Energy and Cost Performance of a Cooling Plant System with Indirect Seawater Utilization for Air-Conditioning in a Commercial Building

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Abstract
This paper presents energy and cost performance of a cooling plant system with indirect seawater utilization for air-conditioning in a commercial building. The energy and cost performance is verified by direct measurement and a model-based simulation analysis. In the simulation, the indirect seawater utilization system is compared with a cooling tower system, an air source heat pump chiller system and a direct seawater utilization system. The electric energy consumption of the indirect seawater utilization system is almost the same as the other systems except the air source heat pump chiller system, because using lower seawater temperature can make the efficiency of the refrigerating machine higher, but this system also needs electric energy for cooling seawater/freshwater pumps. However, the indirect seawater utilization system can largely reduce demand charge compared with the cooling tower system, and cut down initial and maintenance costs compared with the direct seawater utilization system. Using these results, the effectiveness of the indirect seawater utilization system toward environmental conservation, energy and cost reduction is clarified in this paper.

Keywords: indirect seawater utilization system; measurement; model-based simulation analysis; energy and cost performance

Introduction
Recently, new energy installation for HVAC&R systems in commercial buildings is recommended from the viewpoints of environmental conservation and energy reduction in Japan. Special enforced law on promotion of new energy utilization was enacted in 1997, and the targeted energy amount of the installation, which should be reached by 2010, is decided in the law.

The new energy is mainly divided into two types, which are natural energy such as solar photovoltaic power generation and recycled energy such as exhaust heat recovery. Natural energy is widely distributed in nature, and the seawater utilization for building air-conditioning described in this paper is grouped as a method using natural energy.

Hong-Kong, where freshwater resource is short, has many cases installing the seawater utilization system. Japan is surrounded by the sea and also has some cities which are troubled by chronic shortage of freshwater like Hong-Kong. Japan has no more than three cases, although utilizing seawater as cooling water can be expected to be one of the solutions.

Generally, there are some problems which should be resolved before the seawater utilization system is installed. Firstly, environmental assessment must be done carefully so that the system does not have a harmful effect on the sea environment. Actually, there are many restrictions such as laws and regulations on seawater utilization. Furthermore, energy and cost performance of the system haven’t been clarified enough yet in Japan. Especially, it is considered that installing the system increases the initial and maintenance costs because a special ordered machine is needed for corrosion protection.

In this paper, a cooling plant system with ‘indirect’ seawater utilization for building air-conditioning is reported. The plant system has acquired different data on the energy consumption for about two years, and the operation has been optimized during this term. This paper presents the energy and cost performance evaluation based on direct measurement and the model-based simulation analysis.

Outlines of Building and Cooling Plant System
The commercial building was built in 2000 in Nagasaki (Fig.1). Nagasaki is located at the western side of Kyushu Island in Japan and is known as one of the famous port cities. The building faces a harbor of Nagasaki. It has six stories above the ground for clothing and ornament departments and one story below for the food court. The building’s total floor area is about 84,000m², and the floor area supplied with air-conditioning is about 38,000m².
The building only has a cooling plant system because the cooling load occurs throughout the year and the heating load is minimal. The cooling plant system consists of turbo refrigerating machines, a chilled water storage tank, heat exchangers, pumps, etc. One of the characteristics of the system is that seawater is indirectly used as cooling water for the refrigerating machine. The refrigerating machine does not directly pass the seawater inside; it passes freshwater which is heat-exchanged with the seawater in the heat exchanger.

Mainly, there are the following merits in the indirect seawater utilization system:

- Condensing temperature of the refrigerating machine gets lower because the seawater temperature is comparatively lower and more stable than the outdoor air temperature. As the result, an improvement in the machine’s energy efficiency can be expected.
- Compared with heat exchange between air and water in a cooling tower, the efficiency of heat exchange between seawater and freshwater can be higher.
- Using freshwater in the refrigerating machine simplifies its maintenance. In the case of using seawater directly in the machine, it requires more time and money to wash the inside in order to prevent the scales from sticking. On the other hand, washing the inside of the heat exchanger is comparatively easy.

The seawater is pumped up via gate through which it is taken from the sea, and released again from another gate after the seawater has heat-exchanged with the cooling freshwater in the heat exchanger. The heat exchanger for the seawater is a titanium plate type to prevent rust and to make taking it apart for the maintenance easy. Washing equipment which uses hot water is also installed in the system to eliminate scales and shells sticking in the heat exchanger, and a net screen is put on the gate to keep them out of the system.

