THE FIELD MEASUREMENT REPORT OF AN OFFICE BUILDING USING NATURAL REFRIGERANT, TOKYO, JAPAN

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Abstract: We designed and built an office building which does not use HFC/HCFC for air-conditioning system. This is the first heat pump system using natural refrigerant only in Japan. This system uses ammonia as refrigerant for air-conditioning and carbon dioxide as refrigerant for water heating, utilizing geo-thermal through foundation piles in the ground. In addition employing two-pipe dynamic ice transportation system, which were developed from one-pipe system, realized higher thermal efficiency of the whole building.
According to the analysis of operation data after completion, the COP of air-source heat pump is 3.0 to 3.5 at cooling mode and 2.0 to 2.5 at heating mode while the COP of water-source heat pump utilizing geo-thermal is 3 to 7 at cooling mode and 4 to 8 at heating mode.
We collect and analyze the data using BEMS (Building Energy Management System) on operation of the system, and BEMS made it possible to do the fine tune control promoting the energy savings of this office building.
For example controlling volume of fresh air flowing into the system precisely enables us to achieve effective air circulation and energy savings.

Key Words: natural refrigerant, geo-thermal through foundation piles, two-pipe dynamic ice transportation system ,BEMS

1 INTRODUCTION

Using HFC/HCFC for air-conditioning system causes the environmental problem. And the global warming caused by greenhouse gases is another social issue. Having the chance of building construction, we tried to solve these matters with sincerity. Not only applying natural refrigerant system such as the ground source heat pump system, but we evaluated the effect of energy consumption.
In Japan, this is the first time to develop and apply only the natural refrigerant system really operating in the building. So the quantitative evaluation of natural refrigerant system using BEMS and the improvement of the system operation for energy savings would be valuable for the engineers of building equipments and the building owners.

2 ENVIRONMENTALLY CONSCIOUS DESIGN USING NATURAL REFRIGERANT AND GROUND-SOURCE HEAT

The new headquarters building for Company M, a refrigeration equipment manufacturer, was built according to environmentally conscious design principles. The heat pump units used to supply cold/hot water to the building's air-conditioning system use ammonia as refrigerant. No CFC gases are used in the building. A piping diagram of the air-conditioning system is shown in Figure 1.

One heat pump unit uses a ground-source heat pump to produce cold and hot water using a ground heat exchanger. This system is designed to also allow high-efficiency heat recovery during the intermediate seasons and in winter, when both cold and hot water are used at the same time. During the night, an ice-making chiller forms ice, which is then stored for use during the day. A special system for the transport of ice water through pipes (a dynamic ice transportation system) is also employed.

