Replacement of Coal-fired Thermal Power Plant with Highly Efficient GTCC Power Plant with Latest Green F-type Gas Turbine - No. 4 Unit of Sendai Power Station of Tohoku Electric Power Co., Inc. -

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At the Sendai Thermal Power Station of Tohoku Electric Power Co., Inc., the replacement of existing conventional thermal power plants – a 175MW coal- and heavy oil-fired power plant and two 175MW coal-fired power plants that started commercial operation in 1959 – with a single-shaft-type combined cycle power plant using the latest 1,400°C-class heavy duty M701F4 natural gas-fired gas turbine was planned and completed, with commercial operations starting in July 2010. As a result of the completion of this replacement and compared with conventional power plants, the amount of nitrogen oxides emissions has been reduced to approximately 1/20 and the amount of carbon dioxide emissions has been reduced to less than one-half. Accordingly, the power station has been operating satisfactorily with excellent environmental performance. Moreover, the power plant was selected as the "Best Gas-Fired Project" in the "Projects of the Year 2010 Awards" (hosted by Power Engineering Co., Inc.).

1. Introduction

With enhanced global perception of environmental problems, various protective measures for the environment are being implemented around the world. Among such measures, the reduction of carbon dioxide emissions, which contribute to global warming, is an urgent and important task for electric power generation companies. In Japan, about 30 to 40% of carbon dioxide emissions are generated by the electric power generating industry, making it essential for thermal power stations to undertake efforts to improve the efficiency and environmental performance of power plants.

In the replacement of the Sendai Thermal Power Station, Mitsubishi Heavy Industries, Ltd. (MHI) delivered a gas turbine – which is a key piece of machinery – as well as a heat recovery steam generator, a steam turbine and other main auxiliary equipment. In this paper, we present an overview of the latest gas turbine combined cycle power plant, not only from the perspective of high efficiency, but also from the viewpoint of measures for noise protection and the exterior appearance.

2. Overview of Plant

2.1 Overview and main features of plant

In the replacement, the No. 4 Unit of Sendai Power Station (hereinafter referred to as the "Sendai No. 4 Unit") adopted MHI's latest heavy duty and highly efficient gas turbine (M701F4), which is operated at a temperature of around 1,400°C at the turbine inlet, an MHI steam turbine (TC2F-40.5) and an MHI single-shaft-type reheat Rankine combined cycle system in which the generator is arranged along the same shaft.

(1) Adoption of highly efficient combined cycle power generating system

The MHI M701F4-type gas turbine attains a plant output and plant efficiency nearly equivalent to the MHI G-type gas turbine, which adopts a steam-cooling-type combustor

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operated with a 1,500°C-class turbine inlet temperature. The M701F4-type has been developed by enhancing the compressor capacity and the gas-turbine interior cooling system of MHI's conventional F-type gas turbine (1,300°C-class turbine inlet temperature), to bring the turbine temperature to 1,400°C-class. Because the M701F4-type does not require the combustor steam-cooling system adopted in the MHI G-type, the operational flexibility of the M701F4-type is as high as that of MHI F-type, making it easy to handle daily start and stop (DSS) and weekly start and stop (WSS) cycles.

(2) Effective utilization of unused existing facilities

In part of customer construction work, some unused facilities of existing conventional plants were effectively reused. For example, the existing water circulation conduits (sea water) for condenser cooling were reused, while the existing foundation of the No. 3 Unit was reused as the foundation of the No. 4 Unit after being checked for soundness and the required reinforcement was carried out. The replacement was completed by proactively reusing the existing facilities in the new facilities.

