Near-zero-emission IGCC Power Plant Technology

Nobuo Nagasaki
Keisuke Sasaki
Tomoko Suzuki
Satoshi Dodo
Fumihiko Nagaremori

OVERVIEW: Hitachi is participating in the EAGLE project being undertaken jointly by the New Energy and Industrial Technology Development Organization (NEDO) and the Electric Power Development Co., Ltd. (J-POWER) and has been contracted by J-POWER to supply a complete set of equipment and provide support for trial operation. Drawing on the results from EAGLE, Hitachi is also involved in the large-scale experimental testing of 170-MW-class oxygen-blown coal gasification combined cycle power generation technology being undertaken by Osaki CoolGen Corporation. In addition to the design, fabrication, installation, and commissioning of an oxygen-blown, two-stage spiral-flow gasifier (capable of gasifiering around 1,100 t/d of coal) and combined cycle generation plant, the company also has an engineering role in which it acts as technical leader and coordinates the overall demonstration plant. Hitachi is also working to expand applications for the gasifier to include chemical feedstocks, and its aim is to reduce the construction cost of commercial IGCC systems by minimizing the gasifier construction costs through standardization and improved know-how. In Hitachi's work on technical development aimed at achieving near-zero emissions (very low levels of CO_2 and soot emissions), its approach is to seek to minimize loss of net thermal efficiency while also reducing construction costs.

INTRODUCTION

IT is estimated that total global power generation in 2030 will be about 1.7 times that in 2007, and it is also predicted that the use of coal-fired thermal power generation will continue to grow as it remains a key source of electric power(1). Because the price of coal is stable and cheap, with large minable reserves, and because it is not geographically concentrated, with coal mines located in politically stable regions, it is seen as remaining an important primary energy source for some time to come.

However, the amount of carbon dioxide (CO_2) emitted per unit of energy produced from coal is high compared to other fossil fuels, such as natural gas or oil. This has created an expectation for clean coal technologies. There is also a trend toward introducing regulations on the per-unit emissions of CO_2 from thermal power plants, and this creates a potential for requirements that are difficult to achieve in practice, such as higher efficiency and the use of biomass in multi-fuel combustion.

Hitachi aims to expand its environmentally conscious coal-fired thermal power generation business to reduce CO_2 emissions, and it is accelerating the development of clean coal technologies.

This article describes the results of pilot testing of the Coal Energy Application for Gas, Liquid and Electricity (EAGLE) project using an oxygen-blown,

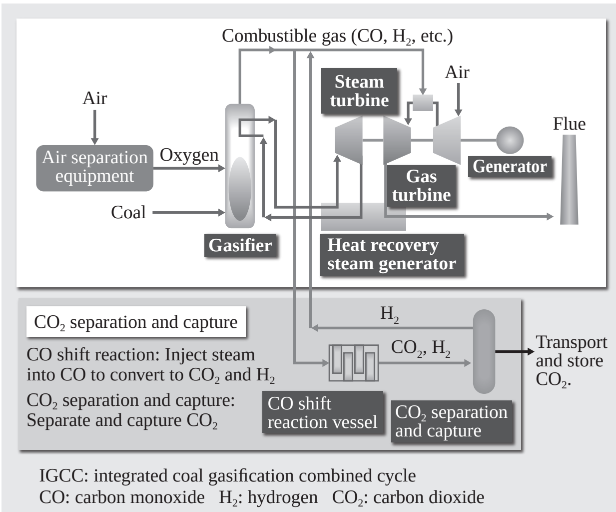

Fig. 1—IGCC System Configuration.
IGCC gasifies coal in a gasifier by converting it into combustible gas (CO and H_2). This combustible gas is used to fuel a gas turbine. Exhaust heat from the gas turbine and reaction heat from the gasifier are recovered and used to produce steam. Using both the gas turbine and steam turbine to generate electric power boosts the efficiency of power generation.

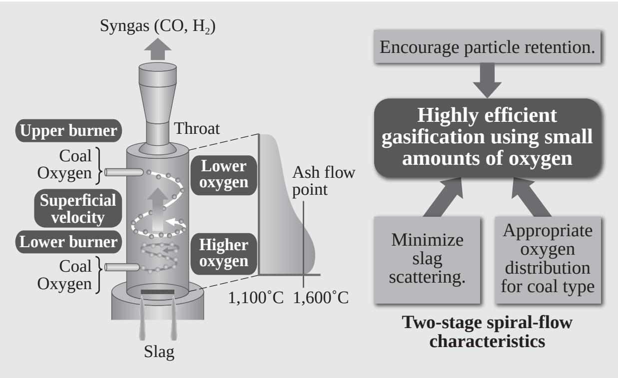

Fig. 2—Gasifier Features.
The gasifier developed by Hitachi uses oxygen-blown, two-stage, spiral-flow gasification to produce gas with high efficiency using small amounts of oxygen.

two-stage gasifier; large-scale experimental testing of oxygen-blown coal gasification drawing on work at EAGLE; and the development and commercialization of integrated coal gasification combined cycle (IGCC) technology with near-zero emissions (very low levels of CO_2 and soot emissions).

