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Ice Thermal Storage System for Kioi Hall

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Abstract:

Some nighttime thermal storage systems generate chilled water or ice by using nighttime electricity and storing the chilled water or ice for cooling during the daytime. Of these systems, ice thermal storage systems attract particular attention because they achieve a higher thermal storage density than the conventional chilled water thermal storage system and allows thermal storage tank capacity to be reduced. Nippon Steel has been working on the development of a supercooled ice-making system that continuously cools water to a supercooled state and feeds the supercooled water to a thermal storage tank where it is converted into ice and 0°C water. For the first time, Nippon Steel has used plate-type heat exchangers in producing supercooled water. The ice thermal storage system installed in Nippon Steel's Kioi Hall is described as a working example.

1. Introduction

Power demand is increasing every year. In particular, the increasing difference in demand between daytime and nighttime caused by growing cooling demand in summer has become a social problem. One way of alleviating this problem is to generate chilled water or ice using nighttime power, then using this chilled water or ice to meet cooling demand during the daytime. Nighttime thermal storage can smooth out the difference in power demand between daytime and nighttime. Since the ice thermal storage system makes use of the latent heat of ice, it can provide a higher thermal storage density than the conventional chilled water thermal storage system and can reduce the thermal storage tank capacity to about one-fifth to one-seventh. With these advantages, the ice thermal storage system is attracting particular attention in urban areas where land prices are high.

The static method, whereby ice is formed on the surface of a heat exchanger, is a popular ice-making method for the ice thermal storage system. But one problem with the static method is that ice-making efficiency falls as heat transfer resistance increases along with the formation of ice crystals. To solve this problem, many dynamic methods have been developed and commercialized in which ice is continuously or intermittently removed from the heat transfer surfaces

Nippon Steel has been developing a supercooled ice-making system that continuously cools water to a supercooled state (in which water retains its liquid phase at temperatures below 0°C), then feeds the supercooled water to a thermal storage tank where it is converted into ice and 0°C water. For the first time, Nippon Steel has succeeded in producting supercooled water by using plate-type heat exchangers.

This report introduces the ice thermal storage system used in Nippon Steel's Kioi Hall as a working example of a supercooled ice-making system using a plate-type heat exchanger.

2. Ice Thermal Storage System at Kioi Hall

2.1 Description of building

The Nippon Steel Kioi Building is located in Kioi-cho, Chiyoda Ward, Tokyo. It was constructed as part of Nippon Steel's program to commemorate its twentieth anniversary. The Kioi Building is a cultural complex, consisting of a medium-sized auditorium of 800 seats for Western classical music, a small auditorium of 250 seats for Japanese traditional music, and a staff club. **Fig. 1** shows a cut-way view of the complex.

