



Review

Clean coal technologies in Japan: A review

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ARTICLE INFO

Article history:

Received 27 April 2016

Accepted 17 December 2016

Available online 13 January 2017

Keywords:

Clean coal technology

Combustion

Gasification

CO₂ recovery and utilization

Gas cleaning

ABSTRACT

Coal is the primary fossil fuel most used in the world for the electricity generation, iron making, and cement/concrete and chemical production. However, utilization of coal also results in emissions of CO₂, SO_x, NO_x and other noxious compounds. The development of clean coal technology (CCT) is a main issue to maintain a clean environment. CCT in Japan is considered the highest level in the world. In this review, the developing CCTs in Japan including high efficiency combustion technologies, advanced gasification technologies, CO₂ recovery and utilization technologies, and flue gas cleaning technologies are introduced and discussed. It is expected to provide some new view-of-points for CCT development.

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1. Introduction

Coal is one of the primary energy resources in the world, and it also produces a large amount of carbon dioxide (CO₂) and other air pollution compounds such as SO_x, NO_x, soot and mercury [1–12]. In Japan, coal consumption has rapidly increased since the end of 1990s. Japanese government is promoting R&D on clean coal technology (CCT) to increase energy efficiency and carbon capture capability, and simultaneously decrease pollutant emissions [1]. To date, the gross thermal power generation efficiency in Japan has been increased from about 38% to 45%, and the pollutant emissions per generated power unit from thermal power plants are far below other industrialized countries. Recently, some new and ambitious R&D plans, such as advanced-ultra super critical power generation technology (A-USC) [13], novel CO₂-captured Integrated coal gasification combined cycle (IGCC) power generating technology [14–18], chemical looping combustion (CLC) power generation technology [19,20], integrated coal gasification fuel cell combined cycle power generating technology (IGFC) [1,2], Advanced integrated coal gasification combined cycle/advanced integrated coal gasification fuel cell combined cycle power generating systems (A-IGCC/A-IGFC) [1,2] and super-IGFC (S-IGFC) [21,22] have been made to further increase the gross thermal power generation efficiency to as high as even 89%. In this review, the developing CCTs in Japan including high efficiency combustion technologies, advanced gasification technologies, CO₂ recovery and utilization technologies, and flue gas cleaning technologies are introduced and discussed. The aim of this review is to look at the potential advances and possible large scale applications of CCTs developed in Japan. It is expected to provide some new view-of-points for CCT development.

2. High-efficiency Coal Combustion Technologies

As the established and highly reliable coal utilization way, various high-efficient combustion techniques with low pollutant emissions have been developed and applied in Japan [1]. The NO_x emission and dust generation levels during the coal combustion in Japan is at the world's lowest level owing to the flue gas and ash treatments at the downstream side of the boiler and the development of SO₂ removal and low NO_x combustion technologies. By using the separation of dense and lean pulverized coal streams and a multilayer charge of combustion air, novel low NO_x-emission pulverized coal burners with the improved ignitability and intraflame denitration ability have been developed by Japanese makers [23,24]. Also, by using the residual hydrocarbons or the hydrocarbon generated from a small amount of fuel oil fed from the top of burner, intrafurnace denitration is realized in the main burner zone of the boiler [24]. On the other hand, the increase in the thermal efficiency of power generation plant is an important issue not only to reduce the cost but also to suppress CO₂ and other pollutant emissions. In this section, high efficiency pulverized coal-fired power generation technology with ultra super critical (USC) steam condition, and internal circulating fluidized-bed combustion technology (ICFBC) are reviewed and discussed.

2.1. USC and A-USC

The power generation efficiency for the coal-fired power generation system is decided by the inlet steam conditions (especially steam temperature and pressure) of the steam turbine. To make the steam achieve USC state, the Rankine regenerative-reheat steam cycle system is generally designed and applied [25]. Fig. 1 shows the history of steam conditions of thermal power plants in Japan [13]. Now, the steam condition of commercial USC power plants has reached 25 MPa × 600/610 °C.

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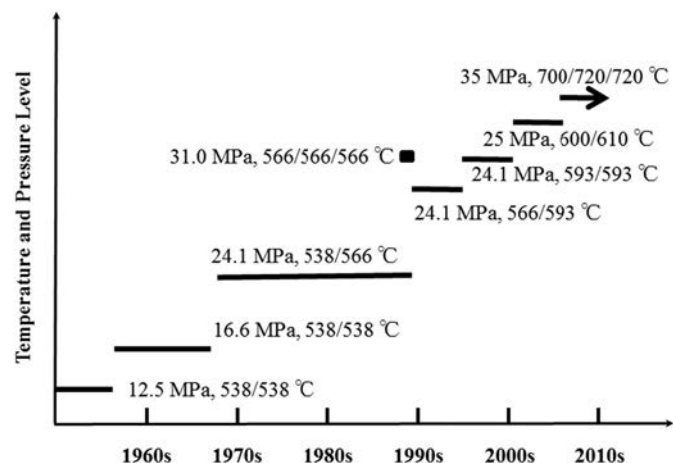


Fig. 1. The history of steam conditions of thermal power plants in Japan (Source [1], edited with permission from NEDO, Japan).

Recently, advanced USC (A-USC) power plants with an inlet steam temperature over 700 °C are under development. It is expected that the net thermal efficiency over 46% can be reached [13]. However, such a high USC condition needs special materials for the fabrication of steam generator, steam turbine and related valves [13,26,27]. To date, nickel-based alloy is considered the optimum material for use above 700 °C. Identification of its viability in A-USC under both laboratory and actual field conditions is being undertaken.

