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Advanced Amine-based CO_2 Capture for Coal-fired Power Plants

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ABSTRACT

Amine-based CO_2 separation is a leading technology expected to be available commercially within the next decade to enable post-combustion carbon capture for coal-fired power stations. Traditional CO_2 capture process utilizing conventional amine solvents is very energy intensive and is also susceptible to solvent degradation by oxygen, SOx and NO_2 in coal-fired flue gas, resulting in large operating cost.

Hitachi addresses the above challenges of amine-based CCS for coal power with the following approach: 1) development of the latest advanced amine-based solvent that has longer service life and lower regeneration energy requirement than commercial solvents; 2) design integration of steam cycle and CO_2 absorption - desorption process; 3) total plant re-optimization involving the boiler, turbine, air quality control system, and CCS system.

Hitachi started post-combustion CO_2 capture R&D in the early 1990s, targeting coal-fired applications from the beginning. Our first pilot test program for coal-fired flue gas was carried out in cooperation with Tokyo Electric Power Corporation (TEPCO). The 1MW_{th} slipstream facility at Yokosuka Power Station was operated for more than 3000 hours, including testing of MEA as benchmark and several commercial and proprietary advanced amine formulations. CO_2 removal of 90% under various plant load conditions was demonstrated. A proprietary solvent blend has shown much lower regeneration energy (at 2800 kJ/kg CO_2) than commercial MEA, as well as very low solvent loss. Hitachi is currently constructing a 5 MW_{th} mobile pilot plant to be tested at several European power plants starting in 2010. This large pilot facility is designed to support further process integration and scaling-up for demonstration and commercial size plants.

This paper will discuss solvent development, bench-scale and pilot testing, as well as system integration considerations of CO_2 scrubbing process into large coal-fired power plants.

INTRODUCTION

In the United States about one half of the electricity is from coal. Worldwide coal contributes to over 40% of the electricity generation today and its share is expected to increase steadily over the coming decades. The continued dominance of coal in global energy structure and the growing concern of climate change necessitate accelerated development and deployment of new technologies for clean and efficient coal utilization. Coal-fired power plants with CO_2 capture and sequestration (CCS) are widely expected to be an important part of a sensible future technology portfolio to achieve overall global CO_2 reductions required for stabilizing atmospheric CO_2 concentration and global warming.

Amine-based CO_2 separation has been implemented since the 1930s for applications such as natural gas purification. It is a leading technology expected to be available commercially within the next decade to enable CCS for coal-fired power stations. However, traditional CO_2 capture process utilizing conventional amine solvents is very energy intensive and is also susceptible to solvent degradation by oxygen, SOx and NO_2 in coal-fired flue gas, resulting in large operating cost. According to recent DOE/NETL studies, MEA-based CCS will increase the cost of electricity (COE) of a new pulverized coal plant by 80-85% and reduce the net plant efficiency by about 30%.

As a global technology and equipment provider for complete thermal power plants, Hitachi addresses the above challenges of amine-based CCS for coal power with the following approach: 1) development of a flexible CO_2 capture process and the latest advanced amine-based solvent with long service life and low regeneration energy requirement; 2) design integration of steam cycle and CO_2 absorption - desorption process; 3) total plant re-optimization involving the boiler, turbine, air quality control system, and CCS system.

DEVELOPMENT OF HITACHI CO_2 CAPTURE TECHNOLOGY

CO_2 Scrubbing Process Overview

The Hitachi CO_2 scrubbing system is designed to achieve 90% capture with significant cost savings and efficiency improvement over current amine scrubbing technologies. The design approach considers the redundancy and reliability requirement according to power industry standards and the flexibility to allow plant owners to utilize common commercial amine solutions and advanced amine-based reagents.

