Power Output Augmentation of Gas Turbine Combined Cycle by Inlet-Air Cooling System of Chiller Type under High Ambient Air Temperature

At Mitsubishi Heavy Industries, Ltd. (MHI), large-scale gas turbines for electric power plants are designed and manufactured at the Takasago Machinery Works. Because of the highly advanced design and manufacturing technologies used for turbo machines and heat exchangers, large-capacity, high-efficient centrifugal-chillers are also designed and manufactured at the Air-Conditioning & Refrigeration Systems Headquarters Takasago Plant that is part of the Takasago Machinery Works. By combining these two product technologies, an inlet-air cooling system with a gas-turbine inlet section has been developed for gas turbine combined cycle power plants (GTCC). For refrigeration equipment, a centrifugal-chiller, cooling tower, water supply pump and power supply unit are packaged in a single unit. An inlet-air cooling coil unit placed in an air-inlet duct is devised so as to be installed during the major inspection period of gas turbines. Our Power Systems Headquarter and Air-Conditioning & Refrigeration Headquarter are integrated to provide one-stop services for our customers.

1. Introduction

At Mitsubishi Heavy Industries, Ltd. (MHI), large-scale gas turbines for electric power plants are designed and manufactured at the Takasago Machinery Works. Because of the highly advanced design and manufacturing technologies used for turbo machines and heat exchangers, large-capacity, high-efficient centrifugal-chillers are also designed and manufactured at the Air-Conditioning & Refrigeration Systems Headquarters Takasago Plant that is part of the Takasago Machinery Works. By combining these two product technologies, an inlet-air cooling system with a gas-turbine inlet section has been developed for gas turbine combined cycle power plants (GTCC). The relationship of the output power of a gas turbine – the core of a combined cycle power plant – to ambient air temperature is shown in Figure 1.

Air density increases by lowering inlet-air temperature, contributing to power output recovery.

Figure 1  Power-output recovery mechanism by inlet-air cooling system in gas turbine combined cycle power plant (GTCC)

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In a gas turbine, atmospheric air is suctioned, compressed, mixed with fuel and burned in a combustor to generate electricity. The air density falls as the ambient air temperature rises, such that the power output decreases depending on the decrease in the mass of air that is sent to the combustor. When air at a temperature of 35°C is cooled to 15°C, the air density increases by about 10 percent, increasing the power output by about 10 percent.

2. Inlet-air cooling system

2.1 Cooling mechanism of centrifugal-chiller

Figure 2 shows the cooling mechanism of the centrifugal-chiller.

The cooling mechanisms are as follows:

(1) A refrigerant gas contained in the top section of an evaporator under conditions below 10°C and around 0.3 MPa is compressed by a turbo (centrifugal) compressor and sent to a condenser, with the conditions of the gas over 40°C and around 1 MPa. (2) In a wet cooling tower (one example here, but many other methods of heat exchange are known), cooling water at around 30°C that has been heat-exchanged with atmospheric air is sent to the above condenser and again heat-exchanged with the refrigerant, liquefying the refrigerant. (3) The high pressure liquefied refrigerant in the condenser is adiabatically expanded to the evaporator via an expansion valve, resulting in a low pressure liquefied refrigerant at a single-digit temperature level. (4) In an evaporator, the low pressure liquefied refrigerant is heat-exchanged with the returned cooling water at 10-some °C from the cooling coil, returning the refrigerant to a gaseous condition and where the cooling water is cooled to a single-digit temperature (for instance, 5°C). MHI’s centrifugal-chiller has a feature that can provide cold energy corresponding to 6.5 times the electric power for the drive motor of a compressor to a cooling coil, which is referred to as a coefficient of performance (COP) of 6.5.

Figure 2  Cooling mechanism of centrifugal-chiller

2.2 Comparison of inlet-air cooling system

Table 1 shows a comparison of general inlet-air cooling systems.

Inlet-air cooling systems include: (a) An eva-cooler system in which air is cooled with the latent heat of water vaporization by dripping water from evaporative elements placed in the downstream of an air-inlet filter housing in an air-inlet duct inlet portion. (b) A fog system in which air is cooled with the latent heat of water vaporization by atomizing water mist in the downstream of an air-inlet filter housing. (c) A chiller system in which air is cooled by introducing chilled water from a chiller such as a centrifugal-chiller into a cooling coil placed in the downstream of an air-inlet filter housing.