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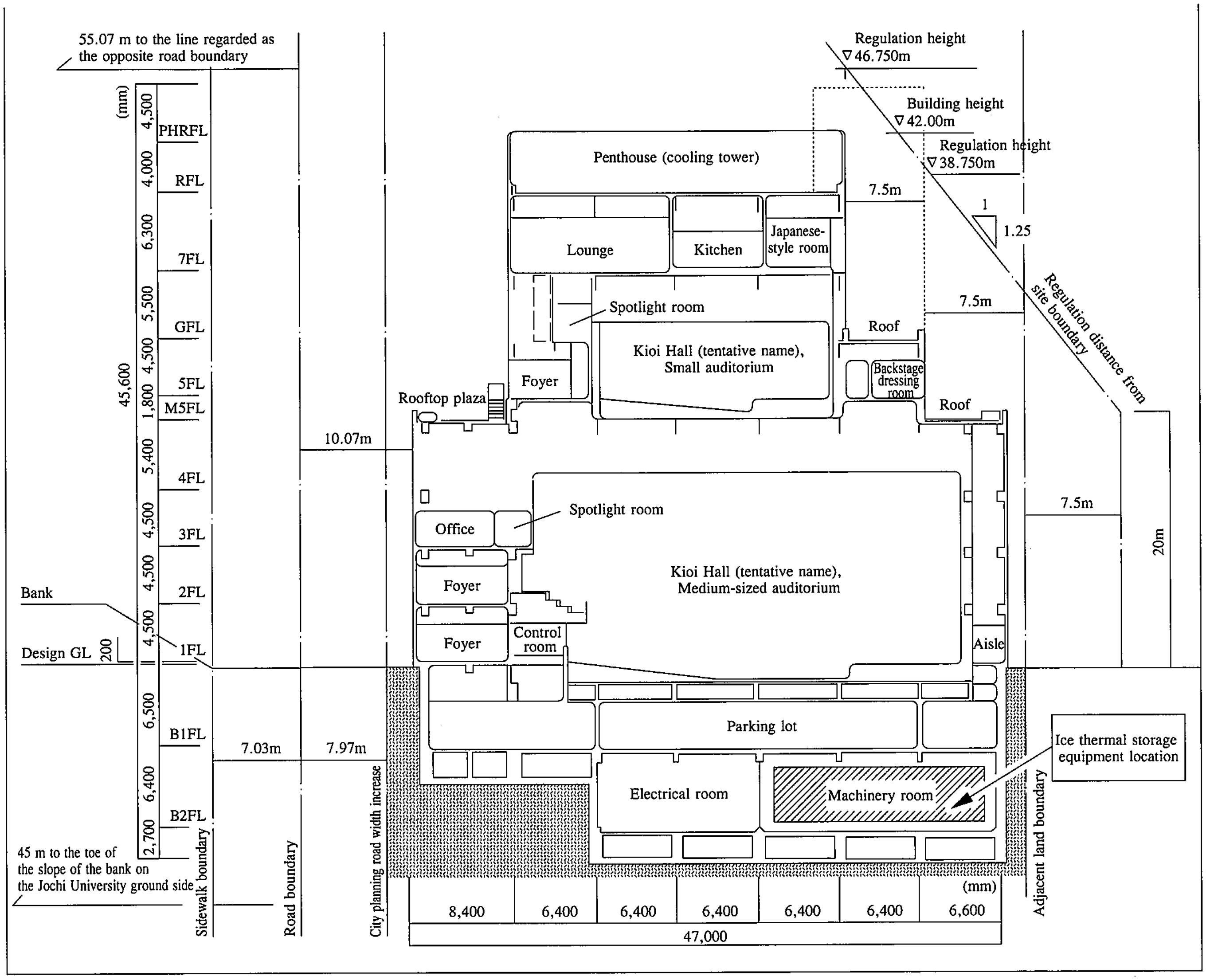


Fig. 1 East-west cut-away view

Name	: Nippon Steel Kioi Building
Location	: Kioi-cho, Chiyoda Ward, Tokyo
Use	: Auditoriums and staff club
Site area	: 3,120.21 m^2
Total floor area	: 12,625.73 m^2
Number of stories	: 2 basement levels, 7 aboveground stories, and 1 penthouse
Construction period	: December 1992 to January 1995

2.2 Cooling/Heating equipment

The cooling/heating equipment combines electricity and gas in an overall plan reflecting such factors as environmental pollution, running costs and supply stability. Full air conditioning is provided by a four-pipe closed piping system that can supply chilled and hot water throughout the year, and by humidification using steam.

A feature of the cooling/heating equipment is the inclusion of ice thermal storage equipment. Of the maximum summer cooling load of 520 USRT, 360 USRT is supplied by two gas-fired chilled/heated water generators, and 160 USRT is supplied by two ice thermal storage tanks. The two chillers for ice-making can supply a load of 100 USRT directly wihtout ice thermal storage tanks.

The machinery room where the cooling/heating equipment and ice thermal storage equipment are located, the electrical room, the emergency power generator room, and the water tank room are located in the lower basement. The cooling tower is installed on the roof.

The system diagram is shown in **Fig. 2**, and the equipment layout diagram is shown in **Fig. 3**.

