District Cooling Plant with High Efficiency Chiller and Ice Storage System

YOSHINORI HIDA*1 SEIJI SHIBUTANI*1
MATSUYUKI AMANO*1 NORIYASU MAEHARA*2

Mitsubishi Heavy Industries, Ltd. (MHI) received an order from Singapore District Cooling Pte, Ltd., for a district cooling plant with a cooling capacity of 57 MW (16,210 RT). This project was an engineering, procurement, and construction contract that included the design, manufacture, procurement, construction, and commissioning of a high-efficiency district cooling plant that would serve as a model for South East Asia where the year-round cooling demand is high. One year has now elapsed since the start of commercial operation, and this plant is currently operating at higher efficiency than originally planned. This report describes the performance improvement technologies, such as the centrifugal chiller and ice storage system, that were introduced to achieve this increased efficiency.

1. Introduction

The Government of Singapore has developed the Marina South area to include a district cooling plant and an advanced telecommunication infrastructure. This area is beginning to take on a role as an important business center in Singapore.

MHI received an order for the first district cooling plant in this area from Singapore District Cooling Pte, Ltd. (SDC)[Note], and delivered and handed over the plant in 2007 as a model of high-efficiency technology.

We were awarded this contract despite serious international competitive bidding because MHI's plant was recognized to be superior in both cost and performance. Five district cooling plants are planned for the Marina South area, and MHI delivered the portion of the first stage construction of 57-MW (16,210-RT) No. 1 plant in the first stage of construction to supply chilled water to two office buildings and one commercial facility near the plant.

Note: The customer, SDC is a joint venture between Singapore Power and the French company Dalkia.

2. Outline of plant facilities

Table 1 shows the main equipment of heat source components at the plant. During the first stage of construction, MHI delivered one 3-MW centrifugal chiller, two 7-MW centrifugal chillers, and two 20-MW ice storage systems. During the plant design, MHI made every effort to facilitate smooth workflow on site using a three-dimensional (3D) computer-aided design (CAD) that integrated all information on the machinery, piping, air conditioning ducts, electrical and control equipment, and architectural details to optimize the layout of the plant space. MHI also made a great effort to simplify maintenance after delivery by integrating the movement and maintainability of each machine and piping system into the design. In addition, MHI reduced the cost of the detailed design using automatic isometric drawings for the plant piping with 3D CAD.

Table 1 Main equipment of heat source components of No. 1 plant

Chillers	Quantity during first stage	Quantity at time of completion
Single-type chilled water centrifugal chiller (3 MW/chiller)	1	1
Parallel-type chilled water centrifugal chiller (7 MW/chiller)	2	4
Ice storage system: Compound-type brine centrifugal chiller + ice storage tank (20 MW/system)	2	6
Amount of chilled water supplied by the plant	57 MW (16210 RT)	151 MW (42943 RT)

3. Centrifugal chiller

3.1 Description

A high-reliability, high-efficiency NART-series compressor was used in the centrifugal chiller. The compressor's high efficiency is due to its aero dynamic profile that minimizes mechanical loss. As well, the heat transfer efficiency of the heat exchanger was improved by optimizing the shape and configuration of its array of tubes.[1]

3.2 Application technologies in this project

(1) Heat exchanger configuration change

The 7-MW chilled water centrifugal chiller is a parallel-type chiller with two compressors. In this project, our aim was to improve the chiller performance using a vertical

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*1 Air-Conditioning & Refrigeration Systems Headquarters
*2 Kanden Energy Solution Co., Inc.

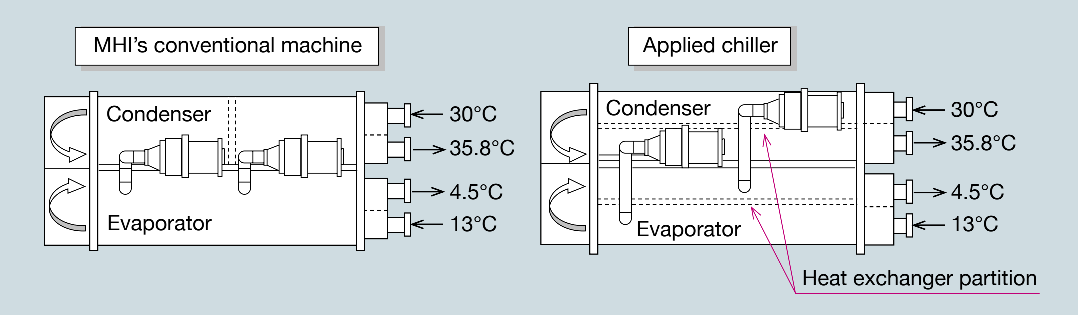

Fig. 1 Comparison of heat exchangers in a parallel type chiller
We use a configuration where two independent chillers are connected in series using vertical division type heat exchangers.

division type evaporator and condenser divided into two sections configured so that two independent chillers could be connected in series. **Figure 1** and **Table 2** show the comparison with a conventional machine, and **Fig. 2** shows a 3D model of the 7-MW parallel-type chilled water centrifugal chiller.