IGCC SYSTEM CONFIGURATION

IGCC is a combined cycle electric power generation system that uses a gasifier to convert coal into combustible gas at high temperature and pressure that is then used to fuel a gas turbine and generate electric power. Heat recovery is also used to recover the exhaust heat from the gas turbine and the reaction heat from the gasifier, using it to produce steam and generate electric power in a steam turbine (see Fig. 1).

CHARACTERISTICS AND DEVELOPMENT HISTORY OF OXYGEN BLOWN GASIFIER

Characteristics of Oxygen-blown Gasifier

The oxygen-blown gasifier (EAGLE gasifier) uses two-stage, spiral-flow gasification[(2)] to adjust the ratio of oxygen and coal in the upper and lower stages depending on the coal type. As the spiral down flow can maintain particle residence time[(3)] and also minimize particle scattering, it is possible to gasify the coal using a small amount of oxygen (see Fig. 2).

Development History of Oxygen-blown Gas IGCC with CO_2 Separation and Capture

The basic concept of the oxygen-blown, two-stage spiral-flow gasifier was established through more than 1,000 hours of continuous operation of a pilot plant (50 t/d) supplied to the New Energy and Industrial Technology Development Organization (NEDO) and the Research Association for Hydrogen from Coal Process Development (HYCOL), and problems with ash were also resolved through experimental testing[(4)].

Drawing on the results of the HYCOL project, Hitachi is also participating in the EAGLE project run by NEDO and Electric Power Development Co., Ltd. (J-POWER)[(5)]. This has been contracted by J-POWER to supply a complete set of equipment, as well as providing support for trial operation by J-POWER. EAGLE has achieved all of its initial development objectives and completed Step 1 trials in March 2007[(6)] (see Fig. 3).

Step 2 involved upgrading the gasifier to expand the range of usable coal types and to verify its

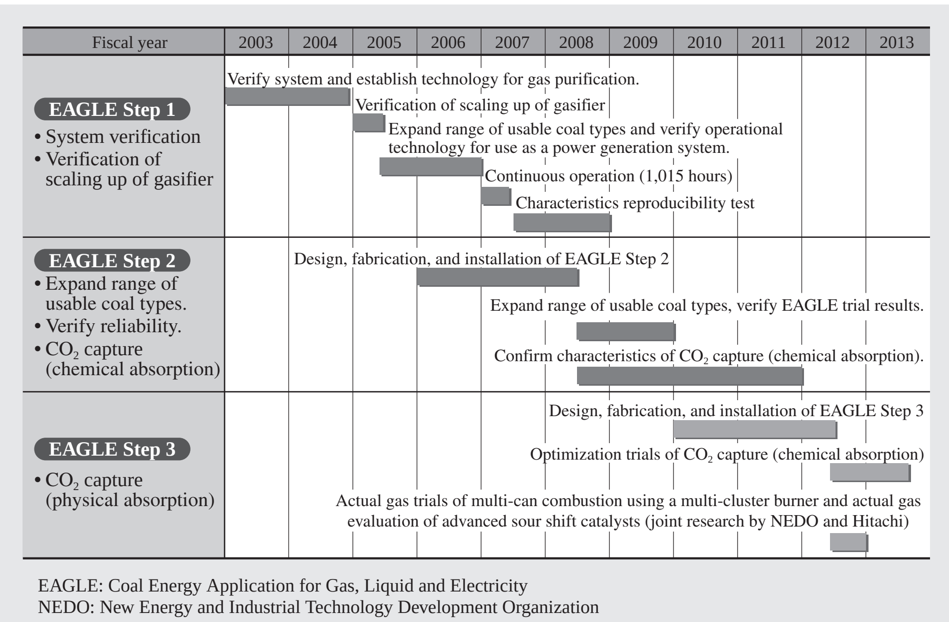

Fig. 3—EAGLE Trial Operation Process.
EAGLE achieved all of its initial development objectives. Step 2 involved upgrading the gasifier to expand the range of usable coal types and to verify its reliability, with trials ending in March 2010. Design data is currently being collected for a 170-MW-class IGCC demonstration plant.

reliability, with trials running up until March 2010. While the EAGLE design was based on the results of the HYCOL project, problems arose that could not be foreseen in the preliminary analysis studies. The gasifier was further upgraded to deal with the problems at EAGLE and the suitability of these countermeasures verified in EAGLE Step 2.

