Progress and utilization of Nakoso 250 MW air-blown IGCC demonstration project

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Abstract

Integrated coal Gasification Combined Cycle (IGCC) is a highly effective power generation system that the gas turbine is operated with the gasified coal in the gasifier. Clean Coal Power R&D Co., Ltd. had been conducting various tests for commercialization with the Nakoso IGCC demonstration plant since September 2007. The plant consists of air-blown gasifier, wet gas clean-up system and 1,200°C class gas turbine to produce 250 MW-gross electricity. Reliability was confirmed by 2,238 h of continuous operation, 18,788 h of accumulated operation and the resulting net thermal efficiency was 42.9% (LHV basis). Various types of coal have been successfully tested, such as North American coal, Indonesian coal, Russian coal and Columbian coal in addition to Chinese plant-designed coal. Although the Great East Japan Earthquake and Tsunami has caused severe damages to plant in March 2011, our IGCC swiftly restored its operation within 4.5 month and has been maintaining stable operation for demonstration project. The demonstration project was finished in March 2013 and the Nakoso IGCC plant is operated commercially by Joban Joint Power Co., Ltd. as high efficiency power generating station.

Key words : Coal, Gasification, IGCC, Air-blown, Nakoso, Demonstration project, Commercial operation

1. Introduction

Integrated coal Gasification Combined Cycle (IGCC) is a highly effective power generation system that the gas turbine is operated with the gasified coal in the gasifier. The coal gasification technology is used extensively in the field of chemical industry, such as ammonia production, methanol production, and gasoline composition. Gasifiers for IGCC developed in Europe and United States are oxygen-blown type, which are converted from the gasifiers for the chemical industry (Higman and Burgt, 2008). In the area of the chemical industry, purity of the product gas is most important, so they are using oxygen-blown gasifiers of which product gas does not include nitrogen gas as an impurity. However, oxygen-blown gasifier requires a lot of auxiliary power for oxygen production. It causes a decrease in net thermal efficiency on oxygen-blown IGCC system. Therefore, it was decided to adopt the air-blown type gasifier which could obtain higher net thermal efficiency, and have been making efforts to develop Japanese IGCC technology (Takanari, 1991).

Figure 1 shows the net plant efficiency by the use of air-blown IGCC and its further improvement as the combustion temperature of the gas turbine becomes higher. In the field of LNG fired combined cycle power plants, many 1,500°C class and 1,600°C class gas turbines are already in operation (Sato, 2007; Yuri, et al., 2014), and 1,700°C class gas turbine is under research and development (Ito, et al., 2011). Although the pressure of gas turbine combustor device is increased with operating temperature upshift, it will be able to raise the coal gasification pressure suitably with adequate plant design. By applying these gas turbine technologies which have been developed in the LNG field to coal gasification IGCC, nearly 50% at lower heating value (LHV) basis would be realized at the commercial stage.

Fig. 1 Thermal efficiency improvement of air-blown IGCC

This paper reports the demonstration project for development of air-blown IGCC technology. Specifications of the IGCC demonstration plant, outline of the test program and project results are explained. And operation properties of the first IGCC commercial plant in Japan are described.

2. Air-blown IGCC demonstration project

2.1 Purpose of the demonstration project

The development of air-blown IGCC started in 1983, from the process development unit test of 2t/day scale (Inumaru, et al., 1991). Next stage was the pilot plant test of 200 t/day scale which was carried out from 1991 to 1996 by Engineering Research Association for Integrated Coal Gasification Combined Cycle Power Systems (Araki and Hanai, 1996). This demonstration project described hereafter is the final stage of development on Japanese IGCC technology. Clean Coal Power R&D Co., Ltd. (CCP R&D) was established in 2001 to be fully responsible to perform the demonstration project. Plant design, construction and demonstration tests were conducted under the support from nine Japanese electric power companies¹, Electric Power Development Co., Ltd. (EPDC) and Central Research Institute of Electric Power Industry (CRIEPI). The purpose of the demonstration project is to confirm actual and practical utilization of IGCC and to acquire all data which are necessary for the design of a commercial IGCC plant.

2.2 Test site

The demonstration test of air-blown IGCC was conducted in the premise of Nakoso power station, Joban Joint Power Company, in Iwaki City, Fukushima Prefecture from September 2007. Nakoso power station was an existing power station with a total of 4 units, 1,625 MW capacity using mainly coal as fuel. This site was chosen because of the existence of infrastructure such as coal handling facilities, power transmission lines, etc. The air-blown IGCC demonstration plant is known as the “Nakoso IGCC” from the name of the place.