(3) Measures for noise prevention and the exterior appearance

Since Sendai Thermal Power Station is located in the class-2 special nature conservation area of Matsushima, (Matsushima has one of the three most famous views in Japan.) a place of great scenic beauty, main structures such as the turbine building and the boiler structure, etc., were designed with an eye toward typical Japanese-style architecture including features such as white walls and Japanese tile roofing in order to fit in with the environment of Matsushima. When seen from aboard the cruise ship that travels between Matsushima and Shiogama port, these structures are well matched with their surroundings and don't spoil the view of Matsushima. On the other hand, as a measure for noise prevention, external soundproofing walls were adopted for the transformer and other facilities, successfully bringing the noise level at the property line under the specified values (i.e., 65dBA in the daytime, 60dBA in the morning and evening and 55dBA at night). These measures make the plant both attractive and quiet.

2.2 Rated performance and environment performance of plant

(1) Rated performance of plant

The Sendai No. 4 Unit generates a total output of 446MW at an atmospheric ambient temperature of -3°C and has attained a thermal efficiency of more than 58% (on a low heating value basis). The equipment was designed to meet each individual specification based on the output characteristics and operational controllability of a combined plant. The Unit has attained the world's highest-class output and efficiency as a 1,400°C-class gas turbine combined cycle power plant.

(2) Environmental performance

The Sendai Power Station replaced three conventional boilers, i.e., one 175MW coal- and heavy oil-fired power plant and two 175MW coal-fired power plants with a natural gas-fired gas turbine combined cycle power plant. **Table 1** shows a comparison of the environmental performance data before and after the replacement.

With a change from a coal- and heavy oil-fired conventional power plant to a natural gas-fired gas turbine combined cycle power plant, sulfur oxides and particulate are no longer emitted and nitrogen oxides have also been reduced to approximately 1/20[Note] compared with a conventional power plant. In addition, carbon dioxide emissions, which contribute to global warming, have been reduced to less than one-half[Note]. Emitted gas data at the inlets of stacks which were measured at 100% load in the commissioning test showed that the concentration of sulfur dioxides was less than the minimum detectable limit (5volppm), the concentration of nitrogen oxides was less than 5ppm (O_2; 16%) and the amount of particulate was also below the minimum detectable limit (0.001 g/m^3N). In addition, as a result of the adoption of a combined plant, the amount of intake water for condenser cooling circulation and the temperature difference between intake and tail water have been reduced, contributing to the reduction of waste heat toward the exterior of the plant (i.e., the sea).

Note : We compared No. 1 and No.2 units (before replacement) with No. 4 unit (after replacement) because No. 3 unit did not operate when the environmental assessment was carried out.

Table 1 Comparison of environmental performance data before and after replacement[Note]

		After replacement	Before replacement	
		No. 4 Unit	No. 1 Unit	No. 2 Unit
Plant type		Single-shaft gas turbine combined cycle	Conventional	Conventional
Fuel		Natural gas	Coal and Heavy oil	Coal
Plant capacity		446 MW (atmospheric ambient temperature; -3°C)	175 MW	175 MW
Sulfur oxides	Concentration of emissions	-	186 ppm	152 ppm
	Amount of emissions	-	108 m^3N/h	92 m^3N/h
Nitrogen oxides	Concentration of emissions	5 ppm	300 ppm	260 ppm
	Amount of emissions	15 m^3N/h	170 m^3N/h	146 m^3N/h
Particulate	Concentration of emissions	-	0.15 g/m^3N	0.15 g/m^3N
	Amount of emissions	-	85 kg/h	85 kg/h
Stack height		59 m aboveground	120 m aboveground	120 m aboveground
Carbon dioxide Emissions rate		0.362 kg-CO_2/kWh	0.832 kg-CO_2/kWh	0.885 kg-CO_2/kWh
Condenser cooling system		Sea-water cooling	Sea-water cooling	Sea-water cooling
Amount of cooling water		10 m^3/s	approx. 6 m^3/s	approx. 6 m^3/s
ΔT between intake and tail water		below 7°C	approx. 10°C	approx. 10°C

Note : We compared No. 1 and No.2 units (before replacement) with No. 4 unit (after replacement) because No. 3 unit did not operate when the environmental assessment was carried out.