Also, some of the existing equipment was diverted for use in world-leading experimental testing of CO_2 separation and capture (chemical absorption) from syngas. The feed gas volume was 1,000 m^3 (Normal)/h and CO_2 capture was approximately 24 t/d. Technology for capturing CO_2 from syngas (pre-combustion capture) is already in widespread use for capturing CO_2 from natural gas, and its use in thermal power plants is under investigation around the world. An important factor when applying the technology to thermal power plants is to minimize the loss of net thermal efficiency when the CO_2 capture equipment is installed. This requires reducing the amount of heat needed to regenerate the CO_2 absorption fluid and fine-tuning the heat recovery system to minimize the reduction in the output of the steam turbine. EAGLE Step 2 used heated flash regeneration to optimize the operating conditions and fine-tune the heat recovery system to minimize the reduction in the output of the steam turbine, significantly reducing the loss of net thermal efficiency associated with CO_2 capture from syngas while still achieving a CO_2 capture ratio of 90% and a CO_2 purity of 99%.

Step 3 of the project from 2011 to 2013 includes operating the gasifier to generate the coal gas required for trialing CO_2 separation and capture (physical absorption) and also collecting design data for a 170-MW-class IGCC demonstration plant. A problem with the CO_2 separation and capture (chemical absorption) used in Step 2 was that the operation of heated flash regeneration caused foaming of the absorption fluid and its dispersal to the downstream side. In response, a new flash drum with appropriate dimensions was installed prior to commencing Step 3, and then operation during the Step 3 trials kept within a range suitable for these dimensions. This succeeded in eliminating the dispersion to the downstream side caused by foaming of the absorption fluid.

In joint research by NEDO and Hitachi, actual gas trials of multi-can combustion using a multi-pore coaxial jet burner (cluster burner) and advanced sour shift catalysts are planned in FY2012.

PLANS FOR EXPERIMENTAL TESTING OF OXYGEN-BLOWN IGCC WITH CO_2 SEPARATION AND CAPTURE

J-POWER and The Chugoku Electric Power Co., Inc. established Osaki CoolGen Corporation in July 2009 to make efficient progress on oxygen-blown IGCC power generation technology and CO_2 separation and capture technology.

For Phase 1 of the Osaki CoolGen Project, Osaki CoolGen Corporation will commence construction of a large-scale demonstration plant for 170-MW-class oxygen-blown coal gasification technology in March 2013. The aims are to verify the basic performance (power generation efficiency and environmental performance), operating characteristics (startup and shutdown time, rate of change of load, etc.), and economics of the oxygen-blown IGCC system. Next, the plan for Phase 2 is to retrofit the IGCC demonstration plant built for Phase 1 with CO_2 separation and capture equipment, and to

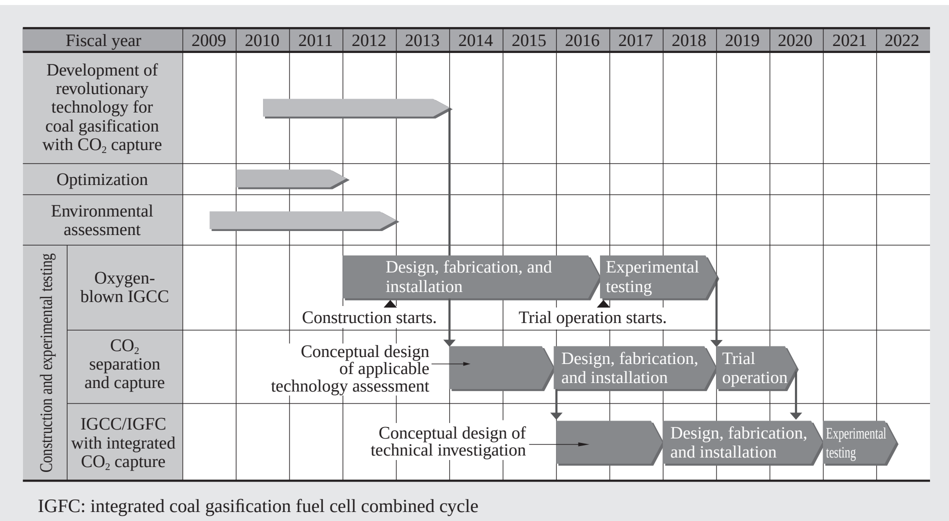

Fig. 4—Process of IGFC Experimental Testing.
The experimental testing is to be split into three phases, comprising respectively oxygen-blown IGCC, CO_2 separation and capture, and IGCC/IGFC with integrated CO_2 capture.

verify the system's basic performance, equipment reliability, operating characteristics, economics, and environmental performance. For Phase 3, the plans include adding a fuel cell to the IGCC system with CO_2 separation and capture built in Phase 2 to verify precision gas purification technology and the potential for using coal gas in fuel cells, and also performing appropriate verification testing of an integrated coal gasification fuel cell combined cycle (IGFC) power generation system[(7)] (see Fig. 4).

In addition to the design, fabrication, installation, and commissioning of an oxygen-blown, two-stage spiral-flow gasifier with a coal processing capacity of about 1,100 t/d, the 170-MW-class combined cycle power generation equipment, and the electrical and control equipment for the large-scale experimental testing of the 170-MW-class oxygen-blown coal gasification technology in Phase 1, Hitachi also has an engineering role in which it acts as technical leader and coordinates the overall demonstration plant. The plans for trial operation in Phase 1 include technical verification of the scaling up of the gasifier, establishment of technology for the operation and control of the gasifier, and total system verification of oxygen-blown IGCC.