2.2. ICFBC

Since 1986, various circulating fluidized-bed combustion (CFBC) technologies were introduced into Japan from USA and Europe. At the same time, the Japanese also began to develop their own CFBC technologies, in which ICFBC technology is the representative one [1,28–30].

Fig. 2 illustrates the structure of ICFBC, in which silica sand is used as the fluidizing material and limestone is applied for desulfurization [1]. The fluidized bed combustor is divided into the combustion chamber and the heat recovery chamber by a tilted partition to create a swirling flow inside the main combustion chamber and a circulation flow between the two chambers. Also, a circulation flow is formed to return the unburned coal and unreacted limestone from the cyclone at the exit of the boiler to the fluidized bed. The main advantages of ICFBC can be summarized as follows:

- Various coals including high-rank and low-rank coals, biomass, waste tires and sludges can be efficiently burned in it due to the vigorous movement of bed materials.

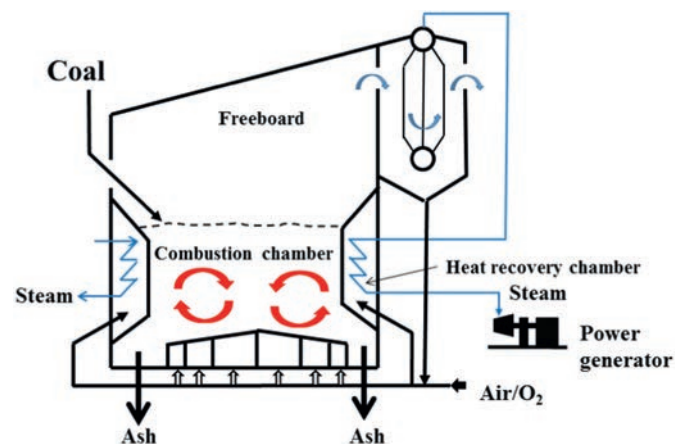


Fig. 2. The structure of ICFBC (source [1], edited with permission from NEDO, Japan).

- Since the quantity of recovered heat is solely controlled by varying the air-flow rate, the bed temperature can be easily tuned.
- The desulfurization efficiency can reach 90% with a limited amount of limestone. On the other hand, denitration is realized in two combustion areas: the reducing combustion in the main fluidized-bed area and the oxidizing combustion in the freeboard area. Herein, the unburned carbon can be effectively recycled to the fluidized bed by cyclone, which can increase the denitration efficiency.
- There are no heat transfer tubes in the fluidizing zone so that its structure is simple and easy to maintain. Especially, desulfurization and denitration can be realized inside the fluidized bed. The circulation flow is extremely effective in increasing the combustion efficiency, decreasing NO_x and SO_x generations.

3. Advanced Gasification Technologies

Gasification is a process to convert carbonaceous feedstock into gases with chemical heating value. Coal gasification is a technology to convert coal into a gas mixture including H₂ and CO by coal pyrolysis and char gasification. It offers one of the most versatile and cleanest ways for converting coal into electricity and chemicals. Compared to conventional coal fired power plants, CO₂ capture and removal of pollutants from coal gasification process is much more easily carried out. The clean syngas can effectively be used for power generation, chemical synthesis or hydrogen production [1–3,7,10,16,17]. Now, coal gasification is considered as the heart of the clean coal technology. In Japan, integrated coal gasification combined cycle (IGCC) power generation system is becoming a key technology to realize high efficiency and environmentally friendly using of coal for power generation [1,2]. Therefore, various IGCC-related technologies have been developed or are under development. Here, the typical coal gasification technologies, IGCC technologies developed in Japan are reviewed and remarked. Furthermore, the developing IGFC, A-IGCC/A-IGFC and S-IGFC technologies are also introduced.

3.1. Hydrogen-from-coal process (HYCOL process)

HYCOL process is a gasification technology with an entrained bed, in which pulverized coal is gasified with oxygen under high temperature (1500–1800 °C) and high pressure (3 MPa) [1,16,31,32]. The main gas products in this process are H₂ (31%) and CO (61%) with a carbon conversion of 98% or more and a cold gas efficiency of 78% or greater. This technology has the following features:

- A two-stage swirling-entrained-bed in one chamber is applied (Fig. 3) [16]. Dry pulverized coal in a pressurized hopper is introduced into the gasifier via four burners at each stage with a swirling mode, which can easily and uniformly distribute coal to the burners. The oxygen feed and the gasification rate at the upper and lower stages are separately controlled to achieve the high thermal efficiency.

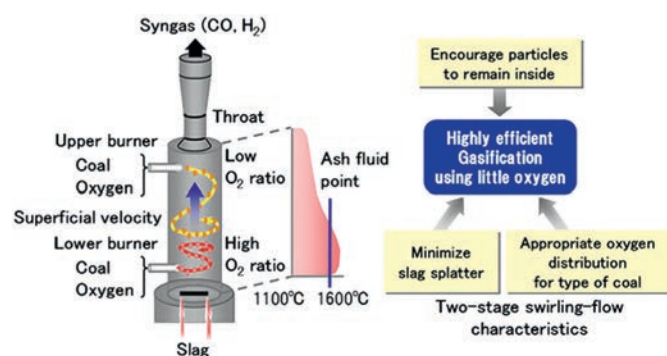


Fig. 3. Two-stage swirling-entrained-bed gasifier/combustor (reprinted with permission from Ref. [16]).

- A technique to let slag self-coated on the water-cooled tubes inside the gasifier chamber is applied for prolonging the life of tubes and improving the reliability of the gasifier.
- The ash in a slag state can be discharged smoothly through a slag hole located in the hearth of gasifier due to the maintained high temperature by the swirling gas flow.
- The unreacted char can be effectively separated by a cyclone and recycled to the gasifier in a high-temperature and high-pressure state, ensuring the high carbon conversion.
- Sulfur and nitrogen components in the coal can be easily recovered in the forms of H_2S and NH_3 respectively.