3. Features of Main Equipment

3.1 Gas turbine[1]

The M701F4-type is the top of the line F-type gas turbine for 50Hz applications and was developed to increase compressor inlet air flow, to raise the turbine inlet temperature and to improve power output and efficiency. It was based on the M701F3-type, which has been operated successfully for years (**Figure 1**).

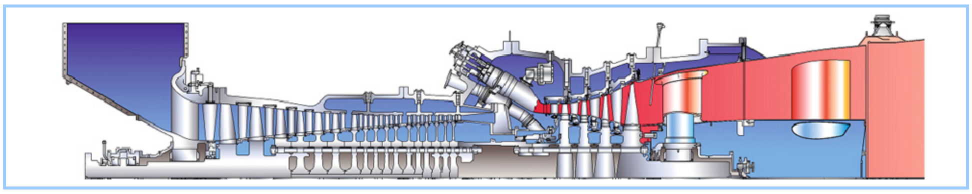

Figure 1 Sectional view of M701F4-type gas turbine

For the compressor, the blade height of the forward 6 rows was raised to increase the inlet air flow rate. This is a technique verified by the M501F3-type gas turbine, which is an F-type for 60Hz applications. In order to reduce the loss resulting from the increment of the inlet air flow rate, the raised blades and vanes of the forward 6 rows were designed to be optimized by means of computational fluid dynamics (CFD) and were modified to the latest blade profile, which was successful in the MHI G-type gas turbine. These modifications enabled the loss increase to be controlled and the inlet air flow rate to be increased by approximately 6% compared with the F3-type, thereby increasing the gas turbine output.

For the turbine, with the gas turbine inlet temperature increased, the cooling structure for the blades and vanes was enhanced to ensure reliability and improve thermal efficiency.

For the last row blades and in order to reduce the exhaust loss caused by the increase of the inlet air flow rate, the final row blade of the M701G-type was adopted as an increased height blade. This blade has been used for a long time in the M701G-type. In addition, in parallel with the adoption of the increased height blade, the profile of the exhaust diffuser located downstream of the last row blades was also modified, enabling the further reduction of exhaust loss and the improvement of turbine performance.

Because this was the first operation for the M701F4-type gas turbine, the compressor inlet air flow rate, the turbine-blade metal temperature and more than 500 other measurements of items including the compressor, combustor, turbine and exhaust were conducted in the commissioning site to confirm the desired performance and reliability.

3.2 Gas turbine combustor

With the turbine inlet temperature increased over that of the conventional F-type gas turbine combustor, a new combustor has been developed that combines the low NOx technology and combustion pressure fluctuation control technology of the MHI G-type gas turbine combustor with air-cooling technology gathered from the extensive experience with the F-type gas turbine combustor (**Figure 2**).