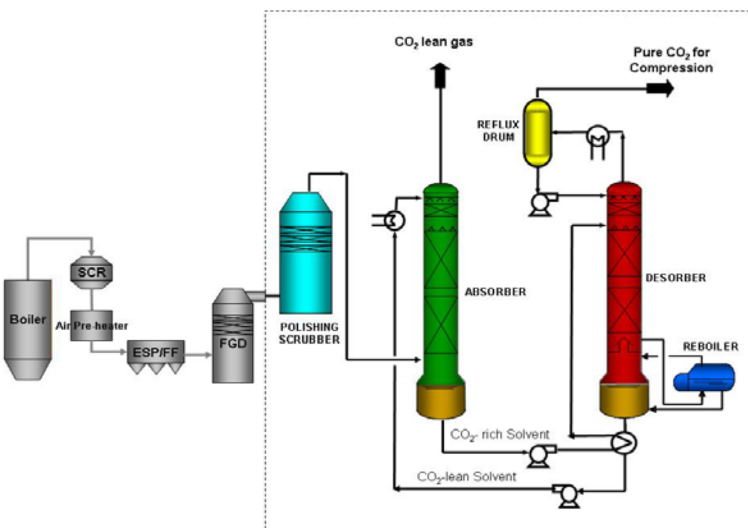

Figure 1: Process diagram of CO_2 capture system

The CO_2 capture system is based on proven process engineering principles. As shown in Figure 1, the main system components are a polishing scrubber (optional), an absorber, a desorber, a reboiler, and a reclaimer (not shown). Flue gas from the power plant or industrial facility is first sent to the polishing scrubber to reduce SO_2 and SO_3 to below about 10 ppm (combined), as well as to cool the flue gas to 40-60°C (100-140^{o}F) range for maximum CO_2 capture in the absorber. Caustic soda (NaOH) solution is used to remove SOx and therefore minimize formation of heat-stable salts (HSS) in the downstream absorber-desorber loop. The clean and cool flue gas leaving the polishing scrubber enters the packed bed absorber where it reacts with the amine-based solvent. Counter-current flow through two or more stages of structured packing maximizes contacting surface area and mass transfer. Solvent solution is injected into the top and collected from the bottom of the packing layers. Because CO_2 absorption is an exothermic reaction, inter-stage cooling heat exchangers may be used to maintain the optimum absorber temperature. CO_2-depleted flue gas leaving the top of the absorber is vented to the stack. The CO_2-rich solution leaving the bottom of the absorber is sent to the desorber via a cross heat exchanger where it gets heated. In the packed-bed desorber, pure CO_2 gas is stripped away from the CO_2-rich solution by contacting it with steam in a counter current direction. A part of the CO_2-lean solution from the bottom of the desorber circulates through a reboiler where auxiliary steam is utilized to partially vaporize the amine solution which, upon returning to the desorber provides the heat needed for amine regeneration to release CO_2. Regenerated solvent is re-sent to the absorber after it gets cooled in the cross heat exchanger. Water washing sections and mist eliminators are located at the top of both the absorber and desorber to prevent entrained liquid droplets from leaving the system. A reclaimer may be operated in batch mode when needed, to control the HSS level in the system.

Process and Solvent Development

Hitachi started post-combustion CO_2 capture R&D specifically for coal-fired applications in the early 1990s, when the first bench-scale and pilot test programs were initiated. Since then, the company has been continually improving process design and the technology for full-scale power plant applications.

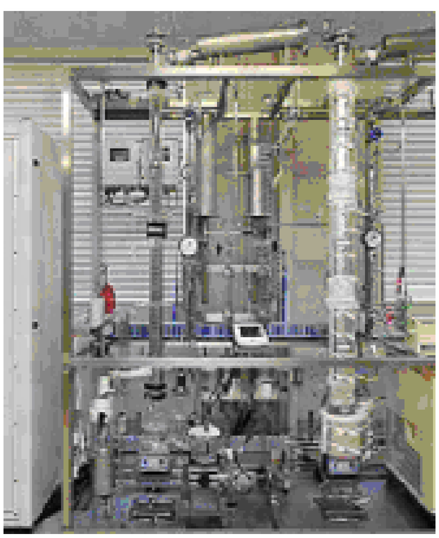

Figure 2: Bench-scale test rig

Figure 3: Pilot plant at Yokosuka

Bench-scale studies (Figure 2) with simulated flue gas have been performed regularly to screen and identify promising absorbents and additives for maximum CO_2 removal efficiencies while keeping solvent degradation and energy consumption low.