Maximum cooling load: 520 USRT
Maximum heating load: 840 Mcal/h
Cooling/heating equipment:

- Water-cooled screw chiller for ice thermal storage
  40 USRT × 2 units
- Ice thermal storage tank
  300 USRTh × 2 units
- Gas-fired chilled/hot water generator
  180 USRT × 2 units
- Once-through boiler for generating humidifying steam
  500 kg/h × 2 units

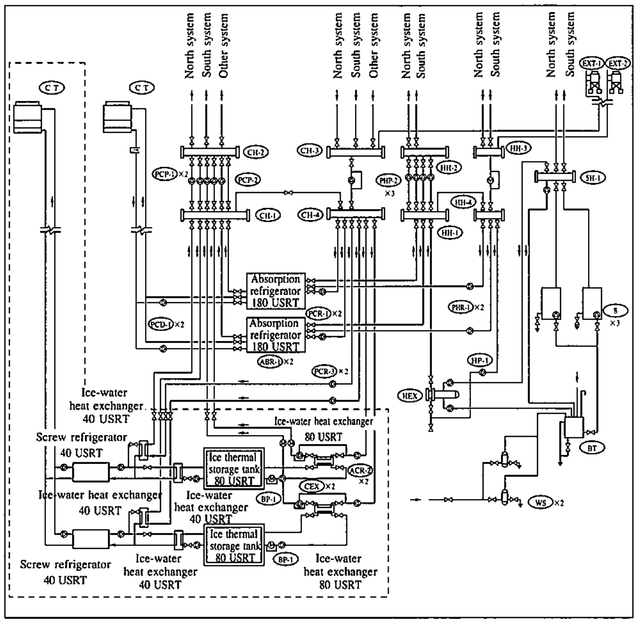


Fig. 2 Schematic diagram

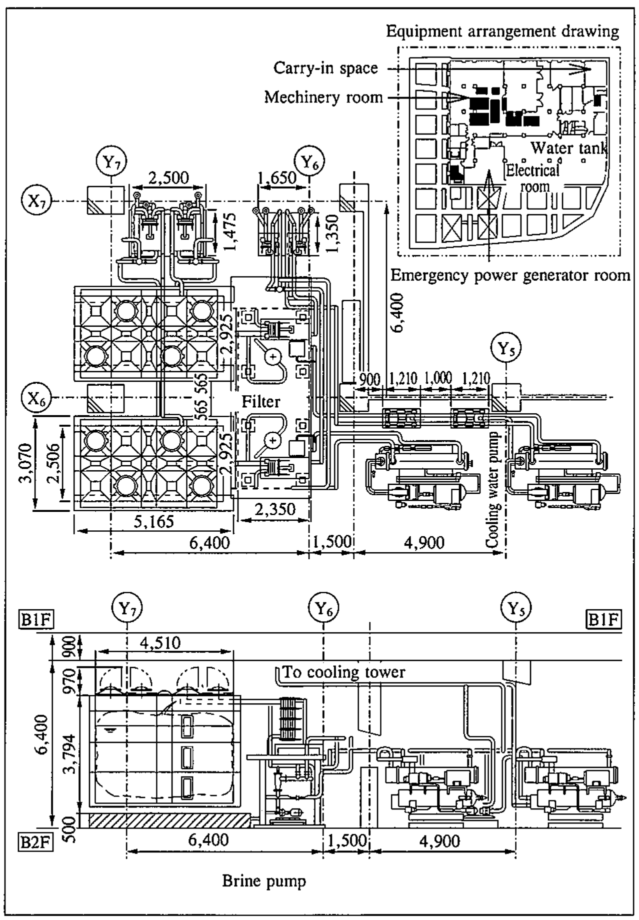


Fig. 3 Equipment arrangement

2.3 Main specifications of ice thermal storage system

(1) Brine refrigerator
- Type : Water-cooled screw type
- Capacity : 40 USRT (ice-making operation during nighttime)
  49 USRT (water using chilled during daytime)
- Compressor : 75 kW
- Refrigerant : R134A

(2) Ice thermal storage tank
- Type : FRP-insulated panel water tank
- Capacity : 300 USRTh × 2 units (thermal storage)

(3) Ice-making heat exchanger
- Type : Plate-type heat exchanger
- Capacity : 40 USRT
- Temperature : Ice-making chilled water 0.2 → −1.7°C
  Brine −2.7 → −0.8°C

(4) Ice-thawing heat exchanger (ice thermal storage)
- Type : Plate-type heat exchanger
- Capacity : 49 USRT
- Temperature : Primary chilled water 4.0 → 9.0°C
  Secondary chilled water 12.0 → 7.0°C

(5) Chilled water heat exchanger (refrigerator load follow-up operation)
- Type : Plate-type heat exchanger
- Capacity : 49 USRT
- Temperature : Brine 0.0 → 5.0°C
  Secondary chilled water 12.0 → 7.0°

3. Ice-Making System

3.1 Ice-making mechanism

It is widely known that when water is cooled and changes to ice, it is transitionally supercooled (retains its liquid phase at a temperature below 0°C under atmospheric pressure). This is explained as follows, using the concept of Gibbs free energy.