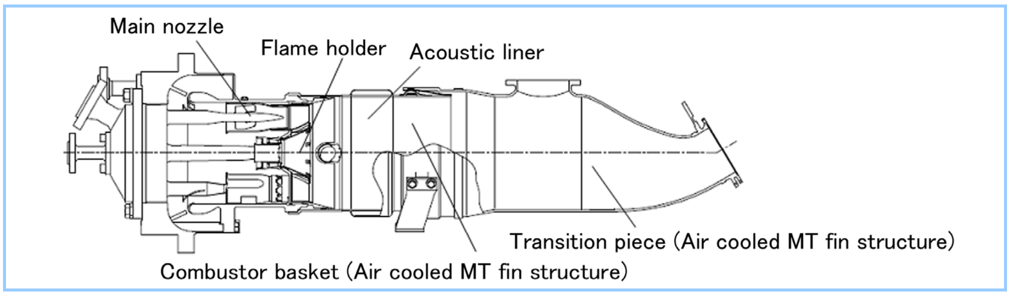

Figure 2 M701F4-type gas turbine combustor

In compliance with the basic configuration of MHI conventional premixed dry low NOx combustors, the combustor has a multi-nozzle structure that stabilizes the flames of the 8 main premix burners using a small-size pilot burner and has an air bypass mechanism that enables the regulation of the fuel-air ratio in the combustion region. Because NOx generation increases exponentially with the local flame temperature, the formation of a homogenized fuel-air mixture is a key factor for low NOx combustion. The main fuel nozzle is integrated with a swirler, the technology of which is applied to the latest MHI G-type[2]. This nozzle can form a more homogeneous fuel-air mixture compared with the nozzle and swirler of the conventional F-type. In addition, with improvements to the flame holder[3], lean premixed flame can be formed in a stabilized condition. The combustor basket and the transition piece are composed of the MT fin structure[4] with an air cooling system, which is designed for the optimum quantity of cooling air based on the extensive operational experience with the MHI F-type air-cooled combustors.

To control the combustion pressure fluctuation, the acoustic liner verified in the MHI G-type and F-type was installed. The acoustic liner works such that the combustion pressure fluctuation (i.e., sound energy) is converted into thermal energy to fade away. This has the effect of controlling high-frequency combustion vibrations. In addition, the Advanced Combustion Pressure Fluctuation Monitoring (A-CPFM) system[3] was installed and continuously monitors the combustion pressure fluctuation during operation and automatically adjusts operational parameters when detecting any indication of an increase in the combustion pressure fluctuation level.

In the commissioning test, the metal temperatures of the combustor and other data were measured to confirm the soundness of the equipment and that the characteristics of NOx emissions were equivalent to or below the conventional F-type gas turbine combustor, despite the increase in turbine inlet temperature.

3.3 Steam turbine

For the steam turbine, a proven two-cylinder turbine used to generate the steam flow rate of exhaust gas boilers, a highly efficient reaction blade designed by means of the latest three-dimensional flow analysis and a group of 40.5-inch integral shroud blades (ISB) for the final row blades, etc., were adopted with the aim of achieving highly efficient operation. A cross-sectional view of the steam turbine is shown in **Figure 3**.

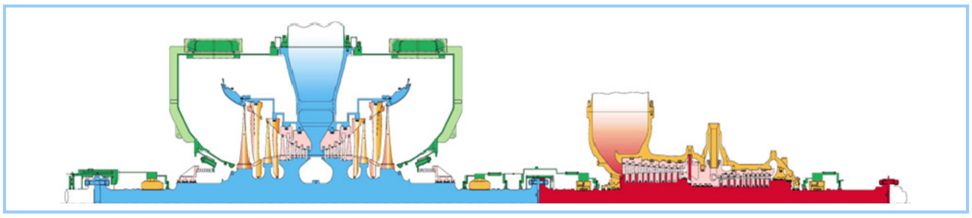

Figure 3 Cross-sectional view of steam turbine

3.4 Heat recovery steam generator

A heat recovery steam generator that enables vertical-type triple-pressure reheating natural circulation with a stack installed on its upper side was adopted. With the exhaust gas temperature increased along with the adoption of the high temperature gas turbine, high pressure steam conditions were applied, i.e., 550°C for high pressure main steam and 566°C for reheat steam (steam turbine inlet), for the purpose of highly efficient operation (**Figure 4** , **Table 2**).

The heat exchanger tubes of the heat recovery steam generator were arranged in the optimum configuration in consideration of the steam conditions and the heat recovery system of the feedwater, which is discussed in the following paragraph. The scale of the heat exchanger tubes module was increased at the factory to be installed onsite, curtailing the amount of work required in the field and improving reliability.