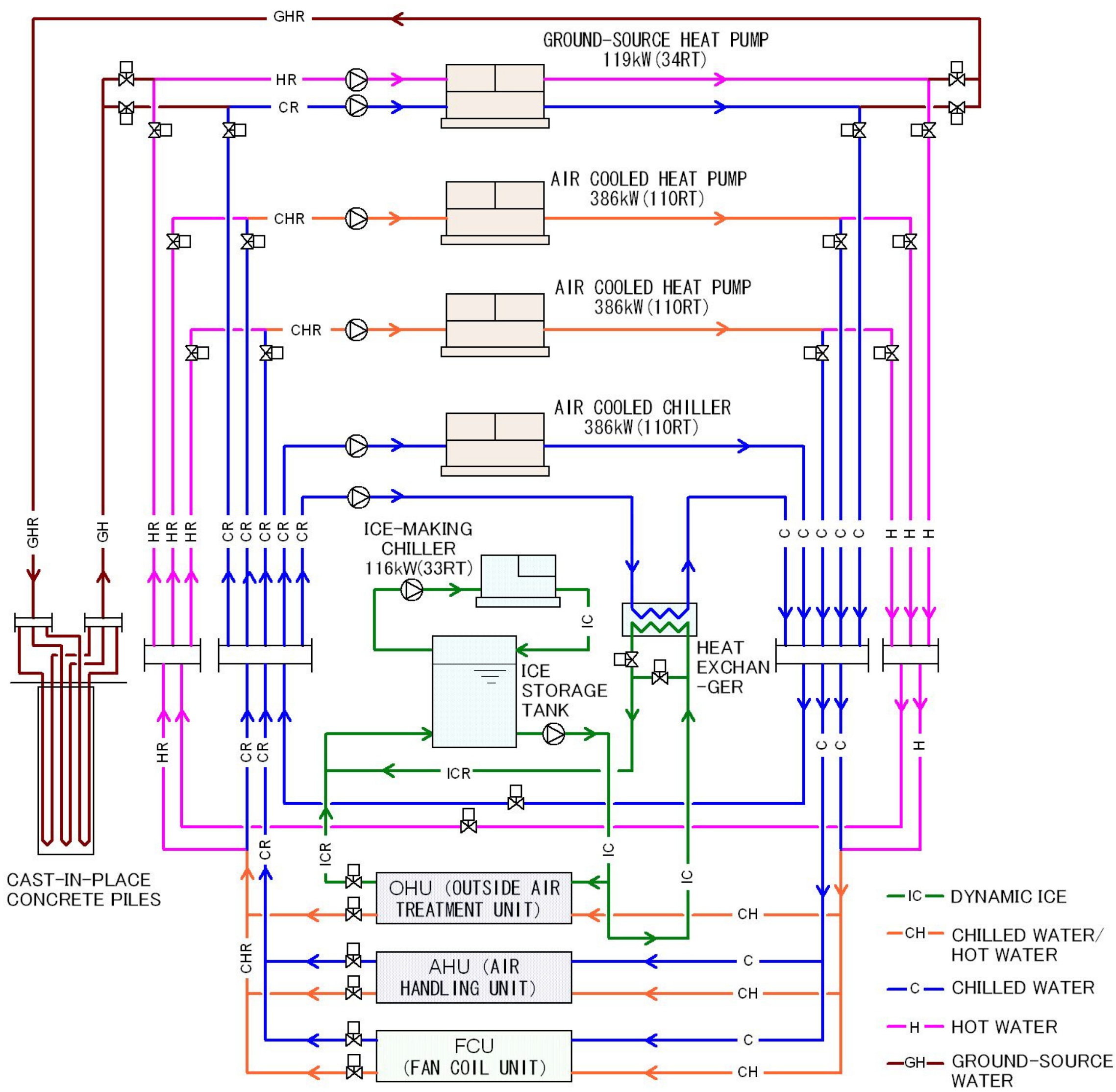

Figure 1: Piping diagram of heating/cooling system

3 DYNAMIC ICE TRANSPORT SYSTEM FOR AIR CONDITIONING

Ice water is liquid water at a temperature very close to zero degrees Celsius. It has better dehumidifying properties than cold water. We have developed a two-pipe (flow and return) dynamic transport system for ice water and incorporated it into the building. The usual problem with flow-and-return transport of ice water is how to maintain temperature control and prevent the pipes becoming blocked with ice. In our system, an experimental approach was used to develop a basic control method and suitable control parameters. With a two-pipe design, the system is able to operate at variable ice water flow rates, which is not possible with a single-pipe transport system, and the return water is at zero degrees Celsius or higher.

To take maximum advantage of the dynamic ice transport system, ice water is supplied to an outside air treatment unit in the summer to remove latent heat (after initial pretreatment using cold water, because the capacity of the ice water storage tank is limited and cannot meet all of the cooling and dehumidifying requirements). As a result, outside air is already low in humidity when it reaches the main air handling unit in the summer. This makes it possible to ensure reduced humidity without lowering the room temperature.
The system operates at an ice packing factor (IPF) of 30% for storage and 10% for ice water transport during the summer. Figure 2 shows the indoor temperature and humidity on 4th floor of the building over three days in the summer. Indoor relative humidity almost never exceeds 50% at any measuring point, indicating a comfortable interior environment. With this reduced humidity, the room air temperature can be set higher, reducing the load on the main air handling unit. The result is significantly improved energy efficiency.

No problems such as blockages caused by ice formation have been reported even when the system is operating at variable ice water flow rates.