HYCOL process was developed by 9 private companies. Its performance indicates that it is one of the world's most advanced gasification furnace. Based on it, a coal gasification fuel cell system for power generation is also being developed, which will be introduced in the following section.

3.2. Multi-purpose coal gasification technology development (EAGLE project)

The purpose of EAGLE (coal Energy Application for Gas, Liquid & Electricity) project is the development of a CCT using the above HYCOL process. The obtained coal-gasified gas is expected to be applied for fuel cell power generation or production of synthetic fuel, hydrogen and chemicals [1,16,33,34]. Now, a pilot test power generation plant with a coal processing capacity of $150 \text{ t} \cdot \text{d}^{-1}$ has been built, in which the system is composed of coal pretreatment, HYCOL gasifier, air separation, gas purification, effluent treatment, produced gas combustion and gas turbine. The gasification temperature and pressure are 1200–1600 °C and 2.5 MPa respectively. The oxygen purity for the gasification is 95%. As a result, the gas electric power generation ability, carbon conversion rate and cold gas efficiency reaches $10100 \text{ kJ} \cdot \text{m}^{-3}$, 99% and 78%, respectively. The concentrations of sulfur compounds, ammonia, halogen compounds and dust are less than 1 ppm, 1 ppm, 1 ppm and $1 \text{ mg} \cdot \text{m}^{-3}$ in the effluent, respectively. Furthermore, a CO_2 recovery and sequestration system including chemical and physical CO_2 adsorptions has also been tested. Based on these achievements, a larger pilot test plant with a coal processing capacity of $1180 \text{ t} \cdot \text{d}^{-1}$ is being built in Japan, in which a larger scale CO_2 recovery and sequestration system with a 90% CO_2 recovery capability is also included. The target purity of recovered CO_2 is over 98%. Furthermore, an IGFC system as shown in Fig. 4 will be built and tested in the near future [1,34]. It is expected

to reduce CO₂ emission by up to 30% when compared with the conventional thermal power plants.

3.3. Nakoso air/oxygen-blown IGCC

Nakoso 250 MW air/oxygen-blown IGCC demonstration plant with a coal processing capacity of $1700 \text{ t} \cdot \text{d}^{-1}$ is the first and successfully commercial IGCC system developed by Japan [17,18,35,36]. As shown in Fig. 5, it is consisted of an air-blown gasifier (Fig. 6) with dry coal feed, a wet desulfurization system for gas clean-up, a high-efficiency G-series gas turbine with a combustion temperature of 1500°C class and a power output of 124 MW, an exhaust heat recovery steam generator (HRSG) and a steam turbine using the exhausted heat from gas turbine with a power output of 126 MW. The compositions of the produced gases are 30.5% CO, 2.8% CO₂, 10.5% H₂, 0.7% CH₄ and 55.5% N₂ and others. SO_x, NO_x and particulate matter in the exhausted gas are less than 1.0×10^{-6} , 3.4×10^{-6} , and $0.1 \text{ mg} \cdot \text{m}^{-3}$, respectively. The net plant efficiency reaches 42.9% (lower heating value, LHV) with a cold gas efficiency of 77.2%. The carbon conversion rate in the gasifier is almost 100%, and the gasifier showed stable syngas production for many kinds of coals including bituminous coal, sub-bituminous coal, and lignite (Texas lignite, Indonesian lignite, Victoria brown coal). Furthermore, it updated the world's longest continuous operation time and reached 3917 h in 2013 with an accumulated operation time of 27000 h. Based on the results of successful demonstration test, a 540 MW IGCC plant is being constructed in Japan.

3.4. CO₂-recovery-type IGCC system

Recently, a CO₂-recovery-type IGCC system as shown in Fig. 7 was proposed in Japan, in which a part of CO₂ in the exhausted gas is recycled and used as the gasification agent with O₂ produced from cryogenic air separation unit [37]. This system has the following features:

- Pure oxygen is used in gasifier so that the energy needed for the separation of CO_2 from exhausted gas can be decreased greatly. As such, the net power generation efficiency will be increased.
- CO_2 recycled to the gasifier can enhance the coal gasification *via* $\text{C} + \text{CO}_2 \rightarrow 2\text{CO}$, and improve cold gas efficiency.
- Since CO_2 has higher molar specific heat, when it is used as working fluid, the heat loss will be reduced in the compressors and the heat transfer efficiency will also be increased to some extent when comparing with the cases using other kinds of gases.
- The gross power efficiency can reach 42% in the case of CO_2 recovery.

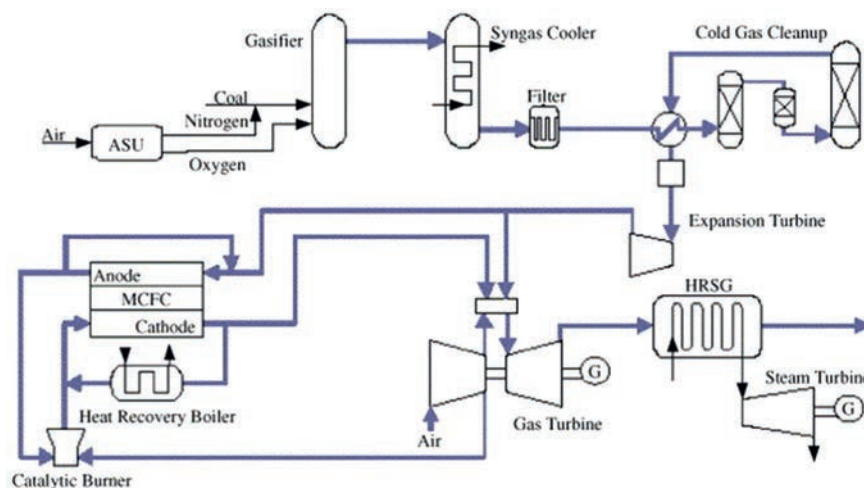


Fig. 4. Proposed IGFC system in Japan (reprinted with permission from Ref. [34]).