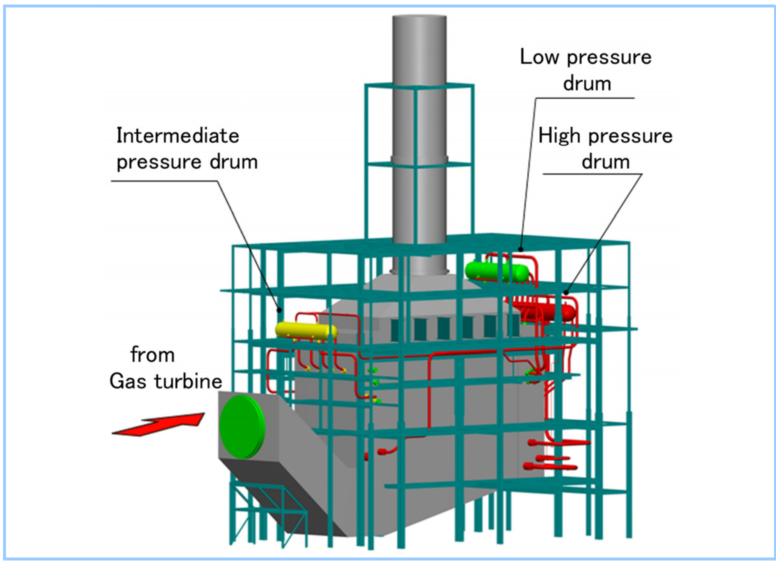

Figure 4 Exhaust gas boiler

Table 2 Specifications of main equipment

General plant items	Type		Single-shaft gas turbine combined cycle
	Fuel		Natural gas
	Station capacity		446 MW
	Unit configuration		446 MW x 1 unit
	Condenser cooling system		Sea water cooling
Gas Turbine	Quantity		1 unit
	Type		Open-type simple-cycle single-shaft M701F4-type
	Turbine inlet temperature		1,400°C-class
	Rotational speed		3,000 min^{-1}
Heat Recovery Steam Generator	Quantity		1 unit
	Type		Heat recovery triple pressure type
	Maximum evaporation	(High pressure)	310 t/h
		(Intermediate pressure)	76 t/h
		(Low pressure)	55 t/h
Steam Turbine	Quantity		1 unit
	Type		Radical fin-type two-stream exhaust-type reheat mixed pressure condensation-type TC2F-40.5
	Steam conditions (Inlet pressure)	(High pressure)	11.8 MPa
		(Reheat)	2.87 MPa
		(Low pressure)	0.38 MPa
	Steam conditions (Inlet temperature)	(High pressure)	550°C
		(Reheat)	566°C
		(Low pressure)	249°C
	Rotational speed		3,000 min^{-1}
Generator	Quantity		1 unit
	Type		Horizontal spindle cylinder rotation-field magnet-type synchronous generator
	Capacity		496,000 kVA (Hydrogen pressure 0.4 MPa)
	Voltage		21 kV
	Cooling system		Hydrogen cooling
	Frequency		50 Hz
	Rotational speed		3,000 min^{-1}

3.5 Turbine cooling air (TCA) cooler and fuel gas heater (FGH)

For the purpose of pursuing highly efficient operation, through the incorporation of a TCA cooler and a fuel gas heater (FGH) into a boiler feedwater system, the heat loss exhausted from the plant cycle could be kept to a minimum.

Conventional TCA coolers cannot effectively recover the heat gained in cooling gas-turbine air to proper temperature by exhausting the remaining heat to the exterior of the plant, the atmosphere or sea water. In the TCA cooler in this plant, gas-turbine cooling air is heat-exchanged with boiler feedwater, so that the recovered heat contributes to the generation of steam in the exhaust gas boiler. Moreover, fuel gas is heated in the FGH, where boiler feedwater heated in the exhaust gas boiler is employed to improve the total efficiency of the power plant by raising the temperature of turbine-inlet fuel gas and improving gas turbine efficiency.

4. Conclusion

The Sendai Thermal Power Station of Tohoku Electric Power Co., Inc. was reborn as a gas turbine combined cycle power plant using the latest technology and has provided the expected outcome. The exterior of the power station suits the environment of the class-2 special nature conservation area of Matsushima, a place of great scenic beauty and the performance of the power station in terms of its surroundings, output and efficiency has received world-class evaluations as a 1,400°C-class gas turbine. We confidently believe that the power plant can contribute to the power supply of the region as an environmentally-friendly prime power source in the future.

References

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