2.3 Specifications of the demonstration plant

Table 1, Figure 2 and 3 show the specifications, schematic diagram and bird’s-eye view of the Nakoso IGCC demonstration plant respectively. The capacity of the demonstration plant was sized to be 250 MW, which is half the size of a commercial plant. This resulted in the use of gas turbine with combustion temperature of 1,200°C class and a target net efficiency of 42% (LHV basis).

¹ Hokkaido Electric Power Co., Inc., Tohoku Electric Power Co., Inc., Tokyo Electric Power Co., Inc., Hokuriku Electric Power Co., Inc., Chubu Electric Power Co., Inc., Kansai Electric Power Co., Inc., Chugoku Electric Power Co., Inc., Shikoku Electric Power Co., Inc., and Kyushu Electric Power Co., Inc.

Table 1 Specifications of the demonstration plant

Capacity	250 MW gross		
Coal Consumption	approx. 1,700 metric t/day		
System	Gasifier	Air-blown & Dry Feed	
	Gas Treatment	Wet (MDEA) + Gypsum Recovery	
	Gas Turbine	1200°C class (50Hz)	
Efficiency (Target Values)	Gross	48% (LHV)	46% (HHV)
	Net	42% (LHV)*	40.5% (HHV)
Flue Gas Properties (Target Values)	SOx	8 ppm	(16%O ₂ basis)
	NOx	5 ppm	
	Particulate	4 mg/m ³ N	
EPC	Mitsubishi Heavy Industries (MHI)		

* While target net thermal efficiency is 48-50% in commercial IGCC plant applying 1500°C class gas turbine, 1200°C class gas turbine was adopted to reduce the capacity of plant for economy as a test plant.

Fig. 2 Schematic diagram of air-blown IGCC

Fig. 3 Bird's-eye view of the demonstration plant

2.3.1 Gasifier

The gasifier is required to satisfy two functions. One is to maintain calorific value of coal-derived syngas which ensures stable combustion at the gas turbine, and the other is to discharge coal ash smoothly as molten slag from the gasifier. It is necessary to maintain the temperature inside the gasifier high enough to achieve these functions. However in the case of air-blown single stage gasification, it is difficult to maintain the temperature high because a large quantity of nitrogen exists in the air and it is harder to raise the temperature in the gasifier compared to oxygen-blown IGCC. Therefore, the technological difficulty of air-blown IGCC is much higher than that of oxygen-blown IGCC. To overcome this challenge, two-staged entrained flow type gasifier which is divided into a combustor and a reductor was adopted.

The pressure of the gasifier is high at about 2.6 MPa, and pulverized coal is required to be injected into this high pressure atmosphere. For safety reason, nitrogen is used to pressurize pulverized coal, and a high-density transportation system is used for decreasing the injection volume of nitrogen to the gasifier. Although cryogenic type ASU (air separation unit) is installed to produce nitrogen, its capacity is very small compared to oxygen-blown IGCC. In addition, co-produced oxygen is utilized as gasifying agent together with the gasification air.

The temperature inside the combustor in the gasifier is extremely high at about 1,800°C, so that coal ash melts and flows down. However, refractory material is not used. The water walls inside of the gasifier are protected from high temperature radiation with a melted ash (slag) self-coating which is formed by centrifugal flow.

Coal-derived syngas contains char which is a mixture of unburned carbon and fly ash. The char is collected by porous filters and is recycled back to the gasifier. Hereby, more than 99.9% of carbon in coal can be gasified, and concentration of unburned carbon in molten ash discharged from the bottom of the gasifier is less than 0.1%.

2.3.2 Gas clean-up

Wet gas clean-up system using chemical solvent is adopted in this plant. Impurities such as hydrogen sulfide (H_2S), carbonyl sulfide (COS), ammonia (NH_3) and hydrogen chloride (HCl) are contained in raw coal-derived syngas. NH_3 and HCl are removed by scrubbing with water. COS is converted into H_2S with catalyst. H_2S is removed using an amine solution. As these impurities are removed up-stream of gas turbine, the gas turbine is protected from these impurities and emission of these components into the atmosphere can be avoided. In addition, the eliminated sulfur is recovered as gypsum.

2.3.3 Combined cycle

There are many LNG fired combined cycle power plants already in operation together with abundant actual experience. Although the calorific value of coal-derived syngas is relatively low, there is no difficulty for using it as gas turbine fuel in terms of stable combustion. A diffusion type combustor with a simpler configuration can be applied, because thermal NO_x caused by syngas combustion is lower than that from LNG.