In Japan, a building generally has double slabs underground to increase earthquake resistance. The underground space surrounded by the two slabs and walls can be usually used as a water storage tank. The water storage tank of this building is only for chilled water and is divided into forty-six small spaces by partitions. These spaces are joined by holes through the partitions, and the holes make a path for the water to flow. The water temperature in each space is uniform, but the first space has the lowest water temperature and the last space has the highest one. Therefore, the chilled water storage tank can be classified as one of temperature stratification types. The total volume of the tank is about 4,500m³, and the difference of the water temperature utilization is 7K (5 to 12 degrees Celsius). This storage tank is designed to cover 32% of the peak cooling load.

Regarding the control strategies for the chilled water storage tank system, the two refrigerating machines’ operation is started at 10pm every night, and is stopped when the water temperature in the forty-fifth space of the tank comes to 6.5 degrees Celsius or below. A night off-peak power usage charge is applied from 10pm to the next 8am. At the starting time of air-conditioning, the chilled water in the tank has priority to be used. After that, the one refrigerating machine is additionally operated if it is judged that the only chilled water in the tank can not provide the building cooling load.

Table 1 shows design parameters of equipment consisting of the cooling plant system, and Fig.2 shows the schematic of the system.

| Equipment | Design parameters |
|-----------|-------------------|
| Turbo refrigerating machine (2units) | Cooling capacity: 2,285kW |
| | Rating input value: 483kW |
| | Chilled water temp.: 5-12°C |
| | Chilled water flow rate: 280m³/h |
| | Cooling water temp.: 32-37°C |
| | Cooling water flow rate: 476m³/h |
| Thermal storage tank (1unit) | Volume: 4,500m³ |
| | Quantity of heat storage: 79,100MJ |
| Heat exchanger for cooling seawater and freshwater (3units) | Quantity of heat exchange: 2,774kW |
| | Seawater temp.: 30-33.1°C |
| | Seawater flow rate: 762m³/h |
| | Freshwater temp.: 32-37°C |
| | Freshwater flow rate: 476m³/h |
| Heat exchanger for chilled water (3units) | Quantity of heat exchange: 2,326kW |
| | Primary chilled water temp.: 5-12°C |
| | Primary chilled water flow rate: 286m³/h |
| | Secondary chilled water temp.: 7-14°C |
| | Secondary chilled water flow rate: 230m³/h |
| Pumps (total 10units) | 762m³/h-110kW (Seawater) |
| | 476m³/h-45kW (Freshwater) |
| | 280m³/h-30kW (Thermal store charge) |
| | 286m³/h-18.5kW (Thermal store discharge) |
Measurement Results

Energy performance of the system was first evaluated by the measured data, which has been acquired on site for about two years (April, 2000- January, 2002). Table 2 shows the measurement items, and Fig.3-Fig.6 show quantity of heat supplied by the system, electric energy used in the system, co-efficient of performance (COP) values of the refrigerating machines and the system, seawater temperature, efficiency of the thermal storage tank, and night-time shifting ratio of the quantity of heat and the electric energy. The data of January-December, 2001 are drawn in these figures as typical ones. The definitions of these indices are shown in Table 3.

The peak values of the monthly quantity of heat and electric energy are respectively about 8TJ and 450MWh (Fig.3, Fig.4). The system operation was begun just after...
the completion, but the pumps for the seawater had always been operated in order to prevent sticking of sea materials inside even if the refrigerating machines were stopped. This operation had caused increasing electric energy consumption, so the operation was changed in February, 2001 as the pumps move together with the refrigerating machines. This change enabled reduction of the electric energy for the pumps by 25%, and there are no problems on the maintenance due to the intermittent operation of the pumps.

The COP values of the refrigerating machines derived from the measured data become smaller as the seawater temperature gets higher in summer. The smallest values of both refrigerating machines are 4.49 and 4.77 in August, but the reference value is 4.73 in a catalog. The yearly mean COP values are about 5.20. Therefore, the COP values are comparatively higher through the year. It is considered that using seawater as cooling water makes the condensing temperature of refrigerating machines lower, and realizes an improvement of COP values. The COP values of the system have been improved largely after changing the pump operation strategy in February, 2001 (Fig.5).

The values of the efficiency of the thermal storage tank, which is used for evaluating the tank’s thermal insulation and utilization, indicate about 90%. These values seem to be slightly lower than the general value. The reason is considered that sensors used to calculate the quantity of heat taken from/into the tank are located near the pumps and the refrigerating machines, and the values would be affected by the equipment heat generation. However, the values of 2001 are improved because some set points for control strategies were adjusted based on the measured data of 2000. The nighttime shifting ratios of the quantity of heat are about 60% even if during summer, and the chilled water in the tank alone can provide all the cooling load of the building during middle and winter seasons. It is confirmed that this system contributes to the nighttime shifting of the electric energy (Fig.6).