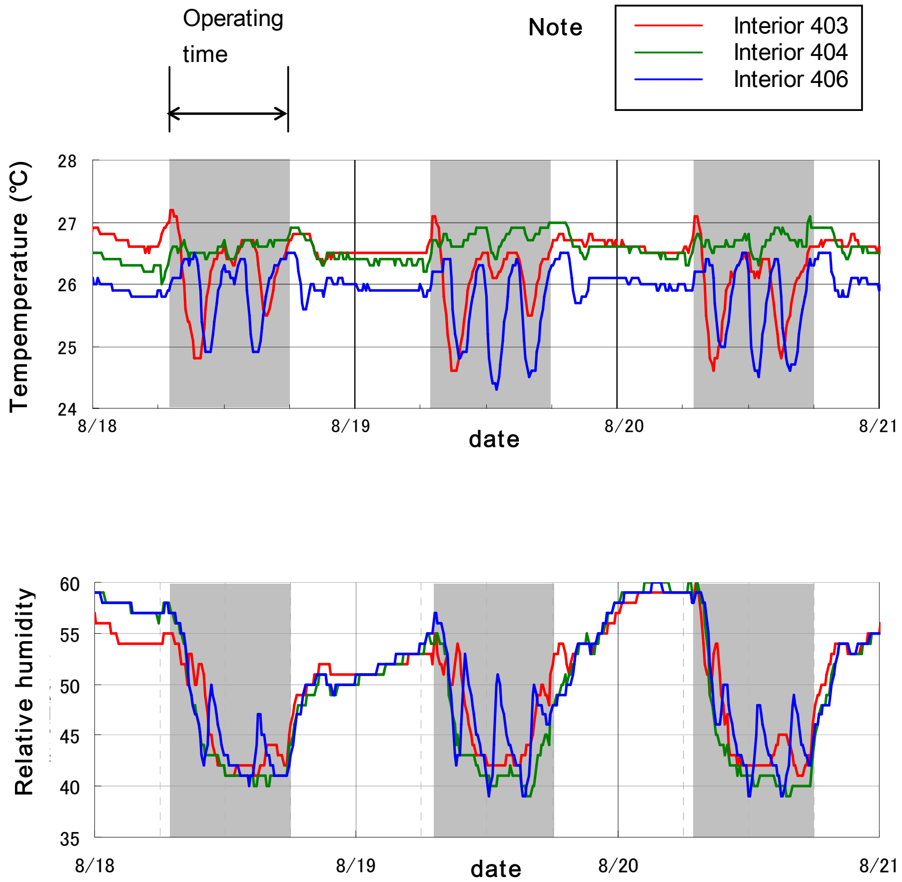

Figure 2: Indoor temperature and humidity environments

4 ENVIRONMENTALLY CONSCIOUS DESIGN USING NATURAL REFRIGERANT AND GROUND-SOURCE HEAT

The thermal properties of soil mean that it keeps a relatively constant temperature throughout the year. A ground-source heat pump takes full advantage of this heat-storage capacity, using the ground as a heat sink for cooling in the summer and as a heat source for heating in the winter. This reduces energy consumption and can help alleviate the heat island effect.

The conventional approach to utilizing ground heat requires excavation to a depth of about 100 m and burying heat exchange pipes to tap the stored heat. This increases the initial costs of system. We have developed a new system, in which the cast-in-place concrete pile foundations of the building are used as the heat exchanger. With a river near the site, the groundwater level is high (GL-0.7 m) and the moist soil is favorable for the utilization of ground heat. Further, the bearing layer is deep and the piles are long, so the piles are favorable for exploiting this resource. As a result, the ground-source heat pump is able to act as the primary energy source for the building’s air-conditioning system.

The building has a seismic-isolation structure with a seismic isolation pit below the 1st floor. A total of 20 piles arranged in two rows of 10 support the structure, each measuring 2 m in diameter and 38 m in depth. All of these are used as heat exchangers.

Eight pairs of high-density polyethylene tubes (20mm (3/4 inch) in diameter) with U-shaped lower ends are installed around the outer perimeter of each pile. The tubes from all piles come together in the seismic isolation pit and are connected to the ground-source heat pump chiller on the roof through a circulation pump.

Prior to drawing up the heat source plan, a numerical simulation was carried out on the amount of heat that could be extracted from and delivered to the ground at the project site (taking into account groundwater flows). This simulation was used to determine the design values: 177 W/m-pile and 150 W/m-pile for cooling and heating, respectively. To control the rise and fall in soil temperature and prevent excessive changes, an upper operating limit of 10 hours per day was set.

Table 1 lists heat pump operating data by operation period (hourly average by month).

Table 1: Measured data by operation period

Operation mode	Month	Amount of heat extracted from and delivered to the ground (W/m-pile)	Heat source (primary) side water			Secondary side		Outside air temp. (°C)	COP
			Inlet temp. (°C)	Outlet temp. (°C)	Flow rate (l/min.)	Outlet temp. (°C)	Output (kW)		
Cooling	May	165	22.3	25.3	595	9.4	86	22.2	5.63
	Jun	184	26.2	29.5	600	9.2	95	24.4	4.99
	Jul	198	29.4	33.0	599	9.7	102	27.1	4.59
	Aug	200	30.4	34.1	594	9.7	104	27.8	4.51
	Sep	184	30.4	33.7	595	9.2	96	25.6	4.41
	Oct	166	29.6	32.5	601	8.7	87	21.8	4.48
	Average	185	28.2	31.6	597	9.3	96	25.2	4.74
Heating	Dec	138	19.1	16.7	605	41.7	120	11.0	5.72
	Jan	143	16.7	14.1	616	42.1	126	8.8	5.66
	Feb	137	15.2	12.8	627	43.1	125	8.0	5.39
	Average	139	16.5	14.1	619	42.4	125	8.9	5.56

* Average values over the operating hours of the month

4.1 Cooling Operation

The amount of heat delivered to the ground was 200 W/m-pile in August when the cooling load was high, and 185 W/m-pile (23 W/m per pair of U-shaped tubes) averaged over the whole cooling operation period. It was confirmed that there was no large fall in the amount of heat delivered to the ground during the long period of cooling lasting about six months. (Table 1)

The water temperature at the inlet to the ground heat exchanger was low when cooling began in May, at 22.3°C, rising to 30.4°C in September. The average was 28.2°C over the whole cooling operation period. This was higher than the design value (26.3°C) for most of the cooling period. The difference in water temperature (between input and output of the ground heat exchanger) was in the range 2.9-3.7°C with an average of 3.4°C over the cooling period, while the flow rate was 597 l/min. These figures corresponded to design values (design heat source water temperature difference: 3.7°C; design heat source water flow rate: 600 l/min).

The water temperature on the secondary side outlet was 9.3°C on average throughout the cooling operation period, which was almost as designed (design cooling water outlet temperature: 9 °C), but there were long periods of time when it was not possible to secure a sufficient cooling water temperature difference between inlet and outlet due to the low return water temperature from the secondary side. The coefficient of performance (COP) of the heat pump unit alone was 5.63 in May just after the operation mode was switched to cooling from heating, 4.41 in September when the water temperature was highest, and 4.74 on average throughout the cooling operation period. This average was below the design value (of 5.57 during rated operation). The primary reasons for this low COP are that cooling began in early May, the soil temperature was high throughout the cooling period, and the operation was at low load because the return water temperature from the secondary side was low.