(2) Switching the number of operating compressors according to operational mode

In this project, for the first time, MHI used brine centrifugal chillers with three compressors for ice storage. This improved the performance compared to that of our conventional machine by switching the number of operating compressors according to the operational mode of either ice storage or chilled water discharge. Since a brine centrifugal chiller has a different brine outlet temperature depending on the operational mode, the compression ratio of the refrigerant changes. Since the compressor for a brine centrifugal chiller is normally selected for the ice-storage mode with a certain greater compression ratio and fixed rotational speed setting, the performance during the chilled water discharge operation where the compression ratio is smaller tends to be neglected. **Figure 3** shows the flow of our conventional machine.

Higher efficiency operation is possible for both ice storage and chiller water discharge modes by using three compressors for the chiller, operating two low-stage compressors and one high-stage compressor during ice storage when the required compression ratio is greater, and operating only two low-stage compressors during chilled water discharge operation when the required compression ratio is smaller.

Table 2 Comparison of performance improvement values for the 7-MW parallel type chilled water centrifugal chiller

Item	MHI's conventional machine	Applied chiller (heat exchanger vertical division type)
Cooling capacity	7 MW (2000 RT)	7 MW (2000 RT)
Chilled water condition	13°C at inlet/ 4.5°C at outlet	13°C at inlet/ 4.5°C at outlet
Cooling water condition	30°C at inlet/ 35.8°C at outlet	30°C at inlet/ 35.8°C at outlet
Electrical power COP	1240 kW 5.67	1074 kW 6.55

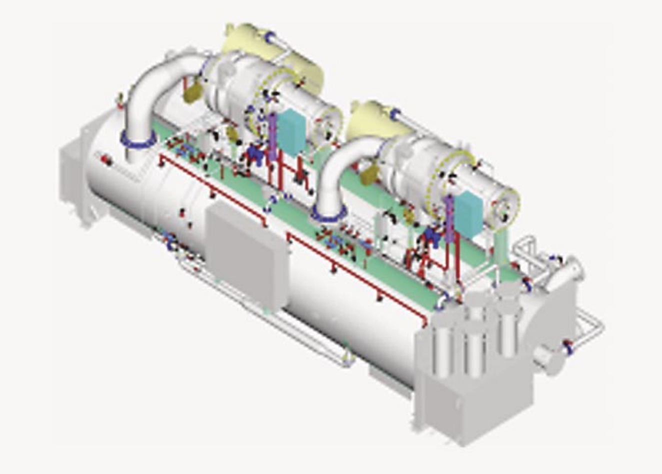

Fig. 2 Three dimensional model of the 7-MW parallel type chilled water centrifugal chiller

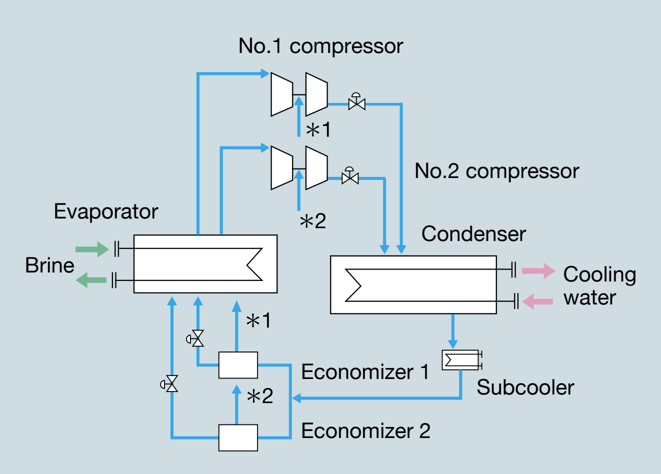

Fig. 3 Flow of the brine centrifugal chiller (MHI's conventional machine)

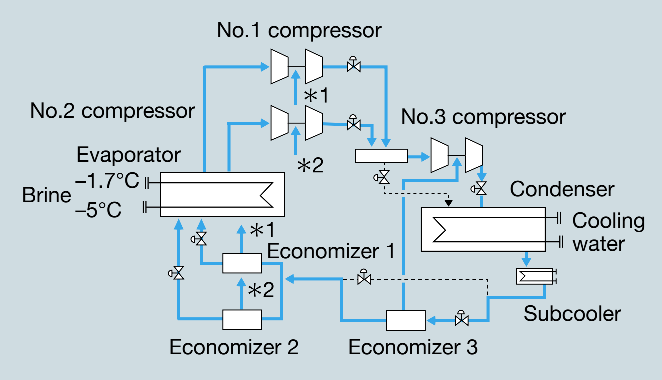

Fig. 4 Flow of the compound type brine centrifugal chiller (for ice storage operation)
During ice storage operation with a high compression ratio, the pressure is raised by the No. 3 high-stage compressor, and then increased to a medium pressure by the No. 1 and No. 2 low-stage compressors.