The free energy for the nucleation of ice in water derives from the relationship between the decrease in the free energy of water, which is an ice nucleation promoting factor (a function of the supercool ΔT and ice particle size), and the increase in the surface energy of water, which is an ice nucleation inhibiting factor (a function of the surface tension and ice particle size). When the former exceeds the latter, ice particles are formed. The decrease in the free energy of the supercooled water, a thermodynamic force for the growth of ice crystals, is proportional to the chemical potential difference Δμ between the water phase and the ice phase. Using the supercool ΔT (= T_m − T), the chemical potential difference Δμ is given by:

$$\Delta\mu = \mu_l - \mu_i = \frac{L\Delta T}{T_m} \quad \cdots\cdots(1)$$

where L = latent heat; T_m = freezing point; μ_l = chemical potential of supercooled water; and μ_i = chemical potential of ice.

The spontaneous nucleation probability of pure water without the benefit of other particles or walls increases with a rise in the chemical potential difference Δμ of Eq. (1) or a rise in the supercool ΔT. When the supercool ΔT becomes extremely large, the viscosity of water increases, the movement of water molecules slows, and the probability of water changing into stable ice particles falls sharply[1].

Ordinary water contains hydrophilic materials. These hydrophilic materials act as nuclei for solidification, sharply increasing even the ice nucleation probability in a relatively mild supercooled condition, and accelerating the growth of ice particles. The supercooling temperature is reportedly −5 to −7°C for tap water, and −3 to −5°C for lake and river water[1].

Saito and Tamaki conducted many experiments in which droplets of pure water were placed on a heat transfer surface and cooled at a constant rate to form ice on the heat transfer surface. They investigated the amount of supercooling when ice formed and the probability of ice nucleation. Some of their results, which are shown in **Fig. 4**, indicate that the supercooling temperature is −6 to −11°C[2].

Nippon Steel's ice-making system can artificially maintain a stable supercooled state by utilizing the above-mentioned supercooling phenomenon and controlling the flow and heat exchange conditions in the ice-making heat exchanger.

3.2 Ice-making system equipment

As shown in **Fig. 5**, the brine cooled by the refrigerator ① is continuously supplied by the brine pump ② to the ice-making heat exchanger ③. The water stored in the ice thermal storage tank ④ is continuously supplied by the ice-making pump ⑤ to the ice-making heat exchanger ③ and cooled to a supercooled condition.

The supercooled water is continuously fed into the ice thermal storage tank ④, where it is converted into ice and 0°C water. Repeating these operations fills the ice thermal storage tank ④ with the desired amount of ice.

3.3 Characteristics of the ice-making system

Because it is a supercooled ice-making method and uses plate-type heat exchangers, the ice-making system has the following advantages.

(1) Advantages due to the supercooled ice-making method:
- (i) As ice cannot stick to the heat transfer surface of the heat exchanger, heat transfer efficiency is not impaired.
- (ii) Ice-handling equipment is not required, as supercooled water is produced for ice-making.
- (iii) The ice is in sherbet form with a superior thermal response (thawing performance) to ice produced as large particles.
- (iv) Low-cost, readily available tap water is used as the thermal storage medium.

(2) Advantages due to use of the plate-type heat exchanger:
- (v) The plate-type heat exchanger has higher heat transfer efficiency than other types of heat exchangers.
- (vi) The plate-type heat exchanger is easy to maintain and inspect.
- (vii) The plate-type heat exchanger is easy to scale up.

3.4 Application and effectiveness of the plate-type heat exchanger

Of the above advantages, let us focus on the heat transfer efficiency mentioned in (v).