Table 3. Definitions of Evaluation Indices

| Evaluation indices       | Definitions                                                                 |
|--------------------------|-----------------------------------------------------------------------------|
| COP of refrigerating machine (-) | Ratio of quantity of heat generated by machine to electric energy used in machine |
| COP of system (-)        | Ratio of quantity of heat supplied by system to electric energy used in system |
| Efficiency of thermal storage tank (%) | Ratio of quantity of heat taken out from tank to one taken into tank |
| Night-time shifting ratio of quantity of heat (%) | Ratio of quantity of heat taken out from tank to quantity of heat supplied by system |
| Night-time shifting ratio of electric energy (%) | Ratio of electric energy used by system in night-time to one used by system in a day |
Model-based Simulation Analysis

Outlines of simulation model and case study

A simulation model of this cooling plant system with indirect seawater utilization was constructed. This model is called ‘Case1’, which corresponds to this actual plant system. The model of Case1 consists of subsystem models of turbo refrigerating machines, chilled water storage tank, heat exchangers, pumps, etc. Each subsystem delivers thermal calculated values such as water temperature and flow rate to the other subsystems in the simulation. The input data is quantity of heat supplied to the building, outdoor air temperature and humidity and seawater temperature. The quantity of heat measured in the actual system is used in the simulation, but the others are standard weather data prepared for simulation. The output data is electric energy consumption of the components and the system. The time step of the calculation is 10 minutes, and the term is one year (October, 2000-September, 2001). Set points and control strategies on system operation in the simulation are basically given as the same with the measured ones. Fig.7 shows the schematic of the simulation models Case1-Case 4, which are designed to provide the measured input heat load appropriately. In the following explanations are mentioned the other three plant systems as compared to Case1 in the model-based simulation analysis. Beforehand, it was verified by comparison between the measured data and the calculated results of Case1 that the simulation had enough accuracy.

Plant system with cooling tower (Case2)

A plant system with a cooling tower is calculated in Case2. Refrigerating machines in the model of Case2 have the same capacity as in Case1, however the model has a cooling tower instead of the seawater heat exchanger of Case1. Pumps for the cooling water are selected by the pump head values needed for the amount of circulating cooling water. In this model, the amount of make-up cooling water is also calculated by adding the amount of evaporation, carry-over and blow-down together.

Plant system with heat pump chiller (Case3)

In Case3, air source heat pump chillers replace the refrigerating machines of Case1. The thermal characteristics of the chillers are given by a catalog data.

Plant system with direct seawater utilization (Case4)

Generally, there are two types as plant systems with seawater utilization, which are indirect utilization (Case1) and direct utilization (Case4). Compared with the direct seawater utilization system, there are some merits in the indirect seawater utilization system such that fresh water can be used in the refrigerating machine and the maintenance is easy. However, on the other hand, the direct seawater utilization system also has some merits which the indirect seawater utilization system does not have. For instance, the direct seawater utilization system can use lower temperature cooling water than the indirect one because an additional heat exchanger

Fig.7. Schematic of Simulation Models (Case1-Ca}
for the seawater is not necessary. Furthermore, there is a possibility in the direct utilization system that electric energy consumption of pumps for cooling seawater and freshwater can be reduced, because those pumps are brought together. The direct seawater utilization system is calculated in Case 4.

Simulation results
(1) Comparison between Case 1 and Case 2, Case 3

Regarding mean COP values in August of the refrigerating machines and the air source heat pump chiller, Case 1 is 4.78 and can reach a higher value than Case 2 (4.71) and Case 3 (2.96) (Fig. 8, Fig. 10 (a)). Fig. 11 shows that outdoor wet-bulb temperature is lower than seawater temperature throughout the year, but Case 2 can not use the wet-bulb temperature itself in summer as condensing temperature of the refrigerating machine. Therefore, condensing temperature of the refrigerating machine of Case 1 becomes lower by using seawater temperature, and the electric energy consumption is reduced compared with the other systems. Especially, the effect is remarkable in May and June. On the other hand, from December to April, the COP values of Case 1 are almost the same as Case 2 because inlet cooling water temperature to the refrigerating machine is controlled above 20 degrees Celsius and the merit of lower seawater temperature can not be used. Compared with Case 1 and Case 2, the COP values of Case 3 are the lowest because outdoor air is directly used in the condensation of refrigerant and the efficient of heat transfer is low.