4.2 Heating Operation

The amount of heat extracted from the ground was 143 W/m-pile in January and 139 W/m-pile (17 W/m per pair of U-shaped tubes) averaged over the whole heating operation period. (Table 1)

The water temperature at the inlet to the ground heat exchanger was 19.1°C in December when heating began and gradually fell during the heating period to 15.2°C in February. The average throughout the heating period was 16.5°C. The COP was 5.72 in December when heating began and 5.56 on average throughout the heating period. This average was higher than the design value (of 4.79 during rated operation), showing that the heating operation was highly efficient throughout the heating period. The primary reason for the high-efficiency of the heating operation is that the soil temperature was high. Further, heating efficiency was affected by the long cooling period, which delivered heat to the soil and left its temperature high.

4.3 Change in Soil Temperature During Cooling/Heating Operation

Figure 3 shows the change in soil temperature in close vicinity to a pile during one year of cooling/heating operation. When cooling began (on May 6, 2009), the soil temperature was 17.1°C at a depth of 8 m, 17.2°C at depths of 18 m and 28 m, and 17.4°C at a depth of 38 m near the tip of the pile. The average was 17.2°C. At the end of the cooling period (on October 31, 2009), the temperature was 22.6°C and 22.7°C at depths of 8 m and 28 m, respectively, 21.2°C at the tip of the pile, and 22.2°C on average. That is, heat release to the ground during cooling caused the soil temperature to rise by 5.5°C on average. The soil temperature fell about 1.5°C to 20.7°C on average during the one month period between November 1 and December 1 when ground heat was not used. Then, as a result of extracting heat for heating, the soil temperature dropped to 17.6°C on average on March 15, 2010, a fall of 3.1°C.

These results show that soil temperature fluctuated by about 5°C during the heating/cooling cycle. The soil temperature before starting operation (on May 19, 2008) was 19.5°C on average. The soil temperature dropped 2.3°C below this level as a result of heating (in the first season) and rose 2.7°C as a result of cooling.

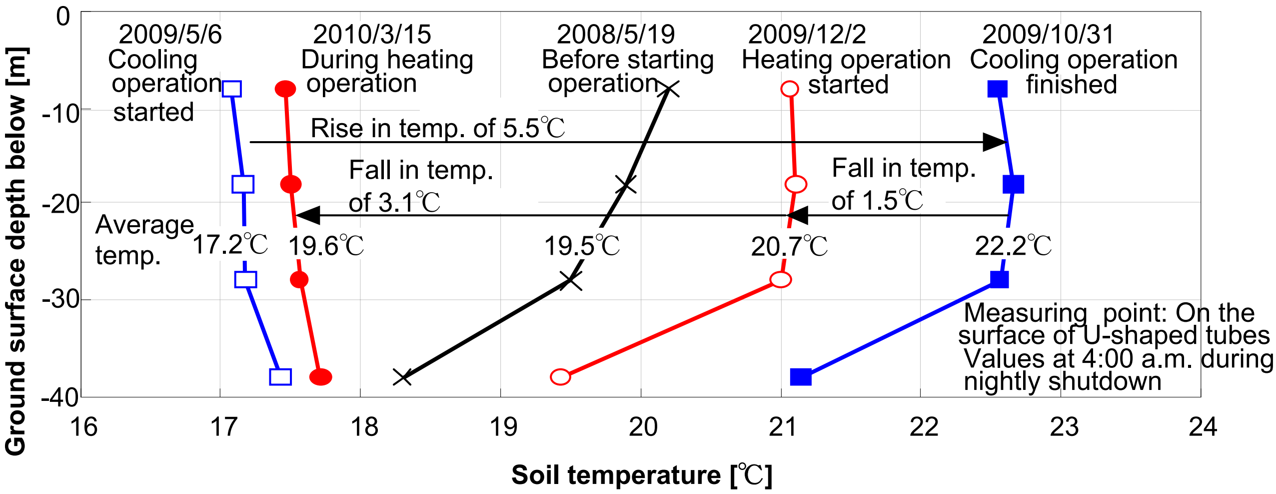

Figure 3: Changes in soil temperature caused by cooling/heating operation

5 STUDIES AND IMPROVEMENTS OF THE SYSTEM USING NATURAL REFRIGERANT AND GROUND-SOURCE HEAT

The operating conditions of the various heat pump units were checked and the system has been tuned for energy saving.

5.1 Air-cooled Heat Pump (HPR-1, 2)

The design COP of the air-cooled heat pump unit was 2.79 and 2.21 during rated cooling and heating operations, respectively. According to the operational data, the actual COP of the unit was 3-3.5 and 2-2.5 at peak hours during cooling and heating operations, respectively, which are close to the design values. (Figure 4)

The COP fluctuated at low levels because of partial-load operation throughout the year.