The ice-making process uses plate-type heat exchangers to produce supercooled water, which is then used to make ice. This is the first supercooling ice-making equipment to use plate-type heat exchangers. Plate-type heat exchangers are reputed to have the highest heat transfer efficiency of any heat exchangers. The ice-making heat exchangers used in this ice-making process have an overall heat transfer coefficient of more than 3,000 kcal/m^2·h·°C.

Fig. 6 shows a method for roughly calculating the plate-type

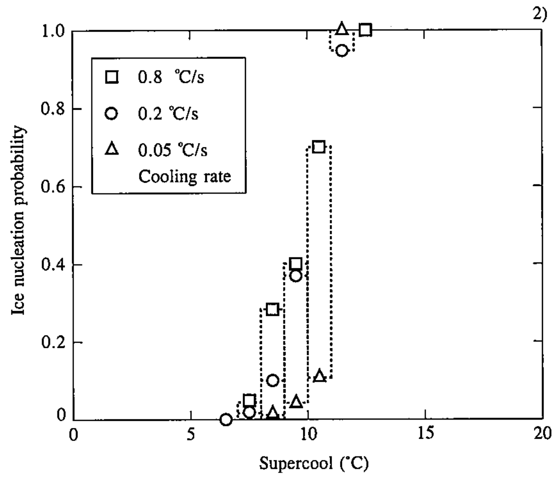


Fig. 4 Ice nucleation probability

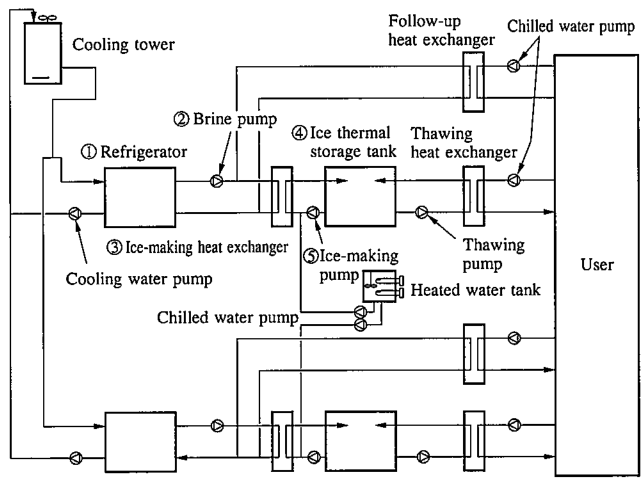
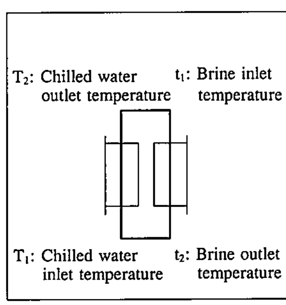


Fig. 5 Ice-making system



$$\Delta T_1 = T_2 - t_1 \quad -①$$

$$\Delta T_2 = T_1 - t_2 \quad -②$$

$$\Delta T_m = (\Delta T_1 - \Delta T_2)/\ln(\Delta T_1/\Delta T_2) \quad -③$$

$$Q = \underline{A} \times \underline{\Delta T_m} \times U \quad (2)$$

- Q : Amount of heat exchanged (kcal/h)
- ΔT_m : Logarithmic mean temperature difference (°C)
- U : Overall heat transfer coefficient (kcal/m^2·h·°C)
- A : Heat transfer area (m^2)

Fig. 6 Method for roughly calculating heat exchanger capacity heat exchanger capacity. The following describes effect of applying the plate-type heat exchangers.

The amount (Q) of heat exchanged by a heat exchanger is calculated as the sum of the heat transfer area (A), the logarithmic mean temperature difference (ΔT_m), and the overall heat transfer coefficient (U), as shown in **Fig. 6**. The heat transfer area (A) represents the size of the heat exchanger, while the logarithmic mean temperature difference is the mean temperature difference between the high-temperature fluid and the low-temperature fluid.

The overall heat transfer coefficient (U) indicates the heat transfer efficiency of the heat exchanger and is a coefficient peculiar to the heat exchanger. Its value varies with the type and operating conditions of each heat exchanger.

