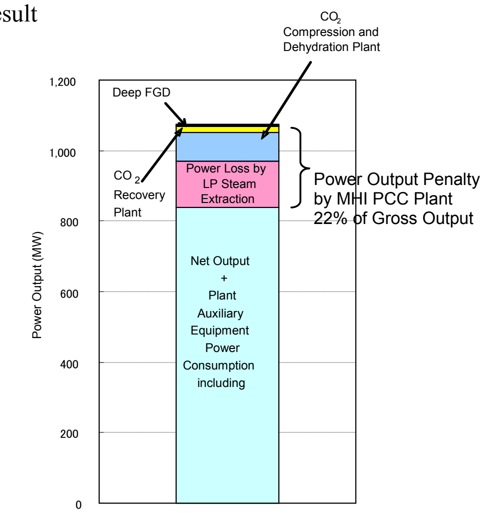


Figure 4-3. Power Output Penalty of PCC Plant (Base Case)

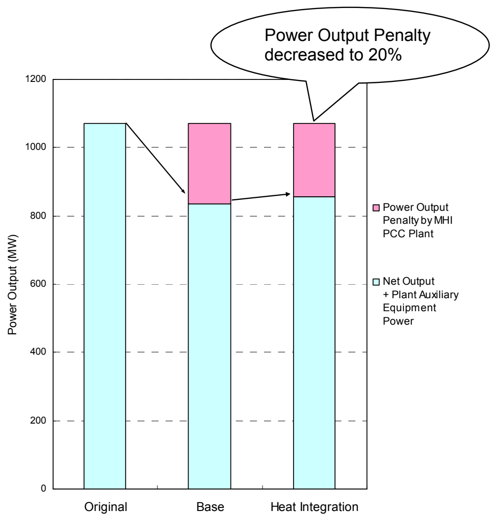


Figure 4-4. Net output improvement with heat integration

The study result are shown in Figure 4-3 and Figure 4-4

(1) In the base case, LP steam which would normally contribute to the electricity generation is extracted from the LP steam turbine, decreasing the net electrical generation considerably as shown in Fig.4-3. One of the main energy losses is the energy required to drive the CO_2 compressor. These losses increase with increased CO_2 capture. Therefore, the application of the PCC plant to a high efficiency power plant with high quality coal and thus an inherently lower specific CO_2 production will be advantageous.
(2) In the above case, the net loss becomes 22% of the gross output by the addition of PCC including the energy requirements of the compression plant.
Through the application of the heat integration method shown in the above diagrams it is possible to decrease the total energy penalty to 20% of the gross out put using MHI's proprietary designs.
(3) Furthermore, by the application of the process improvement to reduce the LP steam requirement, by reducing the LP steam pressure to the reboiler and increasing the CO_2 product pressure at the outlet of the regenerator, further reduction of the net loss is possible and MHI is seeking to demonstrate this concept in the near future.

5. Conclusion

(1) MHI has 16 years of cumulative commercial operational experience of CO_2 Recovery Plants up to 450 T/D capacity and has been awarded a further 4 commercial PCC contracts ranging in size from 340~450 T/D in the chemical and fertilizer industries. Further, MHI is ready to deliver large, single train PCC Plants for natural gas fired application.
(2) For coal fired flue gas application, MHI has undertaken a significant, long term demonstration test at the Matsushima Power Station in southern Japan and has operational experience of more than 5,000 hours, at 10 T/D capacity, applying the KM-CDR Process on coal fired flue gas steams. The effective removal of various coal based flue gas impurities at the pre-treatment section is very important to achieve stable and reliable operation of the CO_2 recovery plant.
(3) Through the deployment of optimization concepts between the PCC plant and the power plant, it is possible to reduce the penalty of the PCC plant to less than 22% of the gross out put of the power plant and a further reduction to 20% can be achieved utilising MHI heat integration concepts. MHI believes a further reduction is possible following an improvement of the process and the optimization of the LP steam pressure to the PCC plant and plans to investigate these concepts in the near future.
(4) One of the absorbents MHI recently tested at the Nanko Pilot Plant demonstrates the thermal energy required for CO_2 recovery can be reduced by about 10%, compared with MHI's proprietary KS-1 solvent [5] .We are continuing the development of additional high efficiency absorbents, which we aim to deploy as a basis for future large scale PCC plants to provide an effective countermeasure to the threat of global warming.

Reference

[1] T.Ohishi Long Term Testing of the Capture of CO_2 from a Coal-fired Boiler
8th International Conference on Green House Gas Control Technology (2006)
[2]M.Iijima Overview of CO_2 Capture and Storage
Technology; an Introduction of MHI's CO_2 Recovery Process
Mitsubishi Heavy Industries, Ltd., Technical Review Vol.45 No.2 (Mar.2008)
[3] M.Iijima Carbon dioxide Capture Technology for Coal Fired Boiler
7th International Conference on Green House Gas Control Technology (2004)
[4] Yasuyuki Yagi Development and Improvement of CO_2-Capture system
8th International Conference on Green House Gas Control Technology (2006)
[5] Yasuyuki Yagi Calculation method for predicting thermal energy required for CO_2 Recovery Plant
9th International Conference on Green House Gas Control Technology (2008)