Regarding mean COP values in August of the systems, Case 1 shows a lower value (3.38) than Case 2 (3.53) (Fig. 9, Fig. 10 (b)). Case 1 can get a high value of the refrigerating machine’s COP, but the system electric energy consumption becomes slightly higher than Case 2 due to the additional seawater pumps.

Based on the calculated results of the electric energy consumption and the amount of make-up water of the cooling tower, the ratio of yearly demand charges were obtained (Table 4, Fig. 12). The demand charge for the make-up water of the cooling tower is unexpectedly

![Fig. 8. Monthly Electric Energy of Refrigerating Machines and Air Source Heat Pump Chiller (Calculation, Case 1-Case 4)](image8)

![Fig. 9. Monthly Electric Energy of Systems (Calculation, Case 1-Case 4)](image9)

![Fig. 10. COP of Refrigerating Machines, Air Source Heat Pump Chiller and Systems (Calculation, Case 1-Case 4)](image10)

![Fig. 11. Outdoor Air Dry-bulb and Wet-bulb Temperature and Seawater Temperature](image11)
large. As a result, the total demand charge of Case2 becomes nearly twice that of Case1.

Nagasaki is one of cities which are troubled by chronic shortage of freshwater. Therefore, the indirect seawater utilization system is considered to be a rather effective system on water resource conservation and demand cost reduction.

(2) Comparison between Case1 and Case4

Cooling seawater temperature of Case4 is definitely lower than Case1, but the electric energy consumption of the refrigerating machine of Case4 becomes larger than Case1 (Fig.8, Fig.10 (a)). The reason is that the titanium material, of which the specific thermal resistance is larger than normal one (copper), is used in the condenser of Case4 for the corrosion protection.

Regarding the electric energy consumption of the systems, Case4 is slightly less than Case1 because of uninstalling the cooling freshwater pumps. As a result, those COP values of the systems are almost the same through the year (Fig.9, Fig.10 (b)).

The demand charges for the energy consumption of Case1 and Case4 are substantially the same, but the initial cost of Case4 is estimated to be considerably higher than Case1 because of using titanium material. In both cases, washing the inside of the refrigerating machine is required as the maintenance without stopping the operation even if in summer when the heat load is large. Preparing a spare expensive machine in Case4 brings about an economical disadvantage. Conversely, a normal machine is enough in Case1 as the spare machine.

According to the model-based simulation analysis, it is considered that the indirect seawater utilization system and the direct one are almost the same in respect of energy consumption, but the indirect one has an advantage with respect to the demand cost and the maintenance.

Conclusions

In this paper, the effectiveness of indirect seawater utilization in a cooling plant was clarified by direct measurement and the model-based simulation analysis. In the simulation, the energy and cost performance of the indirect seawater utilization system are compared with the cooling tower, the air source heat pump chiller and the direct seawater utilization systems.

The electric energy consumption of the indirect seawater utilization system is almost the same with the other systems except the air source heat pump chiller system because this system can make the efficiency of the refrigerating machine higher by using lower seawater temperature, but oppositely needs the electric energy for the cooling seawater/freshwater pumps.

However, the indirect seawater utilization system can reduce the initial cost and demand cost compared with the direct seawater utilization system and the cooling tower system, and also has the large advantage that the maintenance is not as costly or time consuming as the direct seawater utilization system.

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References

1) Architectural Institute of Japan (AIJ) (2000) Expanded AMeDAS Weather Data. Maruzen
2) Harada,S. et al. (2002) Utilization of Seawater for Building HVAC&R system, Part3 Outline of the System and the Results of Measurement 2001. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, D-2, 1175-1176.
3) Inoue,U. (1996) Air-conditioning Handbook (in Japanese), Maruzen, 164-171.
4) Kawamura,Y. et al. (2002) Utilization of Seawater for Building HVAC&R system, Part4 Energy Simulation and System Evaluation. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, D-2, 1177-1178.
5) Kodama,T. (2002) Measurement HVAC&R Operation Results of Commercial Building "Yumesaito" in Nagasaki Motofuna District. Journal of Heating, Air Conditioning, Cooling Technology, No.19, 56-64.
6) Matsuo,Y. et al. (1992) HASP/ACSS/8502 Program Manual. Japan Building Mechanical and Electrical Engineers Association.
7) Nishida,M. et al. (1997) Study on Effective Utilization of Un-used Energy in City and Building in Kyushu Area. Final Report, Grant-in Aid for Scientific Research No. 07305028, 3-10, 188-214.
8) Tanaka,T. (1994) Un-used Energy and Air-conditioning System with Thermal Storage Tank. Rikotosho