The overall heat transfer coefficient of plate-type heat exchangers is reported to be 2,300 to 5,800 W/m²·K (1,978 to 4,987 kcal/m²·h·°C) for liquid-liquid heat exchange[3], the highest among heat exchangers.

$$Q = A \times \Delta T_m \times U \qquad \cdots\cdots(2)$$

Assuming that the amount of heat exchanged (Q) is constant in Eq. (2), the heat transfer area (A) and the logarithmic mean temperature difference (ΔT_m) can be decreased by increasing the overall heat transfer coefficient (U).

(1) Decrease in heat transfer area (A)

The heat transfer area (A) and the overall heat transfer coefficient (U) are inversely proportional to each other. If the overall heat transfer coefficient (U) is increased by a factor of 10, for example, the heat transfer area (A) is reduced to one-tenth. That is, plate-type heat exchangers with a large overall heat transfer coefficient (U) can be used to reduce the heat exchanger heat transfer area (A) or heat exchanger size. This reduces equipment installation space and equipment costs.

(2) Decrease in logarithmic mean temperature difference (ΔTm)

The logarithmic mean temperature difference (ΔT_m) and the overall heat transfer coefficient (U) are inversely proportional to each other. The logarithmic mean temperature difference (ΔT_m) can be decreased by increasing the overall heat transfer coefficient (U). As a result, the temperature of brine supplied to the heat exchanger can be set higher than before (see **Fig. 7**).

This allows the refrigerating equipment to be operated at a high coefficient of performance (COP) and helps to reduce power consumption (see **Fig. 8**).

4. Conclusions

Smoothing out power demand between daytime and nighttime by shifting daytime demand over to the nighttime is an effective way of solving the problems of tightening electricity supply and demand, increasing electricity generating costs and decreasing power plant availability. Cooling and other summer power demand account for nearly 40% of the maximum daytime power demand in midsummer. To shift this demand to nighttime, power companies have introduced such incentives as thermal storage adjustment agreements. Amid the mounting interest in ice thermal storage, the authors will seek to make the usefulness of the ice thermal storage system discussed here better understood by the general public, and will promote the system for use in regional cooling or heating and in many other applications.

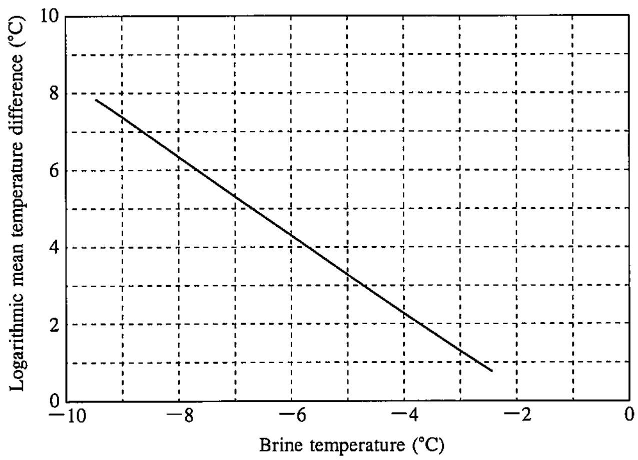


Fig. 7 Logarithmic mean temperature difference

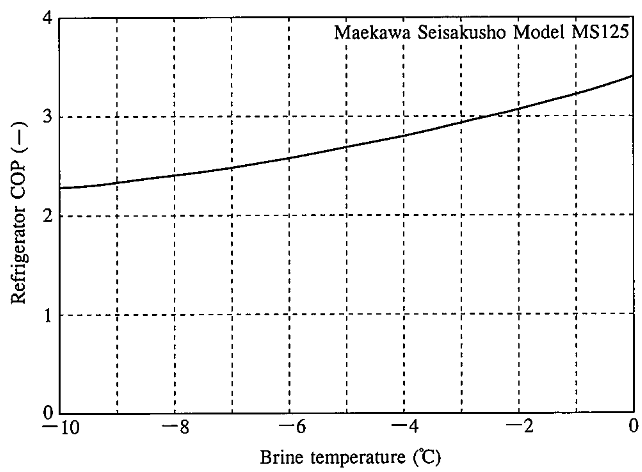


Fig. 8 Method for roughly calculating heat exchanger capacity[4]

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