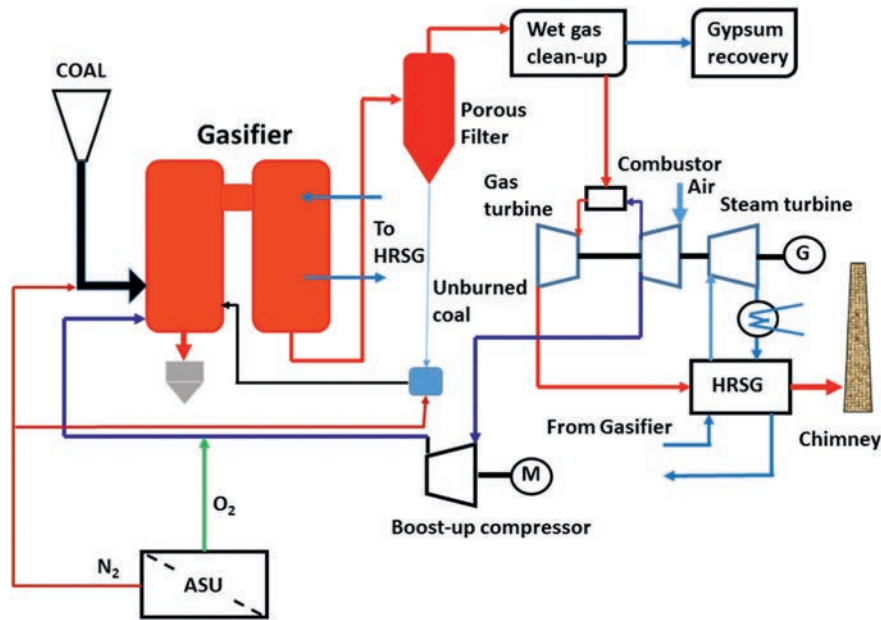


Fig. 5. Nakoso air/oxygen-blown IGCC system (source [1], edited with permission from NEDO, Japan).

3.5. Advanced IGCC/IGFC with exergy recovery technology

The ideal power generation efficiencies of conventional IGCC and IGFC are 48%–52% and 55%–60% (Higher Heating Value, HHV), respectively. To increase these values to higher level, as shown in Fig. 8, based on exergy recuperation theory, Advanced IGCC (A-IGCC) and Advanced IGFC (A-IGFC) concepts were proposed in Japan, in which a steam reforming gasifier is used to replace high temperature gasifiers,

and the exhausted heat from gas turbine or solid oxide fuel cells (SOFCs) is recycled to provide the energy for steam gasification [2,38,39]. As such, the power generation efficiencies are estimated to be approximately 10% higher than those of conventional IGCC and IGFC. To realize these processes, a high-density triple-bed combined circulating fluidized bed (TBCFB) gasifier system as shown in Fig. 9 was proposed, in which a downer pyrolyzer, a bubbling fluidized bed (BFB) gasifier and a riser combustor are included [2,40–48]. The coal is pyrolyzed rapidly in the pyrolyzer and then, the pyrolysis tar and gas are separated from the char using a fast gas–solid separator so that only the char enters the BFB gasifier and is gasified by the steam from the gas/steam turbine and/or SOFCs. The unreacted char is moved to the combustor, in which the char is partially or completely combusted

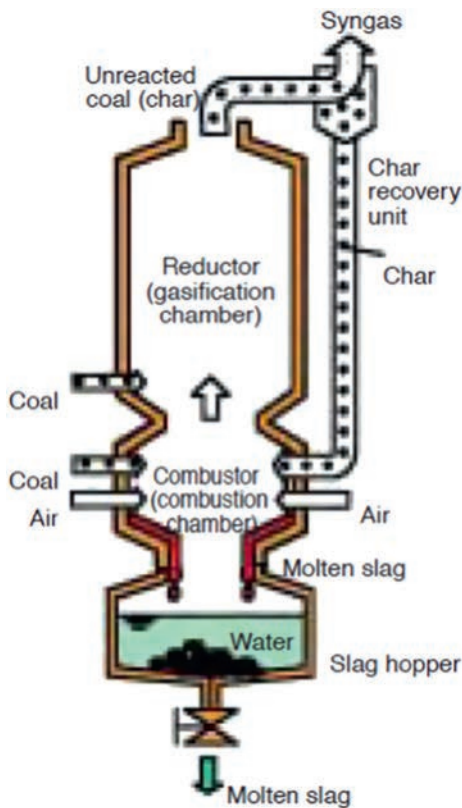


Fig. 6. Air-blown gasifier (source [1], reprinted with permission from NEDO, Japan).

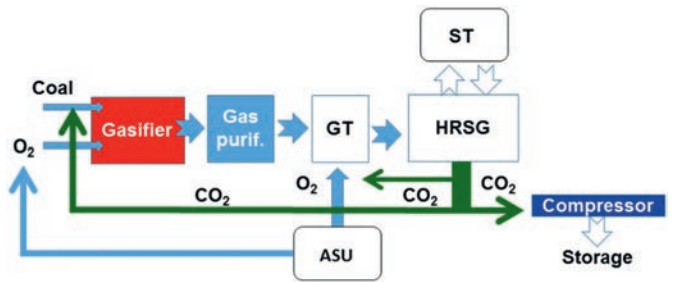


Fig. 7. A proposed CO₂-recovery-type IGCC system [37].