Figure 3 shows Hitachi's first CO_2 capture pilot plant built at Yokosuka Thermal Power Plant Unit 2 in cooperation with Tokyo Electric Power Corporation (TEPCO) in Japan. The slipstream test facility treated about 1000 m^3N/h (620 scfm) of flue gas for CO_2 removal during the two-year demonstration period. Five solvent solutions, including a commercial MEA as benchmark and three proprietary solvent formulations were tested. The test for H3, Hitachi's proprietary solvent formulation and the best performing solution of the five, lasted 2000 hours under various operating conditions and generated a large database of solvent and system behavior.

Figure 4 shows that in the 2000 hours of testing under various loads and inlet CO_2 concentrations, H3 consistently achieved greater than 80% CO_2 removal with the average well above 90%. H3 has specific regeneration energy of 2800 kJ/kg CO_2 which is the best among tested solvents and much lower than commercial MEA. It also has high absorption capacity, thus requiring lower liquid-to-gas ratio for 90% capture than that for MEA and resulting in significant operating cost savings. Hitachi continues the refinement of the proprietary solvent blends in its laboratories. New solvent formulations are also being tested and compared with other commercial or near commercial solvents by independent institutions in Japan and USA.

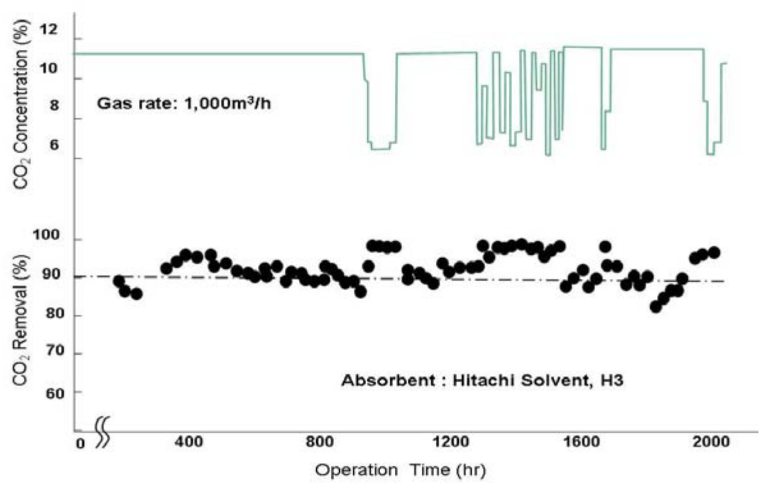

Figure 4: Long-term pilot testing of H3 solvent under various inlet CO_2 concentrations

The latest refinement of the H3 solvent formulation is H3-1, a proprietary blend solvent that has the same advantages of high CO_2 absorption capacity and low regeneration heat as H3, but further reduction in amine loss.

Large Mobile Pilot Plant

Based on earlier experience in Japan, Hitachi Power Europe GmbH, in cooperation with utility partners Electrabel / GDF Suez and E.ON., is building a large mobile pilot plant for the separation of carbon dioxide from coal-fired power plant flue gases. The plant is used to generate data for the development of design concepts for both new power plant integrated with CCS or retrofit of a carbon dioxide separation plant in existing power stations.

Figure 5 shows the general arrangement of the mobile pilot plant. The plant components are built into transportable segments equivalent to overseas containers. These preinstalled segments, shown in Figure 6, are erected at the site of the host power station and connected to a slipstream of flue gas after the plant's FGD unit. The pilot plant is designed to process a flue gas volume flow of approximately 5000 Nm³/h corresponding to 5 MW_{th}. The auxiliaries and steam needed for the operation are supplied by the host power plant. Currently, this mobile pilot plant is being erected at a power plant site in the Northern Europe with testing scheduled to begin in late 2010.