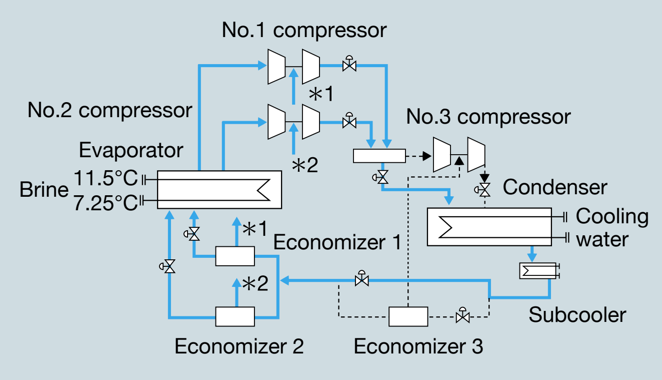

Fig. 5 Flow of the compound type brine centrifugal chiller (for chilled water discharge operation)
During chilled water discharge operation with a low compression ratio, only the No. 1 and No. 2 low-stage compressors operate.

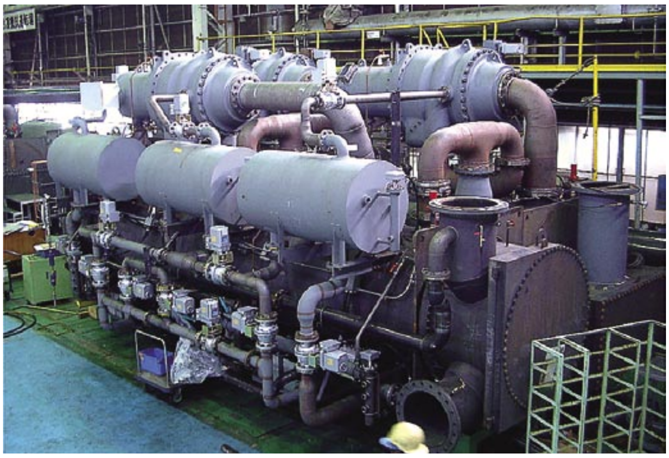

Fig. 6 10-MW compound-type brine centrifugal chiller
The figure shows the appearance of 10-MW compound-type brine centrifugal chiller (state of assembly in shop).

- Ice storage mode

Figure 4 shows the chiller operation flow for the ice storage mode. After compression by the No. 1 and No. 2 low-stage compressors to achieve a medium pressure corresponding to the chilled water discharge mode, the pressure is raised to the required value by the No. 3 high-stage compressor.

- Chilled water discharge mode

Figure 5 shows the chiller operation flow for the chilled water discharge mode. Since the compression ratio for this mode is smaller than that of the ice storage mode, the operation uses only the No. 1 and No. 2 low-stage compressors. **Table 3** shows a comparison with our conventional machine, and **Fig. 6** contains a photograph of a 10-MW compound brine centrifugal chiller.

4. Ice storage system

The ice storage system is important because, along with the centrifugal chiller, it dictates the performance and economy of the district cooling plant. Of the various methods of ice storage that have been developed, the ice ball and ice-on-coil storage systems are the most frequently used. The ice-on-coil system was selected for this plant for reasons that are described below. The coil used was a product developed by MHI.

- Reasons for selecting the ice-on-coil storage system
  (1) Since the average ice storage temperature of the ice-on-coil storage system is approximately −3°C; and since this can be set higher than the temperature of the ice ball storage system, the operating power of the chiller can be reduced.

Table 3 Comparison of performance improvement values for the 10-MW brine centrifugal chiller

Item	MHI's conventional machine	Applied chiller (compressorcompound type)
1. Chilled water discharge mode		
Cooling capacity	2800 RT	2800 RT
Brine temperature	11.5°C at inlet/3.0°C at outlet	11.5°C at inlet/7.25°C at outlet
Electrical power	2014 kW	1563 kW
COP	4.89	6.29
2. Ice storage mode		
Cooling capacity	2150 RT	2150 RT
Brine temperature	−1.7°C at inlet/−5.0°C at outlet	−1.7°C at inlet/−5.0°C at outlet
Electrical power	2020 kW	1801 kW
COP	3.74	4.20

(2) Since the ice-on-coil storage system uses less ethylene glycol as thermal mediation for ice storage than the ice ball storage system, the ice-on-coil storage system has a lower initial cost.

4.1 Ice-on-coil system used in this project

We used a product developed by MHI for the ice-on-coil system. Its features are described below.