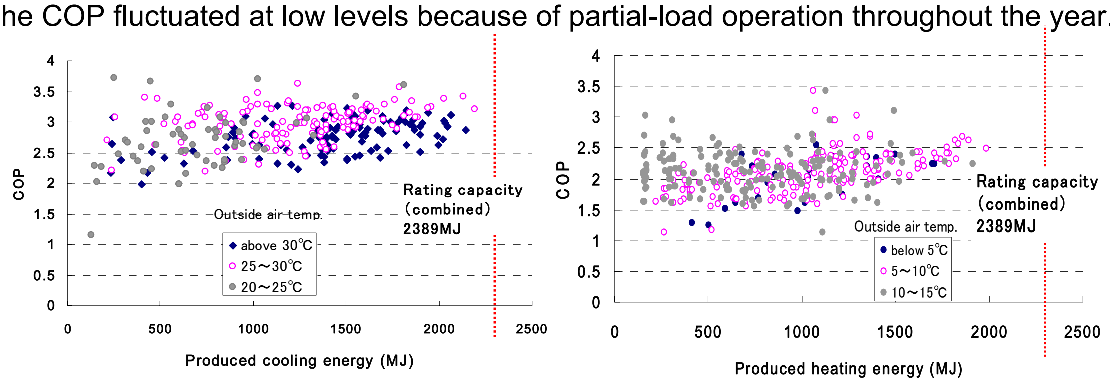

Figure 4: The actual COP of the air-cooled heat pump unit (HPR-1,2)

5.2 Air-cooled Cooling-only Chiller (CR-1)

The air-cooled cooling-only chiller was used mainly to cool the extra-high voltage substation room and the server computer room at night. This means that it was operated at low loads for long periods, so the actual COP of the chiller was lower than the design COP of 2.79. (Figure 5)

5.3 Ice Making Chiller (ICR-1)

The yearly average COP of the ice-making chiller was 2.56. The design COP under rated operation was 1.87. Because the period during which the outdoor air temperature was lower than the design temperature (33.4°C) was long, the yearly average COP was high. For operational reasons, it was important that there was no remaining ice in the system when ice making began, so the amount of ice that could be produced during an operating period was limited. (Figure 6)

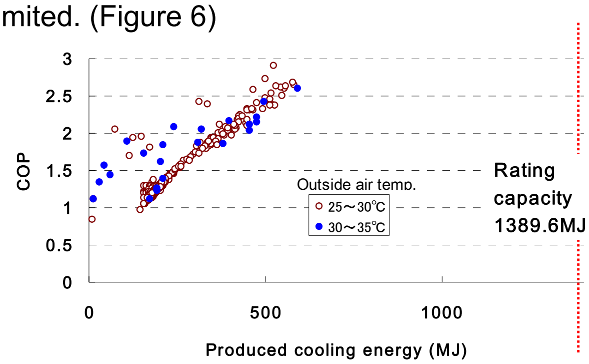

Figure 5: The actual COP of the air-cooled cooling-only chiller (CR-1)

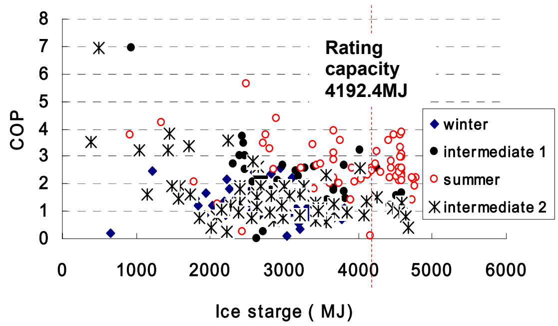

Figure 6: The actual COP of the ice making chiller (ICR-1)

5.4 Ground-source Heat Pump (GHPR-1)

The COP of the ground-source heat pump unit during cooling was 3-7, which was lower than the design value (5.57), and 4-8 during heating, which was higher than the design value (4.79). The primary reasons for the lower than expected COP during cooling are that cooling began in early May, the soil temperature was high throughout the cooling period, and the operation was at low load because the return water temperature from the secondary side was low. (Figure 7)

The higher COP during heating is considered to be due to the fact that the cooling operation period was long, leaving the soil temperature high as a result of the amount of heat delivered to the ground.

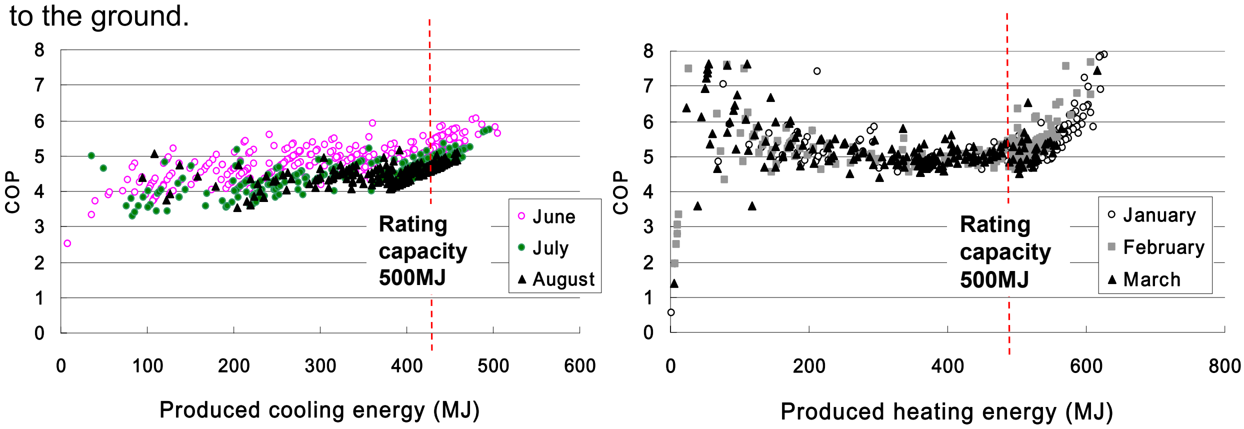

Figure 7: The actual COP of the ground-source heat pump unit (GHPR-1)

