A heat pump system with a latent heat storage utilizing seawater installed in an aquarium

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Received 12 November 2004; received in revised form 24 April 2005; accepted 30 April 2005

Abstract

This paper introduces a heat pump system with a latent heat storage utilizing seawater installed in an aquarium. Heat from the seawater is collected and used as the heat source for the heat pump system. This maintains the indoor conditions at constant temperature and relative humidity. With regard to the heat pump system using low-temperature unutilized heat source, development is introduced on a heat source load responsive heat pump system, which combines a load variation responsive heat pump utilizing seawater with a latent heat (ice plus water slurry) storage system using nighttime electric power serving for electric power load leveling. The desired outcome would be to show that the costs of generating heat energy with the seawater-source heat pump are significantly less than those with the air-source heat pump and the oil-fired system. Additionally, the CO₂ emissions for the seawater-source heat pump compare favourably as they maybe less than those for the other conventional assumed systems described.

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Keywords: Heat pump; Latent heat storage; Unutilized energy; Costs; CO₂ emissions

1. Introduction

In order to reduce the emission of carbon dioxide and thereby to protect against global warming, the effective use of energy, such as the efficient use of various types of waste heat and renewable energy should be promoted. A heat pump system can produce more heat energy than the energy which is used to run the heat pump system [1–4]. Thus, a heat pump system is considered to be a machine system which can use energies efficiently, and the load leveling air-conditioning system utilizing unutilized energies at high levels [5–9].

This paper introduces a heat pump system with a latent heat storage utilizing seawater installed in an aquarium. Heat from the seawater is collected and used as the heat source for the heat pump system. This maintains the indoor conditions at constant temperature and relative humidity. With regard to the heat pump system using low-temperature unutilized heat sources, development is introduced on a heat source load responsive heat pump system, which combines a load variation responsive heat pump utilizing seawater with a latent heat (ice plus water slurry) storage system using nighttime electric power serving for electric power load leveling. The experimental coefficient of performance (COP) of the proposed heat pump with the latent heat storage cooling system will be shown in detail.

The objective of this study is to compare the actual operating characteristics and efficiency of a seawater-source heat pump with ice storage system to the predicted evaluation of the two assumed conventional systems, that is, an air-source heat pump without ice storage, and an oil-fired absorption refrigerating system. The desired outcome would be to show that the costs of generating heat energy with the seawater-source heat pump are significantly less than those with the air-source heat pump and the oil-fired system. Additionally, the CO₂ emissions for the seawater-source heat pump compare favourably as they maybe less than those for the other conventional assumed systems described.
2. System description

Shimane Aquarium (AQUAS) locates an area facing Japanese Sea (Shimane Prefecture in Japan). Fig. 1 is a view of the Aquarium. The total floor area in the building is 10,293 m², the numbers of storeys are two (+cellar), and the bulk of the fish tank is 3000 m³.

The primary cooling loads at the aquarium are building air-conditioning, cooling of ventilation air for the fish tank and cooling and heating of the water in the fish tank. The system selected is one that combines two seawater-source heat pumps, WSHP001 and 002 (cw: 650 kW, hw: 732 kW) and a heat recovery type air-source heat pump, AWSHP003 (cw: 510 kW, hw: 697 kW). Seawater-source heat pumps transfer heat to and from the seawater by means of circulated water and heat exchanger. Air-source heat pump uses the outdoor air for heat absorption and rejection. Air-source heat pump is more common because of its lower initial cost and ease of installation, but seawater-source heat pump is more energy efficient. The heat pump tested in this work transfers heat to the outdoor air and to the sea. It maintains some of the initial cost advantages of the air-source heat pump and some of the performance advantages of the seawater-source heat pump.

These provide cooling of water using off-peak power. The primary heat source is the heat collected from the seawater and stored in the ice storage tank, IS (ts: 4500 kWh \( \times 2 \)). The heat produced by the heat pump at night is stored in the ice storage tank. Fig. 2(a–c) is a diagram of the system. In general, the increased efficiency of the seawater-source heat pump is gained by two mechanisms. First, water is a much better heat transfer fluid than air, so heat is moved much more efficiently. Second, the seawater allows the heat pump to extract heat from water that is usually warmer than the outside air during the winter and cooler than the outside air during the summer. This allows more efficient heat pump operation. The seawater-source heat pump usually provides warmer supply air temperatures during the winter and cooler supply air temperature during the summer, which increases comfort levels.