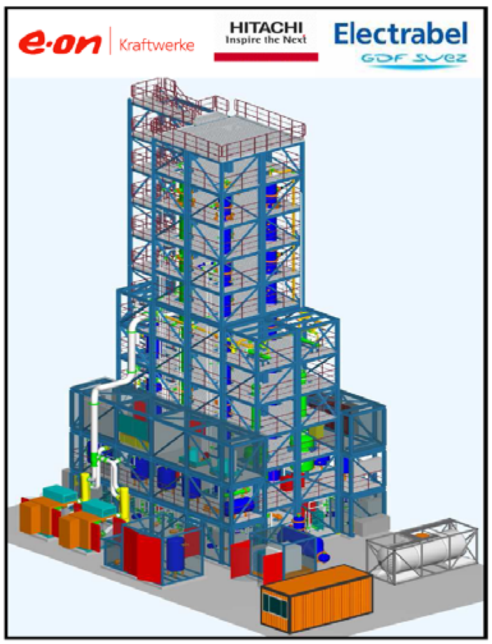

Figure 5. Pilot plant arrangement

Figure 6. Mobile pilot plant segments

The pilot plant can be arranged in different configurations (serial and parallel) to offer maximum flexibility. Therefore, the pilot plant will be able to run under a wide range of operating conditions such as process gas flow, residence time, CO_2 removal rate, etc., and produce reliable data for the scale-up to full size plants.

The primary objective of the pilot program is to investigate the lowest energy demand and to determine design criteria for the optimization of capital investment and operating costs. Besides this the design data to minimize the environmental impact of the CO_2 scrubbing system will be of great interest. The pilot plant will be fully equipped with an on-line monitoring system to continuously measure trace emissions of solvent as well as some of the degradation products. In addition, periodic campaigns will be conducted for the complete measurement of degradation products and emissions.

Demonstration Program

Hitachi will provide an integrated CO_2 capture system and the advanced amine-based solvent H3-1 for a CCS demonstration effort in partnership with industry and the government of the United States. In October 2009 the US DOE selected the CCS demonstration project by Wolverine Power Supply Cooperative, Inc. (WPSCI) as a part of the Industrial Carbon Capture and Storage (ICCS) Phase 1 Projects. The project plans to demonstrate Hitachi's technology to capture 300,000 tons of carbon dioxide (CO_2) per year (1000 metric ton/day on a 50MWe slipstream) from a 600 MW power plant to be built near Rogers City, Michigan. The captured CO_2 will be sequestered through Enhanced Oil Recovery (EOR) operations near the project site. Hitachi is also actively pursuing demonstration opportunities in other global markets, especially in Europe.

Scaling up to Full Size Plant

Figure 7 shows the steps for scale-up from pilot plant to full-size commercial plant. The $5MW_{th}$ pilot plant and 50 MW_e demonstration plant are currently under development, as discussed above. The next logical step is a large demonstration or small full-scale system at about 350 MW_e before achieving a full-scale commercial operation at about 800 MW_e.