The generator output of the Osaki CoolGen Project is in the 170-MW class, and the 40.5% higher heating value (HHV) target for net thermal efficiency will make it one of the most efficient in the world for a system of this output class, demonstrating the high efficiency of oxygen-blown IGCC. Verification of this result would imply that a commercial IGCC system could achieve a net thermal efficiency of 46% (HHV), accelerating the commercialization of highly efficient IGCC.

BOOSTING NET THERMAL EFFICIENCY OF OXYGEN-BLOWN IGCC AND REDUCING CO_2 EMISSIONS

Deployment of Oxygen-blown IGCC

The net thermal efficiency of IGCC can be increased through the use of technology that boosts the efficiency of a natural-gas-fired gas turbine by increasing its temperature. The net thermal efficiency of the oxygen-blown IGCC with a higher gas turbine temperature (Step 2) is 46% (HHV), and it can reduce CO_2 emissions by roughly 20% compared to the latest pulverized coal thermal power generation. For an oxygen-blown gasifier, CO_2 can be captured from feed gas with a high CO_2 concentration (approximately 40%) pressurized to between 2.5 MPa and 3.0 MPa (pre-combustion capture). As the flow rate of the gas being processed is lower than it is when capturing CO_2 from the boiler exhaust gas (post-combustion capture), the equipment can be made smaller than that used for capturing CO_2 from the boiler exhaust gas, and the loss of net thermal efficiency is minimized.

Achieving practical coal-fired thermal power generation with near-zero emissions by combining IGCC with carbon capture and storage (CCS) makes it possible to combine CO_2 emissions reduction with the efficient use of coal. As the high concentration of fuel components in the gasifier syngas (CO and H_2, etc.) for oxygen-blown gas IGCC means that the fuel cell voltage can be increased, using a highly efficient generation system that incorporates a fuel cell can reduce CO_2 emissions by approximately 30% compared to the latest coal-fired thermal power plants in Japan[(8)] (see Fig. 5 and Fig. 6).

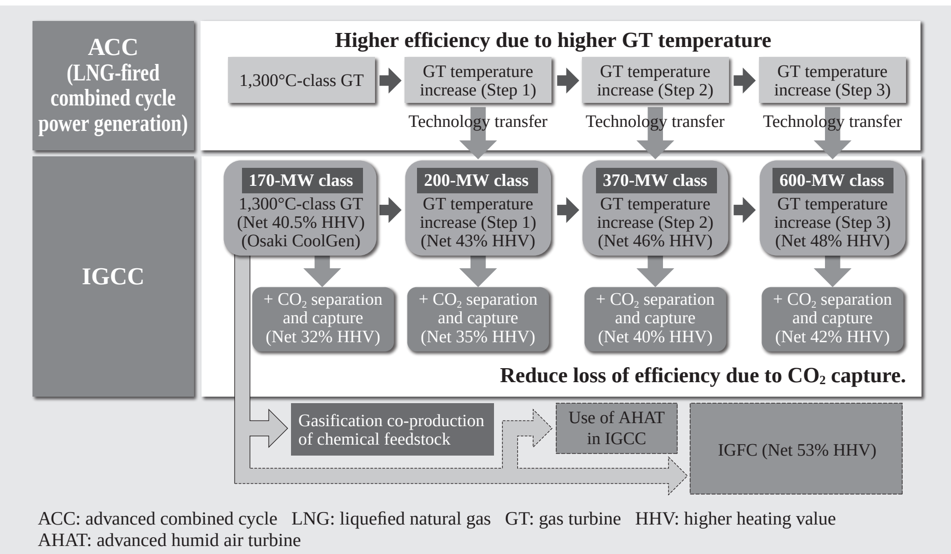

Fig. 5—Outlook for Oxygen-blown IGCC.
IGCC allows net thermal efficiency to be increased through the use of technology that boosts the efficiency of the gas turbine by increasing its temperature. The loss of net thermal efficiency resulting from CO_2 capture can be reduced by capturing the high concentration of CO_2 in the pressurized fuel gas.

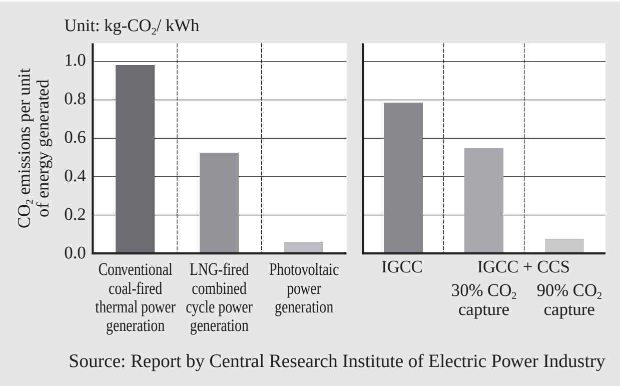

Fig. 6—CO_2 Emission Reductions for IGCC and IGCC + CCS.
IGCC (for 1,500°C-class gas turbines) has 20% lower CO_2 emissions than a conventional coal-fired thermal power generation plant. Adding CO_2 capture to IGCC (IGCC + CCS) results in near-zero emissions of CO_2.