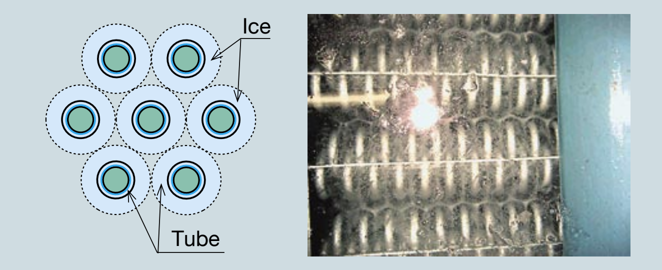

Fig. 7 Ice storage state of the ice storage coil
The figure shows the ice depositing state around the ice storage coil at the end of ice storage

(1) Minimization of installation space for the ice storage system

The ice-packing factor, an index of thermal storage consistency, is as high as 90%, so the installation space can be minimized. **Figure 7** shows a photograph of the coil during ice storage.

(2) Use of a vertical tube array

The heat transfer from the ice to the tubes is accelerated by air bubbling during ice melting. The heat transfer efficiency is improved when air bubbles are generated between the tubes and the ice rises in the water; the effect of agitation can be obtained using a vertical tube array. **Figure 8** shows the system during ice melting.

(3) Coil dimensions and configuration

The coils used in this project and their configuration in the ice storage tank are shown in **Figs. 9 and 10**, and various data for the ice storage system are shown in

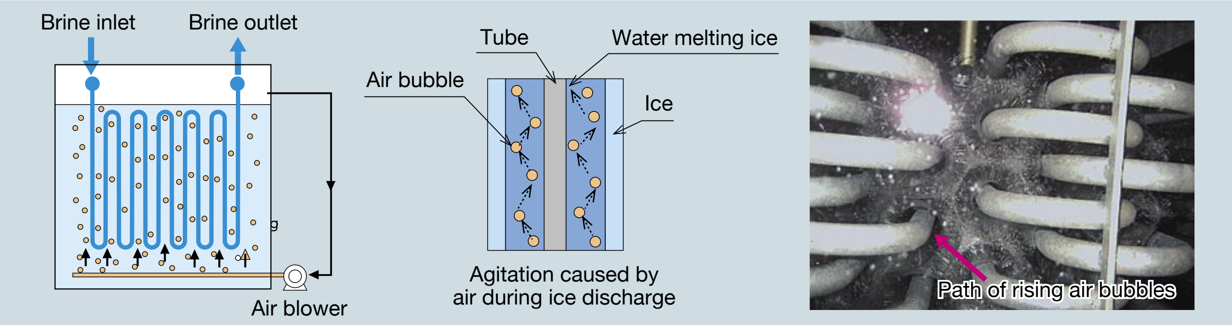

Fig. 8 Ice discharge state of the ice storage coil
The heat transfer efficiency is improved because air bubbling takes place during ice discharge, and the bubbles are agitated while they rise through the water, melting ice around the coil.

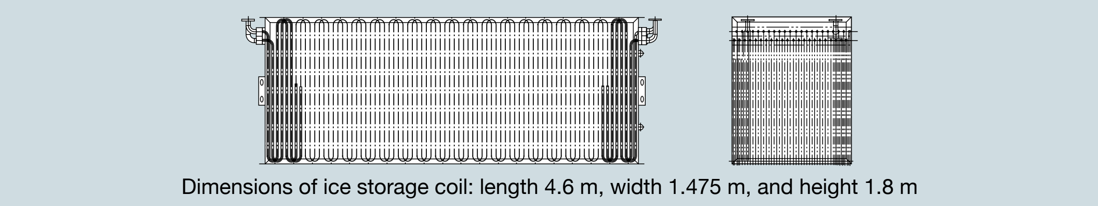

Fig. 9 Appearance of ice storage coil
The figure shows the appearance of the ice storage coil. The coil uses a vertical tube array with characteristics to achieve excellent ice melting during air bubbling. Characteristics of ice melting during air bubbling are excellent.

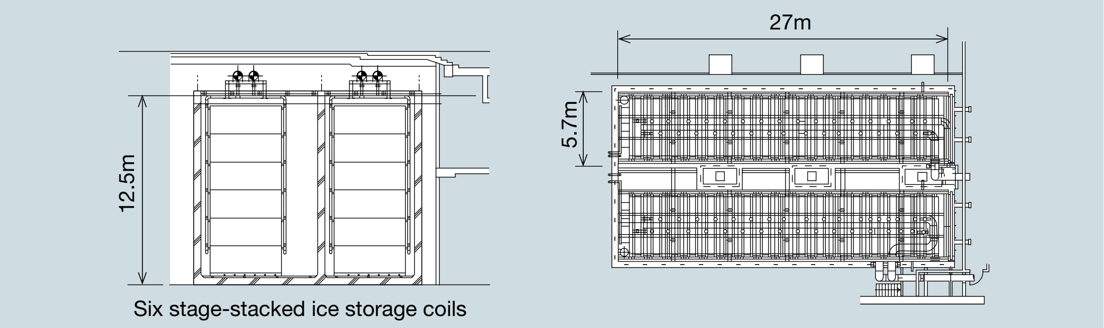

Fig. 10 Ice storage tank (cross section/plane)
The ice storage tanks are made of concrete with 204 coils installed in six stages (102 coils × two tanks).