A-IGCC	A-IGFC
PGE: 57%–59%	70%–76%
PGE: Power Generation Efficiency	

Fig. 8. Advanced IGCC (A-IGCC) and advanced IGFC (A-IGFC) concepts [2].

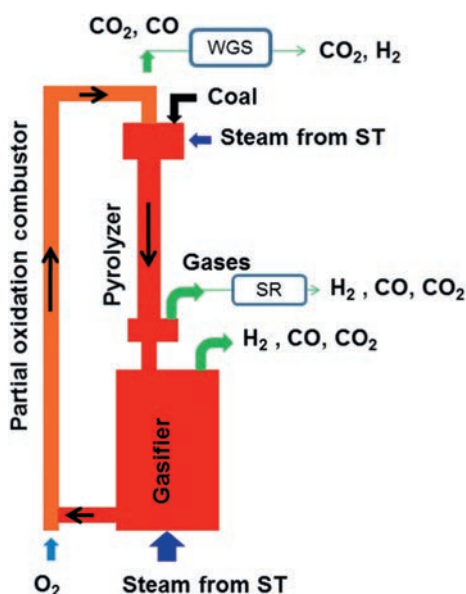


Fig. 9. A developing high-density triple-bed combined circulating fluidized bed (TBCFB) gasifier [2,40–48].

to generate heat. To use the heat efficiently, a large amount of inert solids as the heat carrier circulated in the three beds for providing heat from the combustor to the pyrolyzer and char gasifier is necessary.

3.6. Super IGFC

Recently, a super IGFC (S-IGFC) concept with power generation efficiency of as high as 89% was proposed in Japan [22,49,50]. As shown in Fig. 10, S-IGFC is mainly composed of a steam gasifier and a SOFC, in which the heat and steam generated in SOFC provide directly to the steam gasifier, and no gas turbine as well as steam turbine is needed for this system. How to combine the gasifier with SOFC so that the steam and heat can be effectively used becomes the main issue for this system.

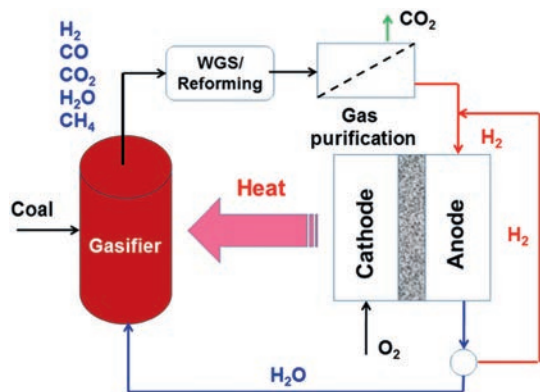


Fig. 10. A proposed S-IGFC concept with ultra-high power generation efficiency [22,49,50].

4. CO₂ Recovery and Utilization Technologies

CO₂ emission from coal is larger than other fossil fuels. Although Japan has achieved the highest efficiency levels of coal-fired thermal power generation in the world for reducing CO₂ emission, it is still necessary to consider how to recover and utilize CO₂ for reducing environmental load [1]. Now, CO₂ capture and storage (CCS) technology and CO₂ conversion technology are being developed to realize zero-CO₂-emission coal-based power generation.

4.1. In-situ CO₂ coal capture utilization technologies

An *in-situ* CO₂ capture chemical looping coal gasification method named HyPr-RING (Hydrogen Production by Reaction-Integrated Novel Gasification), in which CaO is used as CO₂ sorbent and is directly injected into the gasifier with steam, was proposed in Japan [1,14, 51–53]. As shown in Fig. 11 [52], in this process, CaO reacts with H₂O to produce heat for coal gasification and CO₂ generated in the steam gasification is fixed by CaO or Ca(OH)₂ in the form CaCO₃, and CaCO₃ is regenerated into CaO by calcination. 50%–80% of the heat energy needed for CaCO₃ calcination is in fact maintained in the chemical energy of CaO, which can be provided for coal gasification in the later process. Theoretically, 2 mol of H₂ can be produced from 1 mol of carbon. As a result, the product gases from this chemical looping coal gasification process contain approximately 80% H₂ with 20% CH₄ with a dry base. Also, in this process, CaO can be used for sulfur removal. It is expected that the cold gas efficiency reaches 75% or more, the sulfur content in the product gas is less than 1 ppm, and a high purity of CO₂ can be obtained.

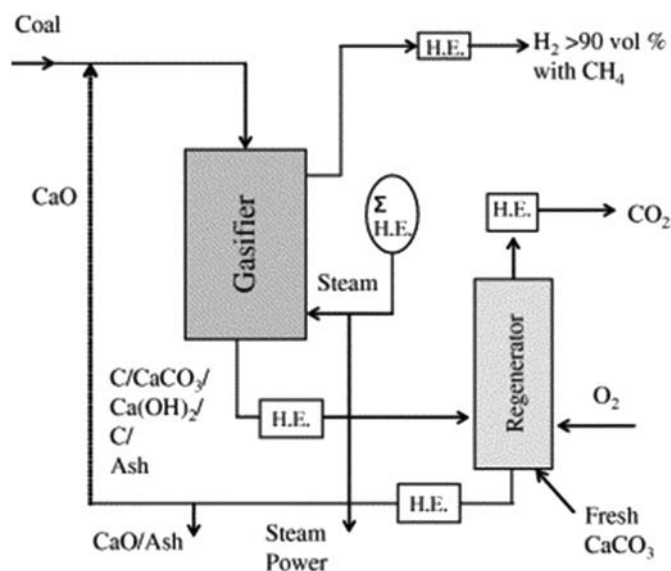


Fig. 11. HyPr-RING system (reprinted with permission from Ref. [52]).