Strategy for Commercialization of Oxygen-blown IGCC

Trial operation in Phase 1 of the Osaki CoolGen Project is intended to commercialize IGCC through technical verification of the scaling up of the gasifier, establishment of technology for the operation and control of the gasifier, and total system verification of oxygen-blown IGCC. The gasifier will be scaled up by a factor of less than 10 to maintain the two-stage spiral-flow characteristics and minimize the risks associated with scaling up.

The target is to build the first commercial system with a gasifier capacity less than 10 times the 150 t/d capacity of the EAGLE gasifier by 2020. The first commercial IGCC will include the higher gas turbine temperature (Step 1), have a coal processing capacity of 1,300 t/d, a generator output in the 200-MW class, and net thermal efficiency of 43% (HHV).

Similarly, a target of the latter half of the 2020s has been set for using IGCC with higher gas turbine temperature (Step 2) to commercialize a highly efficient IGCC with a generator output in the 300-MW to 370-MW class and net thermal efficiency of 46% (HHV).

PROGRESS ON ZERO-EMISSION IGCC THROUGH DEPLOYMENT IN MULTIPLE APPLICATIONS

Development Strategy for Zero-emission IGCC

An issue with IGCC demonstration plants is the high cost of construction. It is recognized that the predicted levels of construction costs for commercial plants are different depending on the development stage, with the predicted construction cost being highest for a commercial plant at the demonstration stage during which the issues to be verified and project risks are clarified. After that greater know-how and standardization bring the construction cost down. With the IGCC currently at the demonstration stage, one strategy for reducing the construction cost of the oxygen-blown, two-stage spiral-flow gasifier is to extend its application to include use as a gasifier for chemical feedstocks. Reducing the cost of gasifier construction also helps reduce the construction costs for commercial and zero-emission IGCC.

In the case of gasifiers for chemical feedstock and zero-emission IGCC, Hitachi is working on the following four initiatives (in addition to enhancing know-how and standardization) to reduce construction costs and increase efficiency (see Fig. 7).

(1) Improve cold gas efficiency by using CO_2 circulation gasification.
(2) Use direct quenching for syngas cooling and humidification.
(3) Use advanced sour shift catalyst.
(4) Establish technology for low-nitrogen-oxide (NO*x*) combustion using cluster burner.

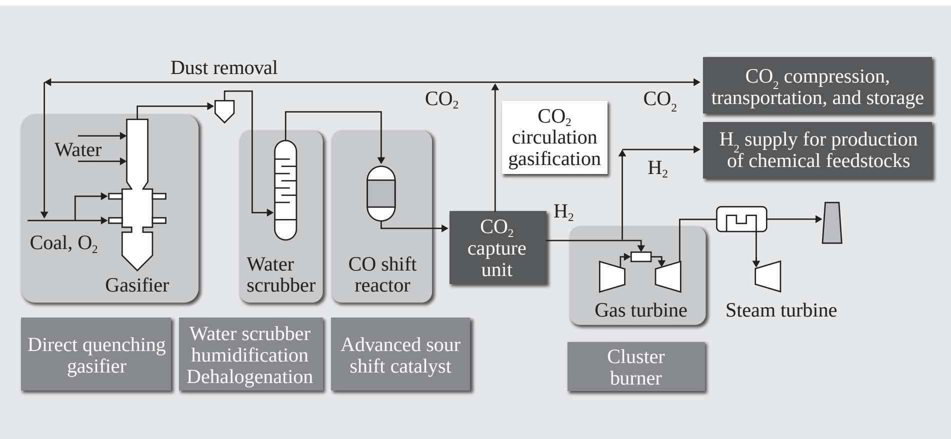

Fig. 7—Configuration of Gasifier for Chemical Feedstocks and Zero-emissions IGCC.
Technologies have been established for the efficient production of hydrogen from coal: (1) Improved cold gas efficiency resulting from CO_2 circulation gasification, (2) Use of direct quenching for syngas cooling and humidification, (3) Use of advanced sour shift catalyst, and (4) Technology for low-NOx combustion using cluster burner.

Improved Cold Gas Efficiency Resulting from CO_2 Circulation Gasification

In gasifiers for chemical feedstocks and zero-emission IGCC, the generated CO_2 is used as the coal transport medium in the gasifier. Because the mixing gas in the gasifier is CO_2 instead of nitrogen, the concentration of impurities (nitrogen) in the syngas is reduced. Also, gasifying coal in the presence of CO_2 reduces the amount of oxygen used and improves, by approximately 3.5 points, the cold gas efficiency that represents the yield ratio for the syngas (ratio of syngas calorific value to coal heat input). As CO_2 has a higher heat capacity than nitrogen, and as the reaction between coal and CO_2 is endothermic, changing the coal transport medium from nitrogen to CO_2 reduces the gasifier temperature. As the ash in a spouted bed gasifier is collected as molten slag, the gasification temperature needs to be kept above the ash melting point.