5.5 Tuning for Saving Energy

5.5.1 Reduction in outside air intake rate

The interior CO_2 concentration in the building was low as a result of its low occupancy of this office building, so the outside air intake rate was reduced to two-thirds of the design value to reduce thermal load. Even after this reduction in air intake rate, the CO_2 concentration did not reach regulation levels.

5.5.2 Review of cold/hot water flow control

The maximum hot water flow rate was reduced. This made it possible to increase the temperature difference between supply and return of the heating system, which in turn reduced the power consumed by the pumps. In addition, unnecessary start-up of the chilling equipments was eliminated. The same is true of the cooling system.

Figures 8 and 9 show hourly fluctuations in outdoor air temperature and power consumption of the heat pump units before and after this tuning of flow rates on days with similar load patterns. Tuning reduced the power consumption by almost 49%.

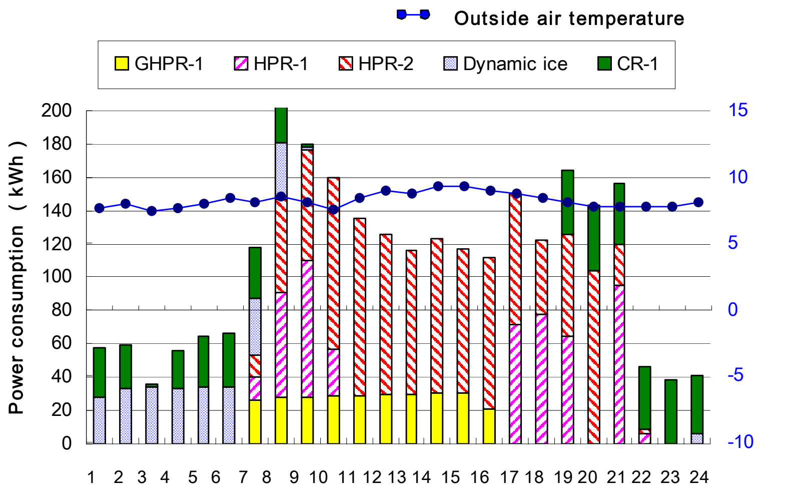

Figure 8: Hourly fluctuations in outdoor air temperature and power consumption of heater/chiller units before tuning(on January 20(Tuesday),2009)

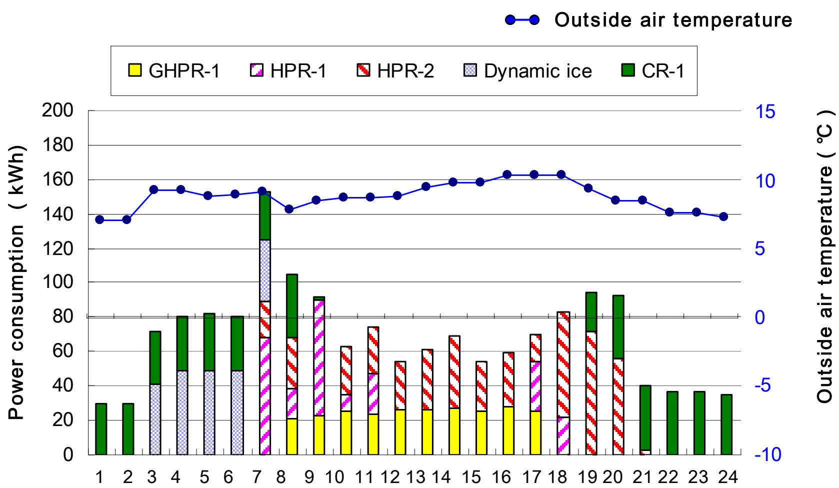

Figure9: Hourly fluctuations in outdoor air temperature and power consumption of heater/chiller units before tuning(on April 23(Friday),2010))

Figures 10 and 11 show daily fluctuations in outdoor air temperature between 9:00 and 17:00, and the power consumption of the heat pump units in March 2009 and March 2010.

The power consumption of the cooling-only units was reduced by 23% while the power consumption of the heating/cooling units was reduced by 21%. The total amount of energy generated by the heating/cooling and cooling-only units was 70,736 MJ and 18,627 MJ, respectively, in March 2009, and 55,771 MJ and 15,650 MJ, respectively in March 2010, a reduction of 21% and 16%, respectively.