4.2. Recovery CO₂ from exhaust gas

In coal-fired power generation processes, CO₂ capture technologies are generally divided into pre-combustion, oxyfuel and post-combustion ones based on the stage of CO₂ captured [54–57]. Monoethanolamine (MEA) liquid absorption method is one of the most mature chemical CO₂ capture methods in the post-combustion technologies. However, the absorbed CO₂ has to be thermally released for the regeneration of MEA, which results in the energy penalty to the power plant. Also, the conventional amine solvents could be degraded by oxygen, SO_x and NO_x in the coal-fired flue gas, leading to large operating cost. Japanese researchers try to solve such problems by (1) development of new amine-based solvent with longer life cycle and lower regeneration energy requirement; (2) integration of the steam cycle with CO₂ adsorption/desorption process; and (3) redesign the total systems including gasification, turbine, air or oxygen supplying and CCS systems to achieve the optimized operation [58–60]. It is expected to reduce the energy consumption in the future to lower than 1.5 GJ·(t CO₂)^{−1}, which is almost 2/5 of present level.

Other new technologies such as membrane separation and chemical looping combustion for CO₂ capture are also being developed in Japan [57,61]. Separation of CO₂ from gas flue by using membrane is a

potential alternative way owing to its low fabricating and operating costs, low energy consumption and easy operation. However, to date, low CO₂ permeability restricts its industrial applications. It is expected to develop novel membrane with high CO₂ permeability and selectivity. The developed membranes always have a trade-off between the CO₂ permeability and CO₂ selectivity, resulting in an upper limit to membrane performance. To solve this problem, facilitated transport membranes (FTMs) using amino acid ionic liquids (AAILs) composed of different sizes and numbers of amino groups as CO₂ carriers in hydrophilic polytetrafluoroethylene (PTFE) microporous membranes are fabricated [61]. It is found that such AAILs-filled membranes have high CO₂ permeability and high CO₂ selectivity against N₂. Another membrane with CO₂ molecular gate function, by which the pathway for gas molecules is occupied solely by CO₂ and other gases cannot pass through it, is also developed in Japan. It is reported that the modified poly(amidoamine) (PAMAM) dendrimers membrane showed the largest CO₂ selectivity of more than 1000 and excellent CO₂ selectivity to date [62,63]. These results are encouraging Japanese researchers to develop more efficient membranes for CO₂ capture from coal fired power generation systems and other processes.

A chemical looping combustion system as shown in Fig. 12, which was proposed in 1987 by Ishida *et al.* [19], is also being developed in Japan for hydrogen production from coal and simultaneously, capture of pure CO₂ without consumption of energy for separation. Various metal oxides including Fe₂O₃, Mn₂O₃, NiO, and CuO with low-cost can be applied in this system [64].



Fig. 12. A chemical looping combustion system [19,64].

4.3. CO₂ utilization technology

As other countries, carbon sequestration, a technology to separate, recover, store CO₂ emitted from large-scale CO₂ emission sources under the ground or sea, is widely studied in Japan [65,66]. The candidate storage sites in Japan are distributed along the coast and in the sea. The influence of earthquakes on the storage safety must be considered and assessed first in Japan. Storage of CO₂ in the sea may have more environmental impact than underground storage and thus, Japan researchers pay more attention on selection of offshore storage sites and geophysical monitoring of CO₂ injection in the onshore saline aquifers. Various field surveys and measurements such as crosswell seismic tomography, well logging, the reservoir formation pressure and temperature, and micro-seismicity monitoring have been conducted. One CO₂ storage site is found to have no any CO₂ leakage from the reservoir even attacked by a huge earthquake (M6.8). Many research projects on this field are undergoing. It is expected that it will be applied at a large scale in the near future.

The captured CO₂ can be also reused in industry, agriculture and energy production. In Japan, the following technologies are being developed

for the utilization of CO₂: (1) recovery of CO₂ for the production of methanol, dimethyl ether, and kerosene and light oil using the conventional routes; (2) economic photocatalytic conversion of CO₂ into methane (CH₄) and/or methanol; (3) making plastics from CO₂; and (4) microalgae culture for bio-oil. The key for the first 3 technologies is the development of novel catalysts due to the stability of CO₂.

5. SO_x, NO_x and Toxic Particles Removal Technologies

Sulfur oxides (SO_x), nitrogen oxides (NO_x) and particulate matters emissions from coal are the main pollution resources in the world. In 1970s, Japan made strict regulations to control their emissions [1]. Since 1970s, most of pulverized coal-fired power generation plants have been equipped with wet limestone and gypsum-based desulfurization systems, selective catalytic reduction (SCR) deNO_x processes, and electrostatic precipitator for particulate treatment. Now, some new desulfurization, deNO_x and particulate matter removal processes are under development.