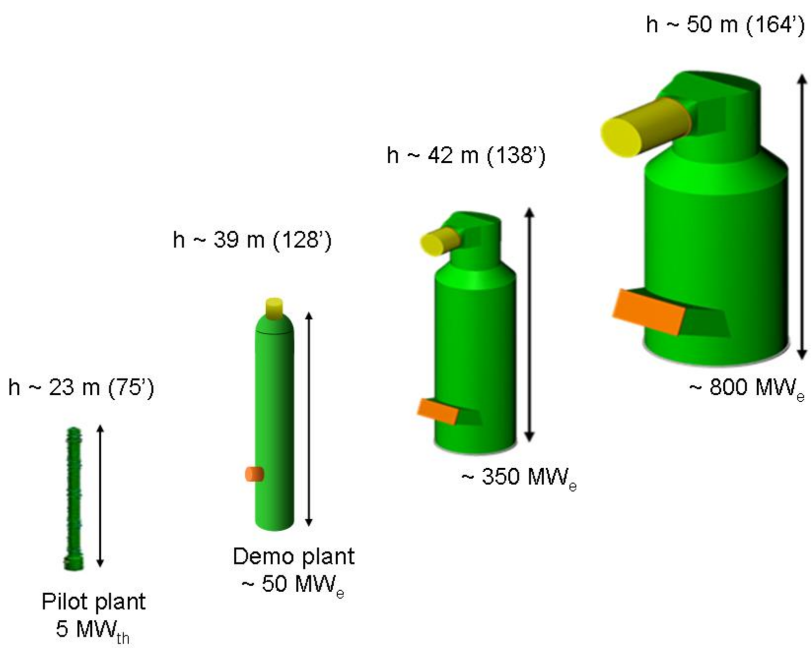

Figure 7: Steps from pilot plant to full size plant

INTEGRATING CO_2 CAPTURE INTO A POWER PLANT

Implementation of CO_2 scrubbing into a power plant poses enormous challenges to the design of the power plant itself and the post combustion capturing system respectively. Several interfaces, shown in Figure 8, have to be considered and optimized which necessitate modifications to the plant components, such as

- Optimization of flue gas cleaning
- Process cooling and heat recovery
- Energy supplied for CO_2 recovery and amine regeneration
- Energy consumption for CO_2 capture process equipment and controls
- Energy supply for CO_2 compression

Aside from using the best solvent with the lowest regeneration energy requirement, the overall net plant efficiency of a power plant with CCS can be maximized by optimizing the integration of available heat sources and heat sinks across the entire plant system including the CCS scope. In addition to process and electrical interfaces, the required space for the carbon capture plant can be a problem especially for retrofits into existing power plants. The minimization of the required space is a major task for both process design and arrangement planning.

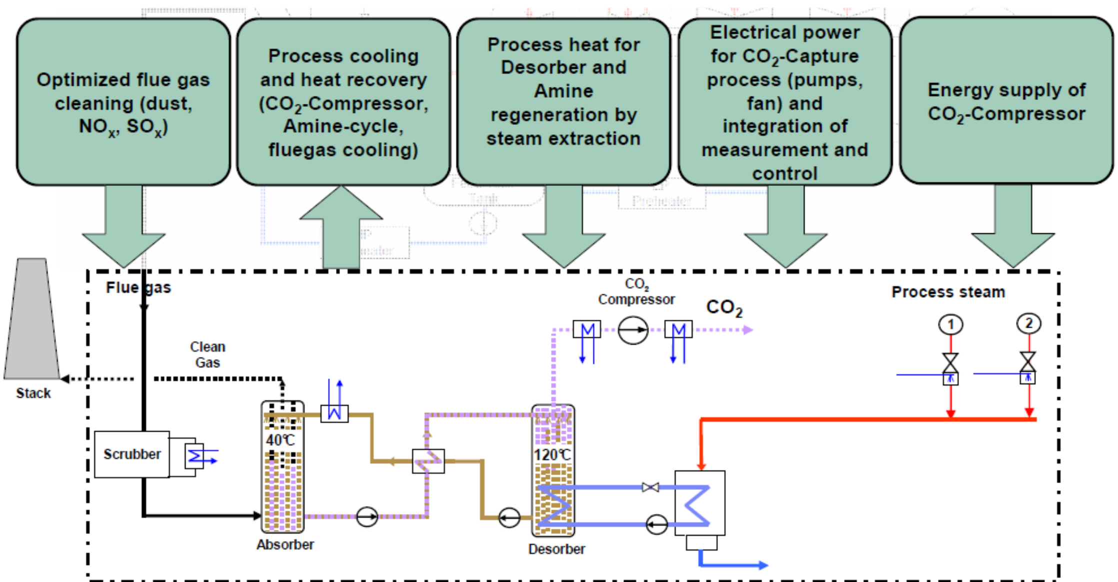

Figure 8: Interfaces between a post combustion CO_2 capture system and a power plant