2.3.4 System integration

IGCC is mainly comprised of the gasifier, gas clean-up facility and combined cycle facility. Net efficiency of IGCC is greatly dependent on the overall plant configuration, especially concerning gasification agent (air) and steam integration. Extracted air from the compressor of the gas turbine is used as gasification agent after boosting up it to necessary pressure for the operation pressure of the gasifier. Steam generated at the syngas cooler of the gasifier is introduced to steam turbine together with those generated from heat recovery steam generator downstream of the gas turbine. Part of high temperature exhaust gas from gas turbine is extracted from the heat recovery steam generator and used as heat source for coal drying. By applying these integrations, Nakoso IGCC achieves high net efficiency.

3. Results of the demonstration test

3.1 Outline of the test program

Air-blown IGCC demonstration tests were conducted for every item including reliability, environmental performance, thermal efficiency, fuel flexibility, economy and operability which are necessary for the commercial plant as shown in Table 2. The demonstration tests were conducted over a period of about five and a half years, starting with

Table 2 Verification items of demonstration test

Item	Goal
System Safety and Stability	Demonstrate safe shutdown when plant malfunctions, and safe handling of coal gas.
Reliability	Run continuously for at least 2,000 h (equivalent to 3 summer months) to confirm reliability.
Coal Type Flexibility	Collect data while running coal types outside of the design specs. Data is to be used to support future commercial design.
High Efficiency	Achieve targeted thermal efficiency, to show that system delivers the high efficiency that is said to be IGCC's greatest advantage.
Durability	Run for long period, then conduct overhaul inspection to demonstrate durability.
Economy	Use operational performance as a basis for comprehensive evaluation of costs (construction costs, operating costs, maintenance costs etc.), and evaluate economic feasibility.

Fig. 4 Operation hours and cumulative gross output

ignition of the gasifier in September 2007, and continuing up to March 2013. Figure 4 shows the operation hours and cumulative gross output through the demonstration project.

3.2 System safety and stability

The system safety and stability of the IGCC system were tested both on rated load conditions. As for atmosphere environmental emission performance, SO_x, NO_x, and particulate concentrations in the exhaust gas were stayed substantially below than targeted level. The other environmental characteristics such as the quality of waste water, noise levels, and vibration levels were all cleared. And safety shutdown system was confirmed with the interlock test intended as malfunction condition.

3.3 Reliability

The IGCC demonstration plant was operated for 18,788 h, including 2,238 h continuous running. The cumulative gross output of demonstration plant was raised 3,704 GWh, and the electricity generated was supplied to a general electricity utility.

In addition, the reliability was verified by unanticipated experience with the 2011 Great East Japan Earthquake. The demonstration plant in active at 225 MW was shaken by the earthquake, and the system was shut down automatically and safely, triggered by the detection of high vibration at the turbine. Following tsunami rushed toward the plant, and almost all equipments on the ground floor were submerged by seawater and suffered serious damage. In spite of amplified damage with aftershocks a month later, the IGCC demonstration plant swiftly restored its operation within 4.5 month and has been maintaining stable operation for demonstration project.

3.4 Fuel flexibility

Coals that have low fuel ratio and low ash melting temperature are suited for IGCC. These are different from coals suited for conventional coal-fired plants. Low fuel ratio means having higher volatile matter content and easier to gasify, and this kind of coal includes sub-bituminous coal which is younger and having low level carbonization. In addition, the reason why coals having low ash melting temperature are suited for IGCC is to melt coal ash in the gasifier and to discharge the molten ash from the bottom of the gasifier. This is a different concept from coals suitable for conventional coal-fired power plants.

Coals used for the demonstration test were selected mainly from coals suited for IGCC. It was verified during the tests that all of these coals can be used for gasification. Stable operation using the Chinese design coal was confirmed as expected. After that, fuel flexibility tests using a total of 9 different kinds of coal, such as sub-bituminous coal from the United States and Indonesia, and bituminous coal from Indonesia, Colombia, Russia and Canada were carried out. Various phenomena were observed when the coal was changed, and it became clear that application of various adjustments and changes in operation were necessary for stable operation.

3.5 High efficiency

Table 3 shows the operational characteristics of the performance test with rated load operation. The resulting net thermal efficiency was 42.9% at LHV basis, which exceeded the 42% efficiency target set in the demonstration project. The operational aspects of gasification, gas clean-up and combined cycle were stable for continuous operation as designed plant performance.

3.6 Durability

Target for durability test was set that any serious damage cannot be found on facilities during overhaul inspection after 5,000 h durability test. During this test, initial incidents occurred, and sometimes it led to plant shutdown. In spite of that, accumulative operation hours reached to 5,013 h in one year after starting the test. The subsequent overhaul inspections indicated that the demonstration plant facilities were not seriously damaged caused by the long-term durability test.