EAGLE has an oxygen-blown two-stage spiral-flow gasifier. In CO_2 circulation gasification, the flow of oxygen to the lower burner is increased to maintain the lower stage gasification temperature and ensure a stable downward flow of slag. In addition to offsetting the increased flow of oxygen to the lower burner, reducing the flow of oxygen to the upper burner in accordance with the reduced oxygen requirement resulting from the use of CO_2 gasification also allows the cold gas efficiency of the gasifier to be increased. The improved cold gas efficiency resulting from CO_2 circulation gasification is a feature of two-stage gasification and is one of the superior technical features of gasifiers for chemical feedstocks and the EAGLE gasifier for zero-emission IGCC (see Fig. 8).

Use of Direct Quenching for Syngas Cooling and Humidification

At the Osaki CoolGen demonstration project, the syngas is cooled to between 350°C and 400°C by the heat exchanger in the upper part of the gasifier and the syngas cooler (SGC), dust removal is performed using a char filter and halogen removal. Further cooling occurs in the water scrubber, and then the sulfur components of the syngas are removed in a gas purifier. The sensible heat in the syngas is recovered as steam in the SGC and the heat exchanger in the upper part of the gasifier. This steam is then supplied to the steam turbine to improve generation efficiency (see Fig. 1).

Direct quenching cools the high-temperature syngas at the exit of the gasifier by injecting a water spray. Direct quenching can reduce gasifier construction costs because it eliminates the SGC and allows the heat exchanger in the upper part of the gasifier to be made smaller. When applied to IGCC, however, the sensible heat of the syngas cannot be recovered in the SGC and the heat exchanger in the upper part of the gasifier and this significantly reduces the net thermal efficiency. In the case of gasifiers for chemical feedstocks and zero-emission IGCC, meanwhile, a shift reaction with the CO in the syngas is used to produce H_2 and CO_2, and therefore the steam recovered from the SGC and the heat exchanger in the upper part of the gasifier needs to be added into the syngas. Direct quenching not only cools the syngas using a water spray, it also has the effect of humidifying the syngas[9]. Direct quench gasification uses a water spray to cool the gas to between 350°C and 400°C, after which dust removal is performed using a char filter, and then a water scrubber is used to perform halogen removal and further cool the syngas to between 180°C and 200°C. The ratio of

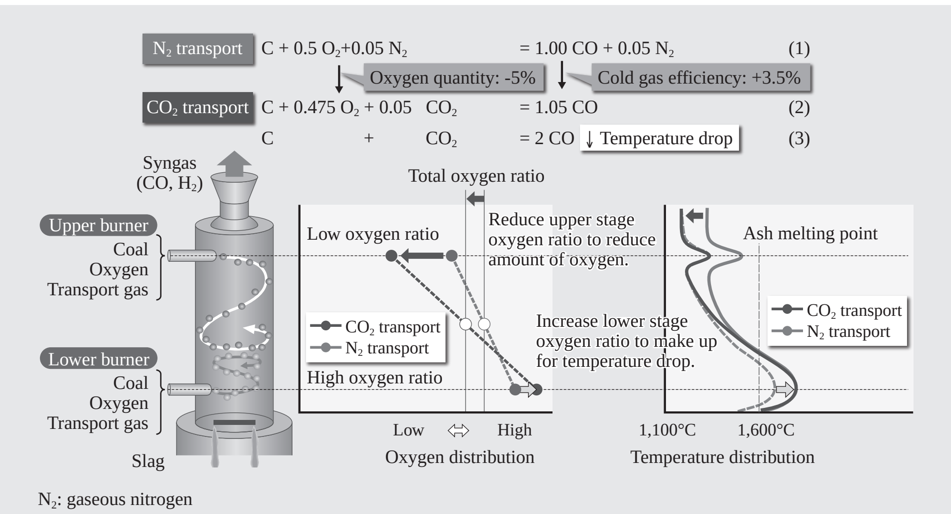

Fig. 8—Improved Cold Gas Efficiency Resulting from CO_2 Circulation Gasification.
The cold gas efficiency and product yield are increased by adjusting the oxygen ratios of the upper and lower burners respectively (Lower stage: Increase oxygen ratio to maintain gasification temperature, Upper stage: Reduce oxygen ratio to lower overall oxygen ratio).