Table 1 summarized the main SO_x reduction technologies in Japan [1]. One can see that limestone is used in these processes and the following reactions are included in the SO_x removal:

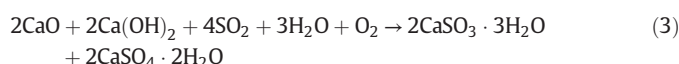
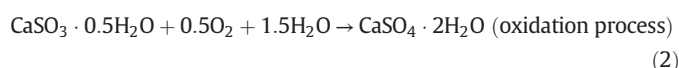
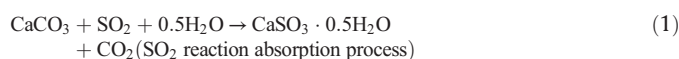


Table 1
SO_x reduction technologies (source [1], edited with permission from NEDO, Japan)

Technology	Features
Wet limestone-gypsum process	Water-mixed limestone slurry as SO ₂ absorption material • Soot-separation process: > Dust tower is installed upstream for dust collection and HCl/HF removal > High-purity gypsum can be obtained > High cost • Soot-mixed process Without dust tower installed > Low cost
Coal-ash-based dry desulfurization process	• The absorbent is from coal ash, limestone, calcium hydroxide and spent absorbent > SO _x removal efficiency: 90% > NO _x removal efficiency: 20% > Dust collection efficiency: >96%
Spray dryer process	• Water is added to burned lime to make Ca(OH) ₂ slurry for SO ₂ chemical absorption > Desulfurization reaction and limestone drying occur simultaneously > High-quality gypsum can be obtained
Furnace desulfurization process	• Limestone mixed with coal for desulfurization

Table 2 summarized the main NO_x reduction technologies in Japan [1]. Here, the selective catalytic reduction (SCR) process is widely used in coal-fired power generation plants. For NO_x removal, it is expected to convert NO_x (mainly NO, NO₂) into N₂ and H₂O. Thus, in the DeNO_x reactor, ammonia (NH₃) is generally used for the following reaction:



As shown in Table 2, in the presence of NH₃, if the reaction temperature is high enough (>850 °C), NO_x can be converted to N₂ and H₂O without the use of catalysts. However, the NO_x removal efficiency is as low as 40% at an NH₃/NO_x molar ratio of 1.5. As such, various DeNO_x

Table 2
NO_x reduction technologies (source [1], edited with permission from NEDO, Japan)

Technology	Features
Selective catalytic reduction process	<ul style="list-style-type: none"> Ammonia(NH₃) is blown into exhaust gas, and reacts with NO_x over catalyst NO_x is decomposed to H₂O and N₂ Grid- or plate-like catalyst is used Catalyst is mainly composed of TiO₂, doped with active ingredients such as vanadium and tungsten. Catalytic reaction temperature: 350 °C NO_x removal efficiency: 80%–90%
Selective non-catalytic reduction process	<ul style="list-style-type: none"> NH₃ is blown into the exhaust gas at 850–950 °C NO_x removal efficiency is not so high
Radical injection method	<ul style="list-style-type: none"> Argon plasma is injected into NH₃, generating NH₃ plasma and other plasmas, which can decompose NO_x into N₂ and H₂O effectively (NO_x concentration < 10 × 10^{−6}) High cost

catalysts such as metals (vanadium, tungsten, and the like) doped TiO₂ are developed to catalyze the above reaction (Eq. (4)) at relatively low temperature (350–400 °C), and a reactor as shown in Fig. 13 is generally set in the exhaust gas line. Now, the NO_x removal efficiency of selective catalytic reduction process reaches about 80%–90%.

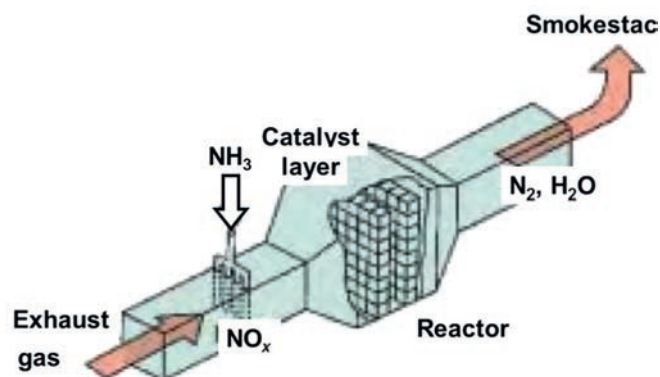


Fig. 13. Selective contact reduction method for NO_x removal (reprinted with permission from Ref. [1]).

However, the existence of SO_x in the exhaust gas will affect the reaction of NO_x with NH₃ and deactivate the expensive DeNO_x catalysts. To resolve this problem and remove NO_x and SO_x from the exhaust gas simultaneously, as shown in Fig. 14, a combined desulfurization DeNO_x process named as “active carbon adsorption method” has been developed [1]. In this process, the injected NH₃ on the active carbon reacts with SO_x in the exhaust gas at 120–150 °C, and SO_x is converted to NH₄HSO₄ and/or (NH₄)₂SO₄ at first and then, the remaining NO_x in the exhaust gas is catalytic converted to N₂ and H₂O by NH₃ in the

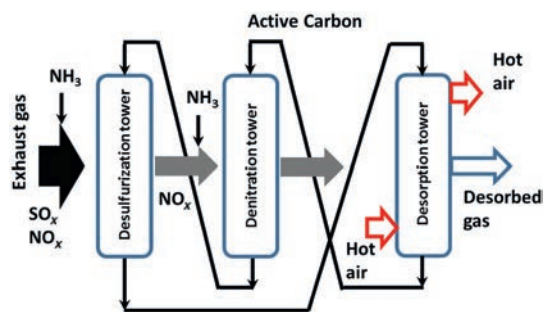


Fig. 14. Simultaneous De-SO_x and De-NO_x using active carbon and NH₃ (Source [1], edited with permission from NEDO, Japan).

following SCR tower. The absorbed NH₄HSO₄ and/or (NH₄)₂SO₄ on the active carbon can be desorbed by heating it at 350 °C or higher. The generated NH₃ and active carbon can be reused in the desulfurization and denitration processes while SO₂ can be oxidized to SO₃ for H₂SO₄ production. Almost all SO_x can be removed in the desulfurization tower while 80% of NO_x can be removed in the denitration tower.