Impact on net plant efficiency

With full integration of the CCS and the balance of the power plants, and necessary of modifications to the water-steam cycle and the steam turbine, the loss of net efficiency can be reduced to only 7.8% points for H3-1 and 7.5% points for Hitachi's next generation solvent (NGS) with regeneration energy of 2500 kJ/kg CO_2 (including CO_2 compression to 2900 psia). The efficiency loss for a conventional approach with minimum integration and an optimized approach are shown in Figure 9 for comparison.

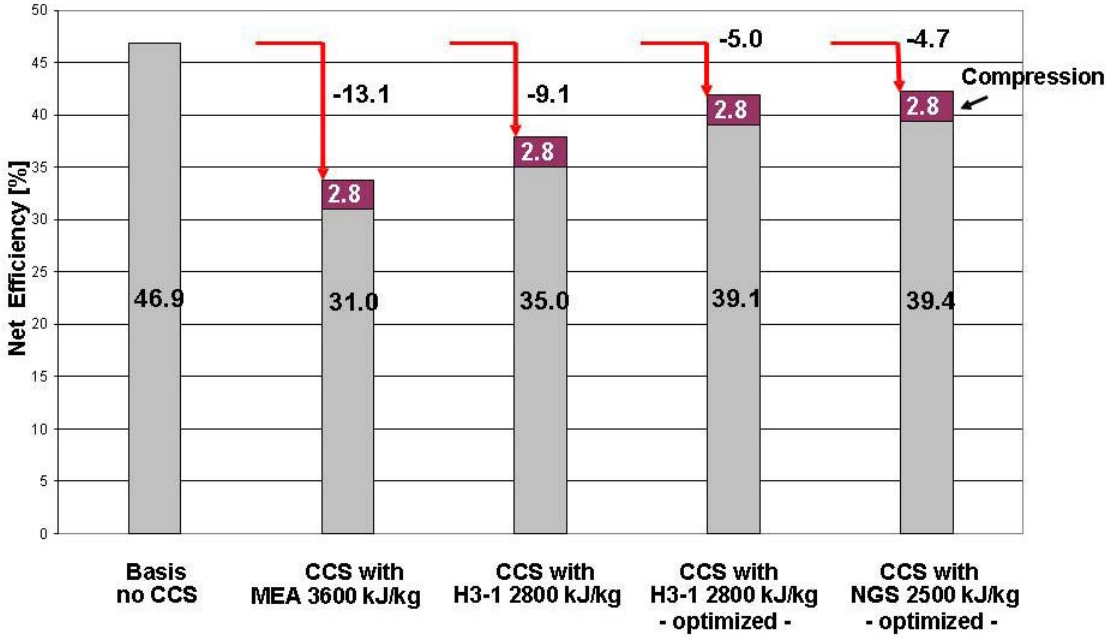

Figure 9: Impact of optimization on net plant efficiency

SUMMARY

Post-combustion solvent based technology is a more mature solution presently being developed for CO_2 reduction from coal-fired power plants. However, many technical challenges still remain that need to be addressed to make it cost-effective. Through bench-scale and pilot tests, Hitachi has developed advanced amine-based technologies that can achieve high CO_2 removal efficiencies with minimum solvent degradation and require less energy for solvent regeneration.

Hitachi is currently building a large mobile pilot plant (5 MW_{th}) in Europe and has developed design for a large CCS demonstration plant (50 MW_e) in the United States, among other development and demonstration activities. In addition to these large testing and demonstration programs that will provide valuable data, Hitachi has developed the expertise to improve integration of the CO_2 capture system with the balance of plant and reduce plant efficiency loss in order to accelerate commercialization of CCS for coal-fired power plants worldwide.