Table 4. The two ice storage tanks are made of concrete, with 102 coils stacked vertically, up to six stages in each tank. These ice storage tanks are the largest in the world, with 579.2 km of coil tubing and as many as 100,000 tube welds. Although the coil itself should be as large as possible for maximum efficiency and reduced construction cost on site, the actual dimensions were dictated by the maximum size of hot-dipped galvanizing tanks in the vicinity of Singapore to handle the essential hot-dipping of the coil for rust-proofing reasons.

Table 4 Ice storage system data

Item	Specification
Ice storage tank	Rectangular concrete tank Concrete thickness: 475 mm Width 5.7 m, length 27 m, depth 12.5 m for each of 2 tanks
Number of coils	102 coils/tank × 2 tanks
Ice storage capacity	74 MWh/tank × 2 tanks
Ice storage coil weight	314 t/tank × 2 tanks = 628 t
Total length of ice storage coil tube	289.6 km/tank × 2 tanks = 579.2 km

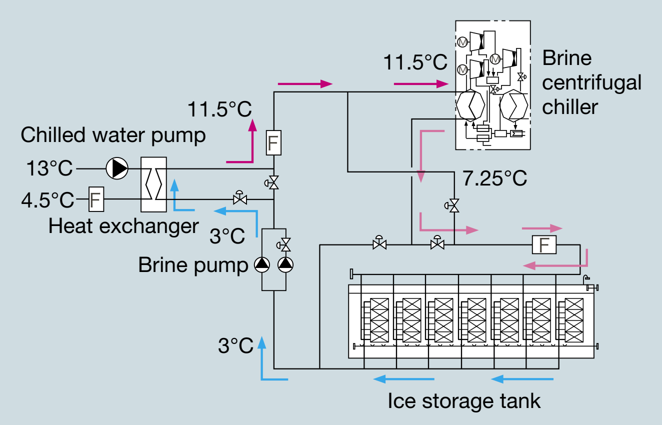

Fig. 11 Operational flow of the ice storage system for both chilled water discharge and ice discharge
The COP improvement of the total ice storage system is achieved by connecting the chilled water discharge operation of the brine centrifugal chiller and the ice discharge operation of the ice storage tank in series.

4.2 Operation of ice storage system

(1) Operation of ice storage

Approximately 700 tones of ice forms inside the tank during ice storage, and the water level in the tank rises approximately 450 mm due to volume expansion during the transition from water to ice. The amount of thermal storage of the ice storage system is calculated by measuring this change in water level, and the measured value is used to control the system.

(2) Ice discharge operation

During ice discharge, the brine centrifugal chiller and the ice storage tank are connected in series. After cooling the brine from 11°C to 7.25°C through the chilled-water discharge operation mode of the brine centrifugal chiller, the brine is further cooled from 7.25°C to 3°C using the low temperature energy at 0°C that is the latent heat of fusion of ice through the ice discharge operation of the ice storage tank. The upstream brine centrifugal chiller can be operated at high efficiency at the high brine outlet temperature, and the improved efficiency contributes to the entire ice storage system. By using this system, the electrical power consumption can be reduced by approximately 120 kW compared to the chilled water discharge operation alone by the brine centrifugal chiller. **Figure 11** shows this system flow.

4.3 Performance of ice storage system

Figure 12 shows the measured performance data during ice storage operation. The brine centrifugal chiller coefficient of performance (COP) was maintained at the design specified value of 4.2 or higher when ice storage was