Ice storage technology has been shown to be effective in reducing operating cost of cooling equipment during the summer time. By operating the refrigeration equipment during off-peak hours to recharge the ice storage, and discharge the storage during on-peak hours, a significant fraction of the on-peak electrical demand and energy consumption is shifted to off-peak periods. Cost saving are realized because utility rates favour leveled energy consumption patterns. The variable rates reflect the high cost of providing energy during relatively short on-peak periods. Hence, they constitute an incentive to reduce or avoid operation of the cooling plant on-peak periods by cool storage. The large differential between on- and off-peak

![Fig. 1. A view of Shimane Aquarium (AQUAS).](attachment:image.jpg)
Fig. 2. Diagram of heat pump system in aquarium: (a) summer mode, charge the ice storage; (b) summer mode, discharge the ice storage and (c) winter mode.
energy and peak consumption rates should make cold storage system economically feasible.

Tests were run in the aquarium for 2 years. Overall performance characteristics of particular interest were integrated COP along with other instantaneous comparison of power, refrigerant flow rate and temperatures. This heat pump system has two operational modes: the first is the ice plus water slurry cooling mode that is a typical mode in summer (Fig. 2(a and b)). In this mode, the ice is produced using the heat pump connected with the latent heat storage system. The second is the winter mode (Fig. 2(c)). In this mode, the circulating water is heated by the heat pump connected with the heat exchanger system to collect heat from the seawater and the ambient air. Energy saving costs and carbon dioxide reducing effects of the heat pump system are evaluated by tests.

3. Results and discussions

3.1. Loads of building throughout the year

Fig. 3 shows the ambient air temperature, the ambient air humidity and the seawater temperature throughout the year. The maximum temperature on August was 35.9 °C, and the averaged temperature was 28.3 °C. Relative humidity ranged from about 70% at night to 95% during the day on August.

Fig. 4 shows the daily loads of the cooling air-conditioning for the space above the fish tank, cooling water and heating water for the fish tank, and air-conditioning for the building during the period from March 26, 2001 to March 9, 2002. The loads of the air-conditioning for the building in the period of summer time exceeded the predicted loads, but loads in the winter were about 70% of the predicted loads. The loads of the cooling water and cooling air-conditioning for the fish tank have been stable and constant since May. The loads of cooling water for the fish tank could be generated during only the summer time, but the loads of heating water for the fish tank could be produced during only the winter.
The primary cooling loads at the aquarium are cooling of cold water in the fish tank, and cooling of ventilation air in the building. Fig. 5 shows the typical building cooling use on a typical summer day from August 13 to August 19, 2001. The loads of the cooling air-conditioning have been about constant every day. The loads of the cooling of ventilation air in the building and the cooling of water in the fish tank were greatest in the afternoon because of hotter outside air. The outside air temperatures increase and, combined with solar gains, lighting and a large audience energy gains, the cooling loads increased during the day. The relationship of cooling air-conditioning and cooling water loads is an important consideration with the type of heat pump system installed in the aquarium. This is because the heat pump produces aquarium cooling water from seawater-source heat and air-source heat.

Winter days tend to be warm in Shimane Prefecture. As an example, Fig. 6 shows typical aquarium heating and air-conditioning use on a typical winter day from February 4 to February 10, 2002. These data are operator records during these periods. On these days, the plant has been running to maximize heating, using air to warm each individual building’s system. By reducing the amount of outside air used in the building, the heat needed is also reduced while the amount of heating (heat recovery) is increased. When using minimum outside air, the major heat use (after initial building warm-up) is for air-conditioning. On an average winter day, large heating (heat recovery) loads could be generated from heating water for the fish tank.

3.2. Energy usage

Fig. 7 compares the daily electrical consumption of the three heat pumps from March 26, 2001 to February 25, 2002. During the first 2 months after the kilowatt-hour meters were installed, the AWSHP003 used about 22% of the electricity that the building used. Average energy usage for those months was 4000 kWh/day for the AWSHP003. This included both heating and cooling modes of operation, with the transition from heating to cooling occurring in April. The electrical requirements of the AWSHP003 remained relatively constant throughout the year. AWSHP003 was running through all day long. The load factor of this heat pump was 50% during the period of the cooling and air-conditioning in the summer time, and the load factor was about 60% during the period of the heating in the winter. The WSHP001 and 002 used relatively more energy during the summer than during the winter. Overall, for the period from April 15 to November 21, 2001, the WSHP001 and 002 have used about 80% of the energy that the AWSHP003 has used. The electrical energy use of both WSHP001 and 002 has peaked during this period from August 13 to August 19 because of the heavy air-conditioning load of the building. Both WSHP001 and
002 supply only the cooling energy for the air-conditioning of the building and the cooling water for the fish tank during the summer time. With more data from the winter months, it was expected that the energy use of the WSHP001 and 002 would approach about zero. WSHP001 and 002 have been stopping except the period of the maintenance of the AWSHP003 during the period of the heating in the winter. 