Like SO_x and NO_x, emission of particulate matter from coal-fired plants should be also controlled. The world's first electrostatic precipitator was applied in coal-fired power generation plant in Japan for fine particles collection and now, this equipment has been widely used [1]. The mechanism of the dust removal by electrostatic precipitator is to let dust be charged by a negative corona at a discharge electrode so that it can be adhered to a positive dust-collecting electrode (Fig. 15). The effectiveness of the dust removal is decided by the electrical resistance of the dust. It is reported that the electrical resistivity of particles should be ranged between 10⁴ and 10¹¹ Ω · cm. To improve power generation efficiency, high-temperature dust collection methods using multi-cyclone, ceramic or metal based filters and granular-bed are under development. On the other hand, there are many trace elements in coal, and among them mercury (Hg) is considered as the one released into atmosphere at the highest rate. About 30% of Hg in coal cannot be removed by the precipitator and desulfurizers. It is found that active carbon, natural inorganic materials and limestone can absorb Hg. To date, about 90% or more of Hg can be easily removed by using the technology developed in Japan.

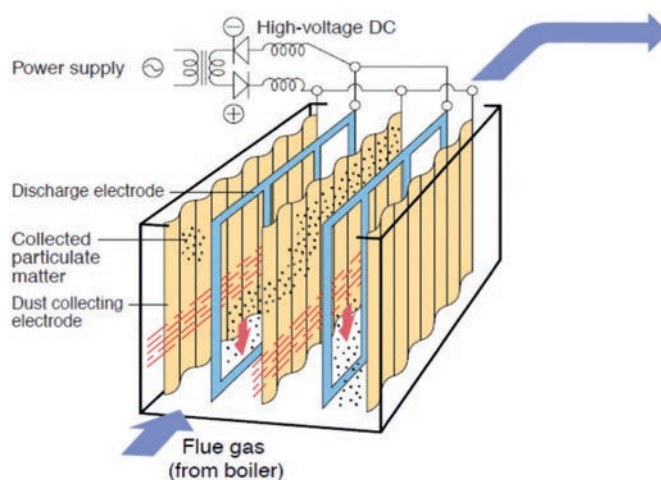


Fig. 15. Electrostatic precipitator for dust removal (reprinted with permission from ref. [1]).

6. Conclusions and Future Outlook

Various technologies including high efficient coal combustion technology, advanced coal gasification technology, CO₂ capture and storage technology, CO₂ utilization technology, dust collection technology and gas cleaning technology have been developed and applied in Japan. To date, the power generation efficiency of coal-fired plants have reached over 42%. Especially, The net plant efficiency of Nakoso 250 MW air-blown IGCC demonstration commercial plant reached 42.9% with SO_x, NO_x and particulate matter in the exhausted gas less than 1.0 × 10^{−6}, 3.4 × 10^{−6}, and 0.1 mg · m^{−3}, respectively. The gasifier showed very stable syngas production for various high and low-rank coals. Now, a larger scale of IGCC/IGFC commercial plants with CO₂ capture and storage are being built and some novel advanced IGCC/IGFC technologies are being developed in Japan. As shown in Fig. 16, it is expected that 1700 °C-class A-IGCC and A-IGFC with power generation efficiencies of 57% and 65% respectively, will be realized in the near future. Besides power generation, based on the syngas (H₂ and CO) produced by coal gasification,

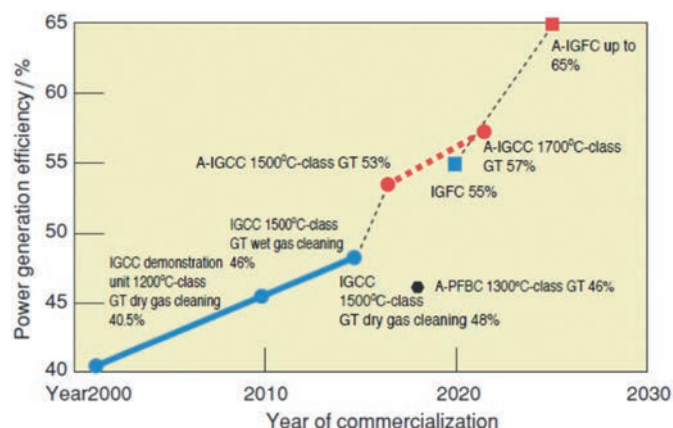


Fig. 16. Roadmap for commercialization of advanced gasification technologies in Japan (reprinted with permission from Ref. [1]).

liquid fuels and basic chemicals can be also co-produced cleanly with zero-emission of CO₂, any toxic gases and dust.

Due to its abundant reserves of low-rank coals such as brown coal, lignite and peat in the world, how to cleanly use them is becoming an important issue. In fact, they are particularly suitable for gasification-based technologies owing to their high gasification reactivities [67–70]. Nowadays, many endeavors are focused on how to utilize effectively, and in an environmentally friendly way the low-rank coals. Recently, Twin IHI gasifier using a two-stage dual fluidized bed gasification technology has been commercialized by IHI Corporation [69,70]. With an aim of positioning coal as a source of CO₂-free energy by 2030, innovative CCT development in Japan is being promoted. Especially, next-generation high-efficiency gasification technology for low-rank coal utilization and CO₂ fixation technology are considered as the key issues to be solved. It is expected that more and more novel technologies for low-rank coal utilization and CO₂ fixation will appear in the near future, and applied in the practical processes.

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