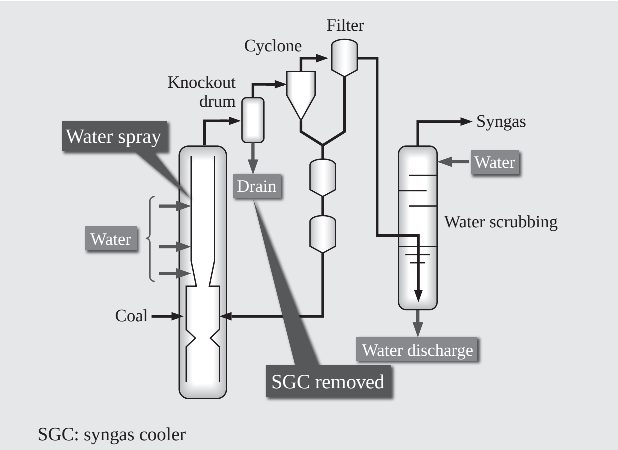

Fig. 9—Use of Direct Quenching to Eliminate SGC.
Gasification with direct quenching uses a water spray to cool the syngas to between 350°C and 400°C. After dust removal by a char filter, the syngas is then cooled to between 180°C and 200°C in the water scrubber where halogen removal is also performed.

water (H_2O)/carbon monoxide (CO) in the syngas at the exit of the water scrubber is about 1.2 or more.

Hitachi's direct quench process has the following three features.

(1) As the quenched syngas is dry, with a temperature of between 350°C and 400°C, a char filter can be used for dust removal.

(2) Halogen removal can be performed in the water scrubber through the washing effect of the cooling water.

(3) The humidity needed for the advanced sour shift catalyst (described below) can be achieved without the supply of external steam.

Because the process can remove dust and halogens, it is suitable for use with commercial shift reaction catalysts and CO_2 absorption processes (see Fig. 9).

Advanced Sour Shift Catalyst

Zero-emission IGCC uses some of the steam supplied to the steam turbine for a CO shift reaction. This diminishes the amount of steam that reaches the steam turbine and reduces the power generation efficiency in proportion to the amount of CO_2 captured. To improve power generation efficiency when performing CO_2 capture, it is necessary to carry out the shift reaction efficiently using a small amount of steam.

Shift catalysts used in the past have had a slow reaction rate at low temperatures, meaning that higher temperatures needed to be used to accelerate the reaction. As the theoretical CO-to-CO_2 conversion ratio (theoretical ratio of CO to CO_2 at equilibrium) in the CO shift reaction falls with increasing temperature, the amount of steam added is increased to boost this theoretical conversion ratio. This has the result of reducing the amount of steam available to the steam turbine and cutting the generation efficiency. In response, Hitachi has developed a shift catalyst that has a fast reaction rate at low temperature, and is able to achieve a CO-to-CO_2 conversion ratio close to the theoretical value using a small amount of steam(10). Laboratory testing has confirmed the ability of this technology to cut the amount of steam required for the CO shift reaction by more than 30%. By reducing the amount of added steam, a CO-to-CO_2 conversion ratio of 96% can be achieved for the moisture concentration of H_2O/CO = 1.2 resulting from the direct quenching and water scrubber humidification process described above. Therefore, the need to add steam from the steam cycle can be eliminated. Compared to using the previous catalyst, this results in a one point reduction in the loss of net thermal efficiency for a CO_2 capture ratio of 90% (see Fig. 10).

In joint research planned for FY2012, NEDO and Hitachi, Ltd. will install two small-scale catalyst test systems, each with a capacity of 50 m^3 (Normal)/h, at the EAGLE pilot plant at J-POWER's Wakamatsu Research Institute and conduct actual gas trials.

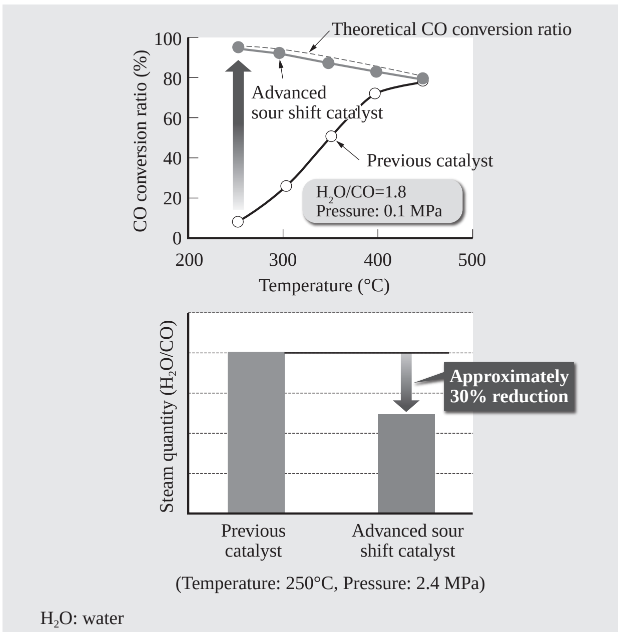

Fig. 10—Advanced Sour Shift Catalyst.
Hitachi has developed a shift catalyst that achieves a fast reaction rate at low temperature and a CO → CO_2 conversion ratio that is close to the theoretical value while using a small amount of steam, and has confirmed that steam use can be cut by approximately 30%.