Fig. 8 shows the typical energy output from the WSHP001 and 002 for the period in the summer. Periodic readings began after August 13, and weekly readings have been conducted until August 19, 2001. Both of the WSHP001 and 002 have been fully running after initial building opening in the morning, and have been stopping during the period from 1:00 p.m. to 4:00 p.m. in the afternoon, and have been running with the ice storage tanks according to the loads from 4:00 p.m. again. Summer days tended to produce more energy from cooling than was needed, and the ice storage tanks run at night to produce ice and water slurry to charge the ice storage tank. Cooling heat was picked up by the ice storage system, resulting in warmer chilled water return. This warmer chilled water return was stored in the ice storage tank. Viewed as a heat source for the building, this increase in ice and slurry water temperature was (potential) heat storage (Fig. 9).

The heat pump operating at night removed energy from the seawater and produced cooling water, which was stored in the ice storage tank. The ice and water slurry were used during the next day, with the largest loads early in the afternoon. The ice storage system provided a match in time between cooling availability and the time of the heat need. By operating the refrigeration equipment during off-peak hours to recharge the ice storage, and discharge the storage during on-peak hours, a significant fraction of the on-peak electrical demand and energy consumption was shifted to off-peak periods (Fig. 10). It also provided the means to recover and produce cooling at the lowest possible cost by using off-peak electrical energy.

3.3. Energy efficiency

Summer mode was most efficient for two reasons. The owner received full benefit from air-conditioning for the building and water cooling for the fish tank at the same time. Also, the cold water from the ice storage tanks kept the condensing temperature, which in turn reduced the work done by the heat pumps. When operating in winter mode the AWSHP003 obtained its heat from outdoor air and accrued air-conditioning benefit. However, the cold water benefit was still taking place. We found from monitoring that the coefficient of performance was relatively high, averaging 3.4 for the summer time. When operating in summer mode with ice storage, COP of WSHP001 was 2.6, and COP of WSHP002 was 3.0 for output for each unit of energy (electricity) used (Fig. 11). This was the best use of
resources and was quite remarkable when considering that it operated in this mode for 60% of the time on a year-round basis.

In winter, when the unit was operating mainly in winter mode the COP was quite low. The COP was even lower for AWSHP003 than WSHP001 and 002, even though it was working throughout the year. By checking the daily results it was found that the partial load running was often done for most of the part of running time to allow a very low COP. Another reason for decreased COP of AWSHP003 was due to the heat recovery running mode, even though the heating loads were almost zero.

The performance of the heat pumps with the ice storage system have been compared to two other systems (assumed systems), which have been installed in the aquarium where heating and cooling are supplied with combinations of the air-source heat pump system without ice storage, and oil-fired absorption refrigerating system. Energy consumptions of the other two alternative systems were calculated by means of the assumed values of these systems. The COP of the absorption refrigerating system was assumed to be 1.0 in cooling time, and to be 0.9 in warming time. Energy consumption of the WSHP001 and 002 was 19% less than in the oil-fired absorption refrigerating system (Fig. 12).

The emissions of CO2 were estimated at 84 g-C/Mcal in the oil, at 103 g-C/kWh in the electricity for day time, and at 83 g-C/kWh in the electricity for night time. The emissions of this system were 86 tonnes of CO2 in a year. This compared favourably to the emissions of the other alternatives for heating and cooling in the two other systems (assumed results): the emissions of the air-source heat pump system without ice storage were 102 tonnes of CO2, and the emissions of the oil-fired absorption refrigerating system were 176 tonnes of CO2. The CO2 emissions of the electric heat pump with ice storage were close to half of those of the oil-fired system for heating and cooling (Fig. 13).