In this development of the cooling system, a chiller system that can lower the temperature of the inlet air below a wet-bulb temperature, which results in a greater increase rate, has been selected.
Table 1 Comparison of inlet air cooling systems

<table>
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<th>System outline</th>
<th>Eva-cooler system</th>
<th>Fog system</th>
<th>Chiller system</th>
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<tr>
<td>Inlet-air cooling with the latent heat of water by dripping water from evaporative elements of an eva-cooler</td>
<td>Inlet-air cooling with the latent heat of water by atomizing water mist</td>
<td>Inlet-air cooling by introducing chilled water from a chiller such as a centrifugal-chiller into a cooling coil placed in the downstream of an inlet-air filter housing</td>
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<table>
<thead>
<tr>
<th>System configuration</th>
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<tr>
<td>Evaporative Cooler</td>
<td>Spray Pump Device</td>
<td>Air cooling coil + Mist eliminator</td>
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<td>Gas Turbine</td>
<td>Gas Turbine</td>
<td>Chilled water</td>
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<td>Deni water</td>
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<td></td>
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<tr>
<td>Circulating water tank</td>
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| Inlet-air temperature drops | approx. 5°C | approx. 5°C | approx. 15°C |
| (atmospheric conditions: 30°C, RH: 60%) | (atmospheric conditions: 30°C, RH: 60%) | (atmospheric conditions: 30°C) |

| Output recovery rate | approx. 3% | approx. 3% | approx. 9% |

| Features | (1) Air temperature is not attained below a wet-bulb temperature, so that the effect of system is small in high humidity conditions. | (1) Drainage system is required in an inlet air duct. (2) Air temperature is not attained below a wet-bulb temperature, so that the effect of system is small in high humidity conditions. | (1) Output recovery rate is high. (2) Inlet air temperature is attained independently of humidity. (3) A cooling coil and a mist eliminator must be installed. (4) The initial investment cost is higher for chiller-system installation. |

2.3 Component of inlet-air cooling system

Figure 3 shows the main components of the newly developed inlet-air cooling system. The newly developed cooling system includes an air cooling coil (1) (that is installed in the downstream of a filter housing in the duct-inlet portion), a centrifugal-chiller (2), a cooling tower (3), a chilled water pump (4) for circulating chilled water from/to an air cooling coil (1) and a centrifugal-chiller (2) a cooling water pump (5) for circulating cooling water from/to a centrifugal-chiller (2) and a cooling tower (3) and electrical facilities (6) for driving a centrifugal-chiller compressor motor, a cooling-tower fan motor and pump motors, wherein the components (2), (3), (4), (5) and (6) are combined in a packaged chiller unit with a cooling tower shown in this figure.
2.4 Selection of refrigeration capacity

Figure 4 shows temperature data and relative humidity data per hour throughout the year in Chon Buri City in Thailand.

In the figure, using the same centrifugal-chiller where the inlet air can be cooled to 10°C at 7,800 Rt, with the cooling-water temperature raised slightly to boost a refrigeration capacity to 8,600 Rt, the cooling range that can cool the inlet air to 13.5°C is shown. In this manner, the proper refrigeration capacity of the chiller can be selected depending on the weather conditions of the targeted location.

Figure 4  Temperature data and relative humidity data per hour throughout the year in the area around the power-station and examples of selecting the chiller capacity of the inlet-air cooling-system

Figure 5 shows the output increases of GTCC under each weather condition, along with humidity parameters.

This shows that greater output increases are obtained, compared with an eva-cooler system. (Note: 1USRT refers to a refrigeration capacity that cools 1US ton (2,000 lb) of water at 0°C into ice within 24 hours.)
2.5 Layout of equipment

Figure 6 shows the layout of an inlet-air cooling system as an example. The inlet-air cooling system includes two sets of chiller modules and a cooling-coil housing that is placed between the filter housing and the inlet-air duct; wherein cooling water is sent by water supply pumps placed in chiller modules through piping connected from chiller modules to the cooling-coil housing and then distributed to cooling coils through headers on both sides. Cooling water is finally returned to the chiller modules after cooling the inlet air.