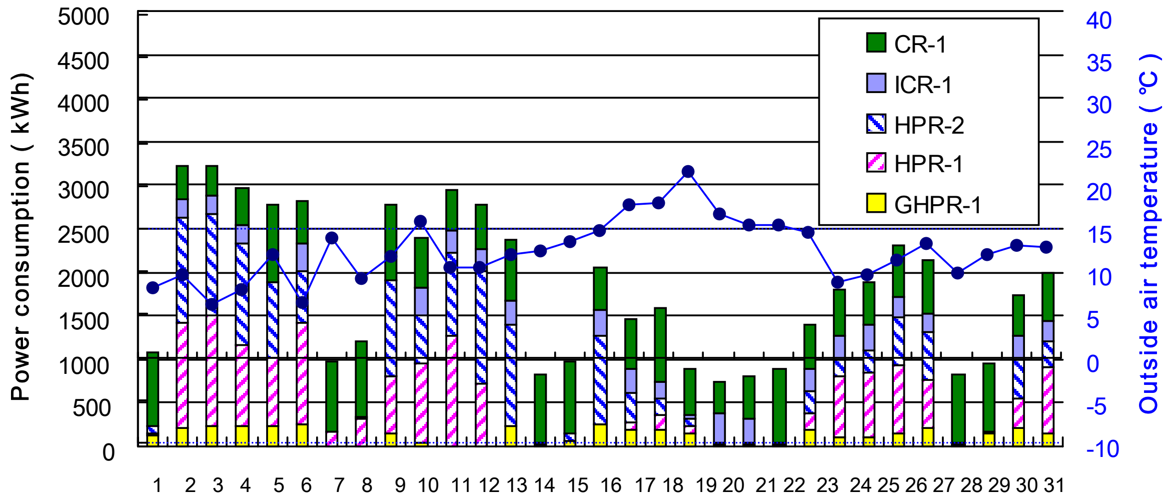

Figure 10: Daily fluctations in outside air temperature and power consumption of heater/chiller units (in March 2009)

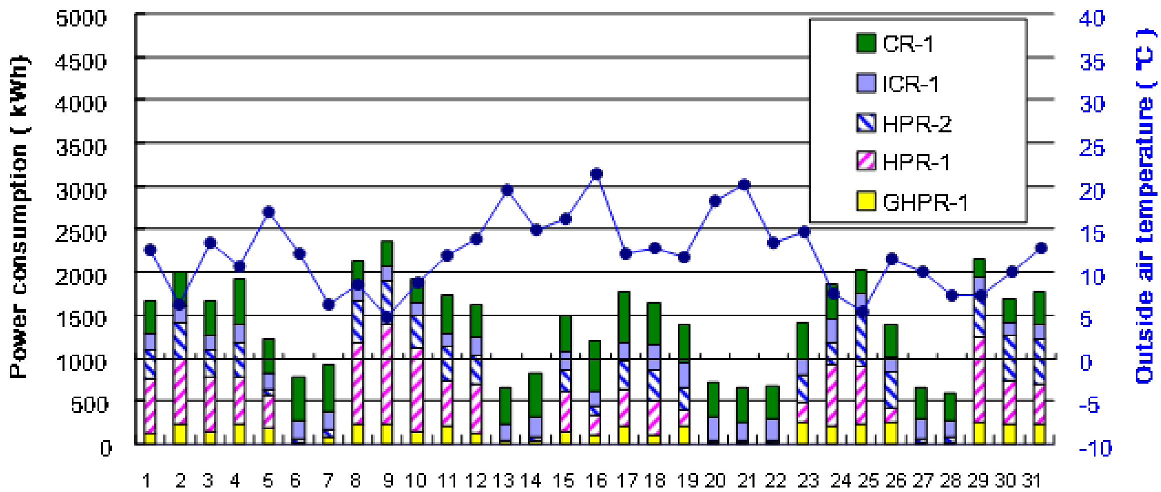

Figure 11: Daily fluctations in outside air temperature and power consumption of heater/chiller units (in March 2010))

5.5.3 Use of ice making chillers in the winter

The high-capacity air-cooled cooling-only chiller (CR-1) operated under the partial load for long periods to keep the extra-high voltage electricity machine room and the server computer room cool throughout the year. (Cooling using outside air was avoided because the site is in an area where salt damage might occur). So, in the winter period, the ice making chiller (ICR-1) was used during the daytime to save energy in dealing with this partial cooling load.

Table 2 lists the cooling energy and power consumption for the three-month periods between January and March of 2009 and 2010. Comparing these two three-month periods, a 27% energy reduction was achieved. For reference, a 24.5% energy reduction would have been achieved even if CR-1 had operated for 24 hours a day in the same manner as in 2009.

Table 2: Use of ice making chiller during daytime in winter to save energy in dealing with the cooling load (measured and simulated)