### 3.4. Cost savings

Power costs in Japan are high, particularly in the summer daytime peak electrical use period. Power costs are divided into on-peak, partial-peak and off-peak periods. The summer period from 12 noon to 6:00 p.m. is the on-peak period and the period of greatest cost to the aquarium for both demand and energy consumption. The remaining weekday daytime hours from 8:30 a.m. to 9:30 p.m. (8:30 a.m. to 12 noon and 6–9:30 p.m.) constitute the partial-peak period. The partial-peak period has moderately high demand and power costs. During the winter period, all daytime hours are partial-peak. The 11 h period from 9:30 p.m. to 8:30 a.m., as well as all hours on holidays, is in the off-peak period. Prior to this test, aquarium electric demand was expected to be slight during the off-peak period. Since energy costs for power are least during the off-peak period, a shift in the time of consumption represents an opportunity to achieve money savings.

Japan is an area of high electrical costs. Most heat pump or heat recovery heat pump projects are installed in regions with low electrical costs. Several factors combine to make a heat pump installation an economical solution in this instance. First, the amount of heat required is relatively small, consisting primarily of building warm-up, heating ventilation air and domestic hot water heating. Second, there are some cooling loads on aquarium almost year around. The aquarium heating and cooling loads can be managed by the central plant staff by adjustments to the mixed air settings of the air-handler units. This can be done from the central plant with the energy management control system. Higher entering mixed air temperature results in less building heating requirement and more cooling (heat recovery). As long as minimum ventilation air requirements are met, the operators can select between the value of free cooling with outside air and the value of the heat in the air exhausted. When adequate heat has been recovered to meet aquarium heat needs, outside air is used for cooling. On a day when heating and cooling are both required, heating costs are the incremental increase in power required by the heat pump over a chiller (taking into account that no condenser pump or cooling tower is required with the heat pump). A third, and most important, factor is that heating is provided entirely with off-peak power during the night and early morning hours. Winter off-peak power is very inexpensive in contrast to the summer on-peak power. As indicated above, the total...
electrical costs for aquarium were JPY 16,317,000 according to costs for off-peak power in 2001. On-peak, electricity costs more and the demand costs are greater.

Fig. 14 presents record information on energy use and cost both measurement and simulation was conducted. The electrical costs of the air-source heat pump system without ice storage were estimated at JPY 27,999,000. The total costs of the oil-fired absorption refrigerating system were estimated at JPY 17,038,000 and the expenditure was broken down into JPY 4,258,000 for the electrical costs, JPY 6,147,000 for costs of the oil and JPY 6,634,000 for those of the water. This reduction in electrical unit cost is primarily due to the shift in the time of day that electric use occurs. This figure tends to understate savings because of the factors outlined above, but it clearly indicates the substantial savings achieved by operating the refrigerating equipment during off-peak hours to recharge the ice storage, and discharge the storage during on-peak hours. Electric energy costs per kilowatt-hour are lower now than those of the conventional air-source heat pump system without ice storage because of a large shift in energy consumption to the less expensive off-peak period. Electrical costs are 42% lower for the same comparable periods. This shows that, with experience, the operations staff is improving its ability to shift electrical consumption to the off-peak period.

4. Concluding remarks

A seawater-source heat pump system installed in a new-built aquarium in Shimane Prefecture in Japan provided simultaneous heating and cooling. A COP of WSHP001 at running conditions was 3.4 for cooling and 2.8 for ice storage. By operating the refrigeration equipment during off-peak hours to recharge the ice storage, and discharge the storage during on-peak hours, a significant fraction of the on-peak electrical demand and energy consumption was shifted to off-peak periods. In the following, this case study was compared to two other assumed systems in which heating and cooling was supplied by the conventional air-source heat pump and the conventional oil-fired refrigerator. The energy consumption of the seawater-source heat pump for heating and cooling was 19% lower than in the oil-fired absorption refrigerating system. Also, the CO2 emissions for heating and cooling compared favourably as they were close to half of those for the oil-fired system described. The actual operating costs of the seawater-source heat pump for heating and cooling was 42% lower than in the conventional air-source heat pump.

Acknowledgements

The concept of a specially designed seawater-source heat pump with ice storage system is formerly due to The Chugoku Electric Power Co., Inc. I wish to thank Mr. M. Koyama and Mr. T. Kuriyama of Nikken Sekkei Ltd. for their guidance in planning the present work. I also wish to thank the staff of The Aquarium (AQUAS) in Shimane Prefecture for assisting with the project. The work was sponsored by The Chugoku Electric Power Co., Inc.

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