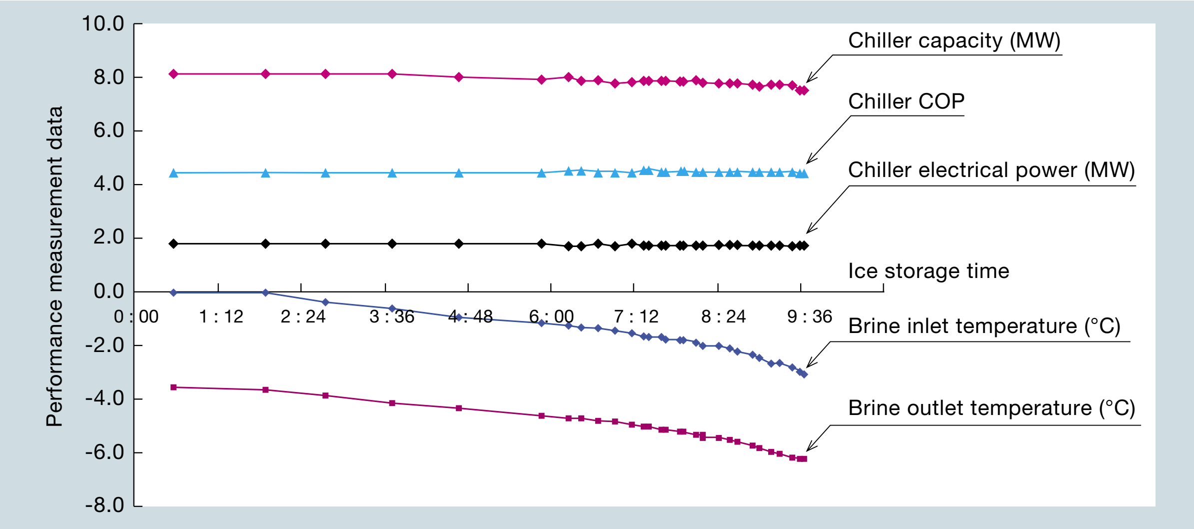

Fig. 12 Performance characteristics of the 10-MW brine centrifugal chiller measured during ice storage operation
The figure shows performance data measured during operation in ice storage mode.

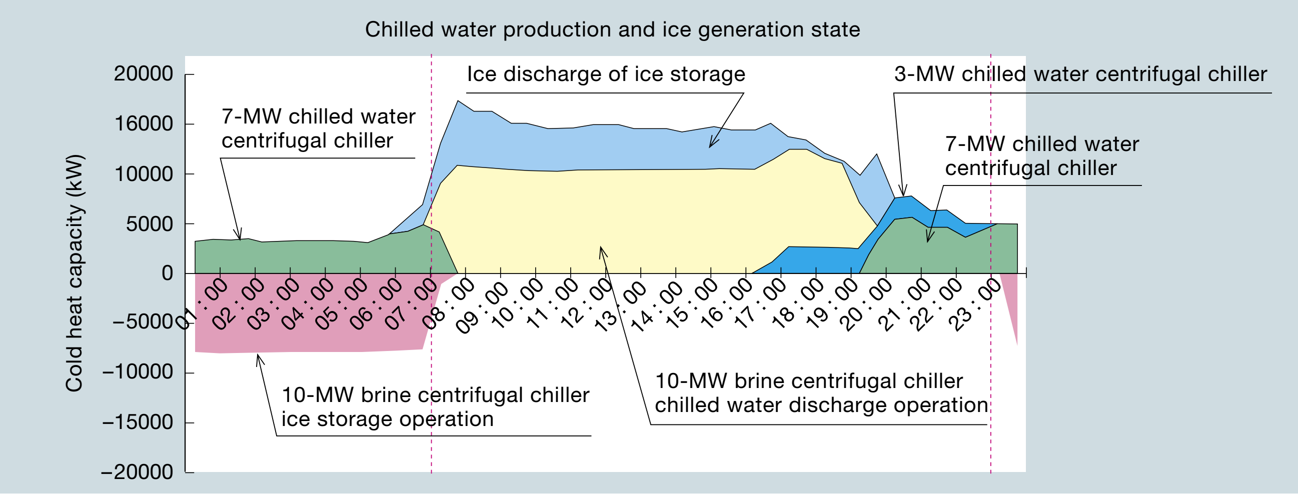

Fig. 13 Operation state of main-equipment of heat source on the typical day
The figure shows the cold capacity and the operation state of the main-equipment of heat source on the typical day (October 1, 2007).

complete to achieve high efficiency. The average brine outlet temperature of the chiller was −4.3°C. Since the operation takes place at a temperature higher than the −5°C specified for ice storage, this contributes to reducing the electric power required by the brine centrifugal chiller.

5. Historical plant operational data

5.1 Outline

One year has passed since the start of operations at the Marina South Area District Cooling Plant. The plant operation experience to date is summarized below.

The peak cooling load of this plant for users is approximately 17 MW (4,834 RT). **Figure 13** shows the cooling load and the operational data of the main equipment of heat source on a typical day (October 1, 2007). The operational data of the main equipment of heat source is as follows:

- Nighttime cooling load (20:00–8:00):
  chilled water supplied by 7-MW centrifugal chiller.
- Daytime cooling load (8:00–20:00):
  10-MW brine centrifugal chiller chilled water discharge and ice discharge series operation, as well as 3-MW chilled water centrifugal chiller operation.
- Nighttime ice storage (23:00–8:00):
  10-MW brine centrifugal chiller ice storage operation.

Figure 14 shows the cooling load and the plant electrical power consumption data for the selected day (October 1, 2007). The electrical power consumption shifted from daytime, when the electricity unit price was high, to nighttime, when the electricity unit price was low, since the brine centrifugal chiller operation takes place at night and the ice storage tank ice discharge operation takes place during the day.