		ICR-1			CR-1			Total		Compared with 2009 (reduction effect)	CR-1 Operating ratio with 2010 heat generation (reduction effect)
		Ice thermal storage (GJ)	Power consum-ption (MWh)	Operating hours (hr)	Heat gene-ration (GJ)	Power consum-ption (MWh)	Operatin g hours (hr)	Heat gene-ration (GJ)	Power consum-ption (MWh)		
2009	Jan	71.3	5.1	183	111.2	21.3	744	182.6	26.5	100%	-
	Feb	55.0	4.7	137	88.1	17.7	672	143.3	22.4		
	Mar	55.7	5.2	138	88.4,	19.2	744	144.2	24.5		
Total		182.1	15.0	458	287.8	58.3	2,160	470.0	73.3		
Ratio of ICR to CR		39%	21%		61%	79%		100%	100%		
2010	Jan	66.6	5.6	147	50.7	13.0	450	117.3	18.6	72.9% (27.1%)	75.3% (24.7%)
	Feb	55.5	4.8	121	45.7	11.2	405	101.2	16.1		
	Mar	76.3	6.4	168	47.7	12.4	410	124.1	18.8		
Total		198.5	16.9	436	144.0	36.6	1,264	342.6	53.5		
Ratio of ICR to CR		58%	32%		42%	68%		100%	100%		
2010 (assumed ※)	Jan	33.5	2.8		83.8	21.5		117.3	24.3	-	100%
	Feb	25.3	2.2		75.9	18.6		101.2	20.8		
	Mar	37.4	3.1		86.6	22.6		124.1	25.7		
Total		96.2	8.2		246.3	62.7		342.6	70.9		
Ratio of ICR to CR		28%	12%		72%	88%		100%	100%		

※ Operation of CR-1 for 24 hrs in the same manner as in 2009

Figure 12 shows the monthly primary energy consumption of the building before the tuning (between July 2008 and June 2009) and after the tuning (between July 2009 and June 2010). Annual primary energy consumption per gross floor area of the building was 2,091 MJ/m^2-year and 1,836 MJ/m^2-year before and after the tuning, respectively. The building incorporates a server computer room with a large capacity; excluding this server computer room, the calculated annual primary energy consumption per unit floor area was 1,927 MJ/m^2-year and 1,669 MJ/m^2-year before and after the tuning, respectively.

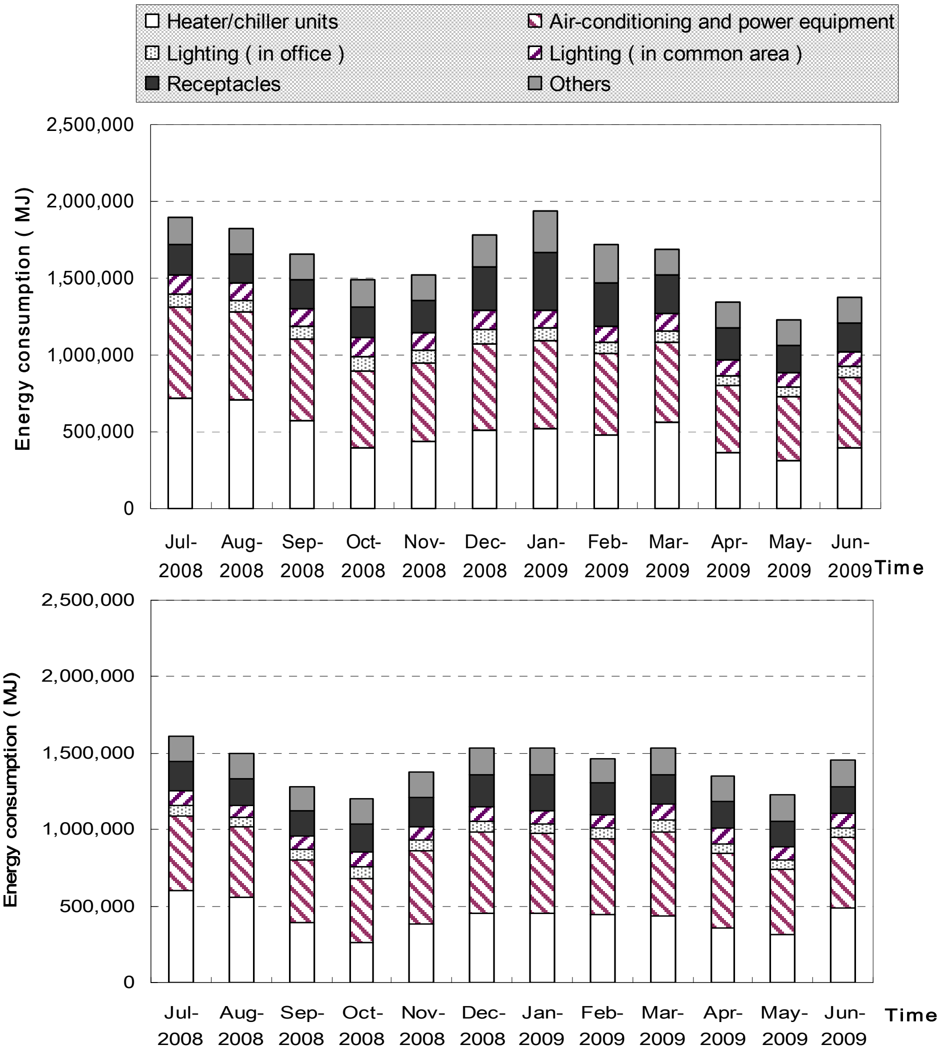

Figure 12: Monthly primary energy consumption of building before and after equipment tuning (between July 2008 and June 2010)

6 CONCLUSION

This building incorporates a range of advanced equipment technology for energy savings and improved environmental performance. Optimization of the equipment, carried out during actual use, proved to be very beneficial to its efficient operation.

ACKNOWLEDGEMENT

The authors would like to thank those people who gave us their considerable guidance and cooperation in the planning, design, construction and operation phases of the building.

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