2.6 Chiller module

Figure 7 shows the chiller module. The chiller module includes two sets of centrifugal-chillers, four sets of water supply pumps (two sets for chilled water, two sets for cooling water), their motor panels, transformer panels (e.g., 6kV to 400V, etc.), incoming panels and control panels, where those panels are placed on the first floor and a cooling tower is installed on the second floor, wherein piping and cable wiring between each piece of equipment are connected in the module.

Chillers are installed with AART-200s in series and have a capacity of 4,400 USRt, wherein chilled water is circulated at 1,200 m³/hr, under the conditions of incoming cooling water at 16°C and outgoing water at 5°C.

2.7 Cooling-Coil Housing and Assembly Method

Figure 8 shows an example of the inlet-air cooling-coil housing. The cooling-coil housing is installed in a space of 3m in width between the filter housing and the inlet air duct. In this example, cooling coils each having a cooling capacity of 2.3 MW are arranged in two rows and stacked in six tiers, amounting to a cooling capacity of 28 MW.
Figure 9 shows an example of the coil-assembly method.

In the case of existing facilities, the coil-assembly method is as follows: (1) The filter housing is separated from the duct to move to the upstream side by 3 m. (2) Each side of the coil housing (i.e., the filter housing side and the duct side) is assembled to be connected with the filter housing and the duct, respectively. (3) The cooling coils are lifted up to be connected with the steel frame of the floor. (4) The cooling coils are stacked in order and connected with each other. (5) The nozzles of the cooling coils (i.e., the nozzles of the inlet and outlet of the chilled water) are extruded to exit out the side portion of the coil housing. The space between the cooling coils and the upstream side and downstream side of the coil housing are covered by seal plates. (6) The headers and nozzles are connected. (Each nozzle and each header nozzle are connected by valves and flexible joints.)

In addition, not shown in step (2) above, a stage structure which has a height corresponding to the height of the second floor coils, is fabricated in the filter housing side of the coil housing. In the side face of the housing, a stairway (shown in Figure 8) is assembled, allowing access to each stage and the top of the coil housing.

This assembly manner is devised so as to make it possible to install the coils during the major inspection period of the gas turbine.

![Figure 9](image)

**3. Engineering and service**

As shown in Figure 10, centrifugal-chillers are developed, designed and manufactured at their own plant in the same area of the Takasago Machinery Works where gas turbines are also developed, designed and manufactured. This inlet-air cooling system is also developed by a joint team from the Power Systems Headquarter and Air-Conditioning & Refrigeration Headquarter, together with members of the Takasago Research & Development Center, which are adjacent to each other.

In the application of an inlet-air cooling system to the gas turbine combined cycle power plants of each customer, plant information as the OEM from the Power Systems Headquarter is communicated to the Air-Conditioning & Refrigeration Headquarter, so that an optimum system aligned with weather conditions can be proposed immediately and presented to our customers.

In maintenance services as well, when you contact the Power Systems Services Headquarter, the information will be communicated to the Air-Conditioning & Refrigeration Headquarter, so that maintenance services can be smoothly provided.
4. Conclusion

We have developed a chiller type inlet-air cooling system in which a highly efficient centrifugal-chiller is applied for gas turbine combined cycle power plants. The system includes a cooling coil module and a chiller module. The optimum cooling temperature of the inlet air and the capacity of the chiller for each plant are selected based on plant information as the OEM and the weather conditions of the targeted area. The capacity can be met by combining several chiller modules. For chiller modules, a centrifugal-chiller, a cooling tower, a water supply pump and an electric power unit, a transformer and a control unit are packaged in a single unit. Inlet-air cooling modules, in this example, are placed in a space of 3m in width between the filter housing and the inlet-air duct, with coils arranged in two rows and stacked in six tiers and can be installed during the major inspection period of a gas turbine. Our Research & Development Center, Design and Engineering Section, Manufacturing Section and Service Section for gas turbines and chillers are gathered in the same area of Takasago, Hyogo Prefecture, allowing one-stop services to be provided for customers.