Low-NOx Combustion Using Cluster Burner

The hydrogen-rich fuel burned in the gas turbine for zero-emission IGCC is highly reactive, with a burning rate about seven times that of natural gas, and requiring only about 1/14th as much energy for ignition. Because the pre-mixed combustion technique used with natural gas carries a strong risk of problems such as ignition occurring in the premixer (mixing chamber located upstream of the combustion chamber), or damage to the combustion chamber due to burn-back from the combustion chamber to the premixer, its use with hydrogen-rich fuel is very difficult. While reducing the NO*x* generated from diffuse combustion of hydrogen-rich fuel requires the injection into the flame of a quantity of inert gas equal or greater than the quantity of fuel to reduce the flame temperature, the energy required to pressurize the inert gas reduces the net thermal efficiency.

Hitachi has participated in NEDO's Zero-emission Coal-fired Power Generation Project since 2008, and is developing low-NO*x* technology for use with high concentrations of hydrogen in coal gasification power generation. Low-NO*x* combustion performance similar to pre-mixed combustion is achieved by reducing the space in which fuel and air mix, and by using a multi-pore coaxial jet burner (cluster burner) to adjust the jet direction to produce a flame that is shifted upwards in the combustion chamber space so that rapid mixing occurs in the space opened up between this flame and the burner (see Fig. 11).

Replacement of the burner in EAGLE with a cluster burner, followed by multi-can combustion trials using actual gas, is planned for FY2012.

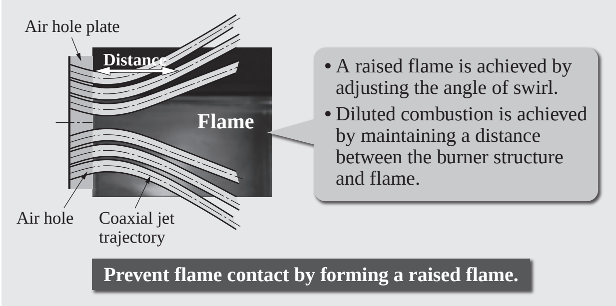

Fig. 11—Features of Cluster Burner.
A diluted gas mixture equivalent to pre-mixed combustion is formed in the region before the raised flame to achieve low-NOx combustion.

CONCLUSIONS

This article has described the results of pilot testing of EAGLE using an oxygen-blown, two-stage gasifier; large-scale experimental testing of oxygen-blown coal gasification drawing on work at EAGLE; and the development and commercialization of integrated coal gasification combined cycle (IGCC) technology with near-zero emissions (very low levels of CO_2 and soot emissions).

Hitachi has used EAGLE to verify the reliability of IGCC through long-term operation, and to establish technologies for scaling up the gasifier, gas purification, operation as an electric power generation system, and CO_2 separation and capture (chemical absorption). Hitachi is also drawing on the results of trial operation of EAGLE to perform the detailed design of the gasifier and combined cycle power generation equipment for Osaki CoolGen Corporation's 170-MW-class IGCC demonstration plant.

In parallel with the 170-MW-class IGCC demonstration plant, Hitachi is also proceeding with the commercialization of a gasifier for chemical feedstocks. By expanding the scope for earning a return on its investment, Hitachi aims to cut the construction costs for commercial IGCC plants and near-zero-emission IGCC. Through the use of CO_2 circulation gasification, direct quenching, and the advanced sour shift catalyst, as well as the application of cluster burners to gas turbines, Hitachi is simultaneously cutting the construction costs for zero-emission IGCC and minimizing the loss of net thermal efficiency.

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ABOUT THE AUTHORS

Nobuo Nagasaki
Joined Hitachi Engineering Co., Ltd. in 1979, and now works at the OCG Project Management Division, Thermal Power Systems Division, Thermal Power Business Division, Power Systems Company. He is currently engaged in the development of technology for IGCC with CO_2 capture. Mr. Nagasaki is a member of The Japan Society of Mechanical Engineers (JSME).

Keisuke Sasaki
Joined Hitachi, Ltd. in 1981, and now works at the OCG Project Management Division, Thermal Power Systems Division, Thermal Power Business Division, Power Systems Company. He is currently engaged in management of the Osaki CoolGen Project and commercialization of zero-emission IGCC.

Tomoko Suzuki
Joined Hitachi, Ltd. in 1992, and now works at the Department of Thermal Power & Water Purification Systems Research, Hitachi Research Laboratory. She is currently engaged in the development of the technology for IGCC with CO_2 capture. Ms. Suzuki is a member of the JSME and The Society of Chemical Engineers, Japan.

Satoshi Dodo
Joined Hitachi, Ltd. in 1994, and now works at the Energy and Environment Research Center, Hitachi Research Laboratory. He is currently engaged in research and development of syngas-fired low-NOx combustors. Mr. Dodo is a member of The Visualization Society of Japan and the Gas Turbine Society of Japan.

Fumihiko Nagaremori
Joined Babcock-Hitachi K.K. in 1983, and now works at the Coal Gasification System Center, Plant Engineering Division, Kure Division, Babcock-Hitachi K.K. He is currently engaged in gasifier development and coordination of a IGCC system.