Table 3 Results of plant performance test

		Design Values	Results
Atmospheric Temperature		15°C	13.1°C
Gross Output		250 MW	250 MW
Gas Turbine Output		128.9 MW	124.4 MW
Steam Turbine Output		121.1 MW	125.8 MW
Net Efficiency (LHV)		42%	42.9%*
Syngas	LHV	4.8 MJ/m³N	5.2 MJ/m³N
Composition	CO	28.0%	30.5%
	CO₂	3.8%	2.8%
	H₂	10.4%	10.5%
	CH₄	0.3%	0.7%
	N₂ etc.	57.5%	55.5%
Environmental Performance		<Target>	
(16%O₂ Corrected)	SOx	8 ppm	1.0 ppm
	NOx	5 ppm	3.4 ppm
	Particulate	4 mg/m³N	<0.1 mg/m³N

*Correction value at 15 °C

3.7 Economy

It seems that IGCC systems will have higher construction and operation costs relative to conventional Pulverized Coal Firing (PCF) system, because it need numerous equipment and facilities such as reactor under high temperature and pressure. On the other hand, IGCC will also deliver better thermal efficiency and environmental performance. Applying higher temperature gas turbine technologies which have been developed in the LNG field to IGCC, the plant efficiency would be improved close to 50% at LHV basis (*cf.* Fig. 1). In addition, different concept from coals suitable for conventional PCF will also deliver to lower fuel cost. Based on these results, it seems quite possible that the IGCC system may deliver power-generating cost equal to or lower than that of conventional PCF system.

3.8 Achievements of the IGCC demonstration project

The results of Nakoso 250 MW air-blown IGCC demonstration project are summarized in Table 4. The verification items of demonstration tests were generally cleared, and operational procedures and performance were confirmed. Since the technological expertise and know-how for a commercial design of air-brown IGCC plant were obtained, the demonstration project was finished on a successful note at the end of March 2013.

4. Utilization of IGCC demonstration plant after the project

After the demonstration project, the IGCC plant has been utilized as a commercial power plant. The reasons for continued operation of the demonstration plant are to produce electricity efficiently from coal, and to obtain valuable experience and knowledge of the air-blown IGCC technology.

CCP R&D was merged to Joban Joint Power Co., Ltd. in April 2013, and the IGCC plant was taken over as Unit No.10 of Nakoso power station. After a periodic inspection of IGCC facilities, commercial operation was started at the end of June 2013 as the first IGCC power plant in Japan. Figure 5 shows the operation properties of IGCC commercial plant. Continuous operation hours until an intermediate inspection in December had attained 3,917 h, which exceeded the record time of predecessor IGCC plant (3,287 h in Buggenum IGCC, Netherlands). Total operation time in the initial year period was 4,802 h, and cumulative gross output was attained to 1,111 GWh.

Table 4 Status of targets and achievements

	Targets	Results	Status of Achievement
Safe and Stable Operation	250 MW	250 MW	Achieved
Long Term Continuous Operation	>2,000 h	2,238 h	Achieved
Net Thermal Efficiency	>42% (LHV basis)	42.9%	Achieved
Carbon Conversion Rate	>99.9%	>99.9%	Achieved
Environmental Performance	SO _x <8 ppm NO _x <5 ppm Particulate <4 mg/m ³ N	1.0 ppm 3.4 ppm <0.1 mg/m ³ N	Achieved
Coals	Bituminous (B) Sub-bituminous (SB)	Chinese (B) USA (B, SB) Indonesian (B, 2SB) Colombian (B) Russian (B) Canadian (B)	Achieved
Start-up Time	<18 h	15 h	Achieved
Minimum Load	50%	36%	Achieved
Load Change Rate	3%/min	3%/min	Achieved
Durability, Reliability and Maintainability	Evaluate during 5,000 h test	5,013 h in one year, No serious damage	Same as conventional PCF
Economy Estimation	Less than or equal to PCF power generation cost	Construction and operation costs were estimated.	Could be compatible with PCF

Fig. 5 Operation properties of IGCC commercial plant

5. Conclusion

The air-blown IGCC investigated in Japan is a highly effective power generation system. CCP R&D demonstrated the performance and functionality with Nakoso 250 MW air-blown IGCC demonstration plant since 2007. Reliability was confirmed by 18,788 h of accumulated operation with 3,704 GWh power supply, and the resulting net thermal efficiency was achieved to 42.9% at LHV basis. The demonstration project was finished in March 2013, and now the Nakoso IGCC plant is operated commercially by Joban Joint Power Company as high efficiency power generating station. It will pursue a further progress in high efficiency coal power generation technology with the air-blown IGCC in the near future.

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