5.2 7-MW parallel chilled water centrifugal chiller

The 7-MW centrifugal chiller operates over a wide load range at high efficiency because the number of operating compressors is controlled according to the cooling load and a variable speed drive control is used for the chilled water pump. **Figure 15**, which shows the relationship between

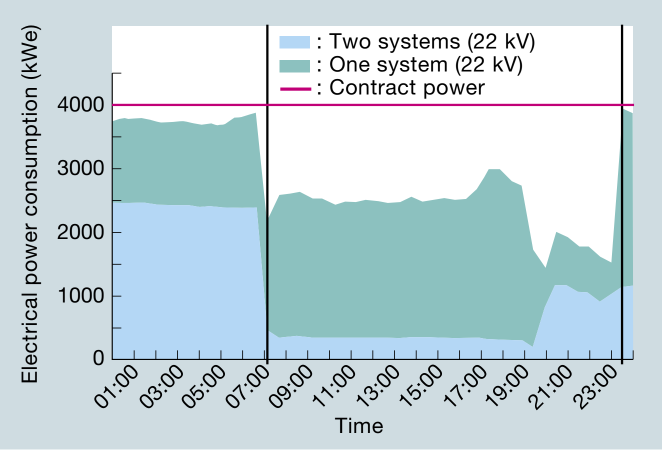

Fig. 14 Plant electrical power consumption on the typical day
The figure shows the plant electric power consumption on the typical day (October 1, 2007).

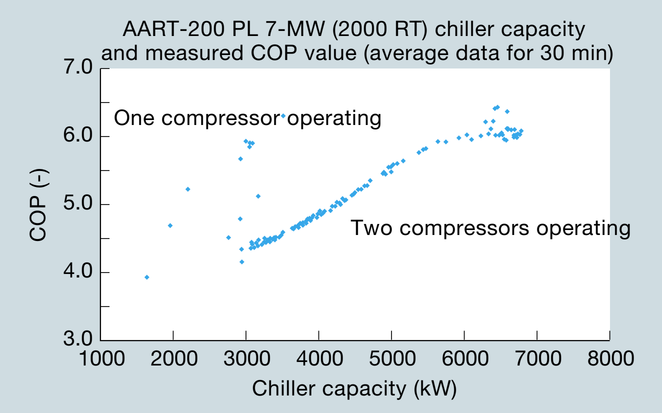

Fig. 15 7-MW chilled water centrifugal chiller COP
The figure shows the measured COP data for the 7-MW parallel-type chilled water centrifugal chiller.

the chiller cooling capacity and the measured COP value for the period from January to October, 2007, indicates that the chiller nearly met its performance specification.

5.3 10-MW brine centrifugal chiller

The 10-MW brine centrifugal chiller is used for ice storage operation at night and for chilled water discharge during the day. In both operational modes, the brine centrifugal chiller operates at 100% capacity. **Figure 16**, which shows the measured COP value data of the brine centrifugal chiller on October 1, 2007, indicates that the efficiency of the operation is equal to or greater than the planned value because the COP during the night-time ice storage operation is approximately 5.1 and the COP during the daytime chilled water discharge operation is 7.0 or higher.

5.4 Total plant efficiency

The COP of the plant is calculated from the electrical power consumption through electrical power supply line of the Marina South District Cooling Plant and the amount of chilled water sold to users, both of which are measured simultaneously. The electrical power consumption includes all the electrical power used in the plant, including the main equipment of heat source, sub-equipment, air conditioning and ventilation equipment, and lighting, amongst others. **Figure 17** shows the total COP of the plant during the period from February to October, 2007.

As the users of this plant are mainly office buildings, the total COP of the plant depends on the day of the week. The total COP of the plant increases during weekdays due to the high air conditioning cooling load, and it decreases during weekends when there is a low air conditioning cooling load. The total weekday COP of the plant is approximately 3.7 as of October, 2007. This COP significantly exceeds the average total district cooling plant COP of 3.0 because of the ice storage system, and this contributes to reducing the plant life-cycle cost.

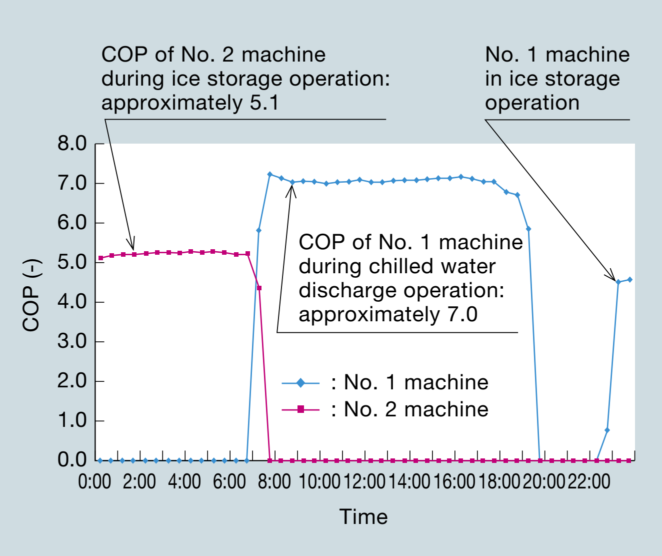

Fig. 16 Measured data for the 10-MW brine centrifugal chiller
The figure shows the measured COP data for the 10-MW brine centrifugal chiller on the typical day (October 1, 2007).

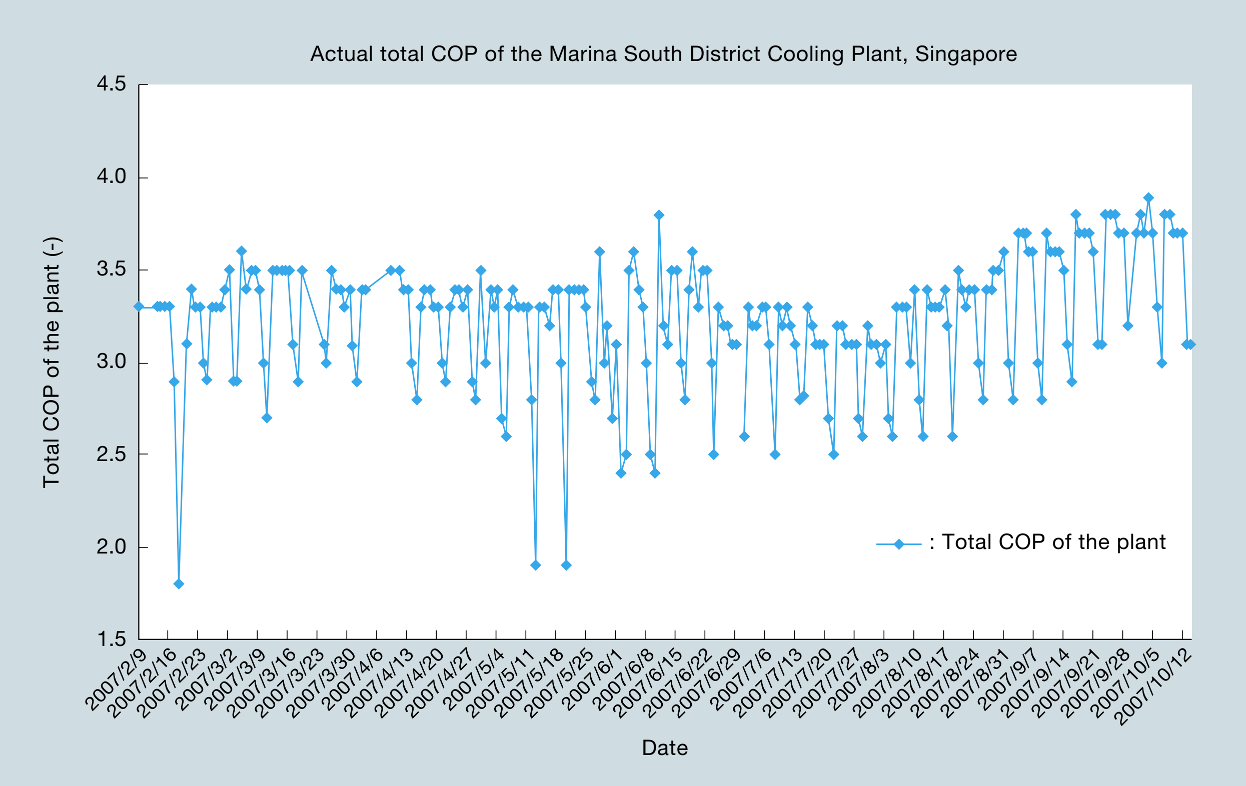

Fig. 17 Total COP of plant
The figure shows the measured total COP data for the plant from February to October 2007.

6. Conclusion

During the first stage of construction of the Marina South District Cooling Plant, we introduced MHI's latest high-efficiency centrifugal chiller and ice storage system technologies. Development plans for the Marina South Area indicate that the number of tenants of this plant will increase. It is expected that the number of orders for MHI's centrifugal chillers will also increase.

A situation where the chiller operates with a COP as high as 7.0 or more in an area like Singapore, which is located right on the equator, focuses attention on the use of chillers inside and outside Japan.

Reference

1. Seki et al., High-Efficiency Turbo Chiller (NART Series), Mitsubishi Heavy Industries Technical Review Vol.39 No.2 (2002)


Yoshinori Hida


Noriyasu Maehara


Seiji Shibutani


Matsuyuki Amano