Continuous Energy Management of the HVAC&R System in an Office Building System Operation and Energy Consumption for Eight Years after Building Completion

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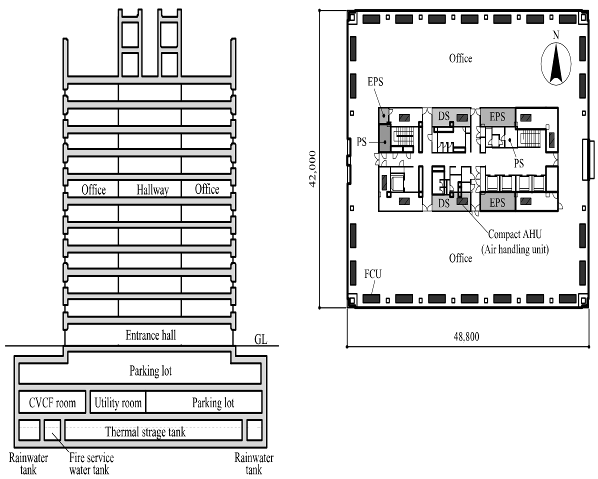
Abstract: The authors continuously studied the energy consumption of a heating, ventilating, air- conditioning and refrigerating (HVAC&R) system in an office building after the building was newly constructed. For the first two years after building completion, the HVAC&R system was checked to veri for the operation of the system in terms of its expected performance. A fault in the system control setting was detected, and the system performance improved significantly as a result of correcting the fault. Recently, however, problematic issues, such as the malfunction of chillers and deteriorated performance of the heat exchangers, have emerged, resulting in the degradation of overall system performance. This paper describes (a) changes in the energy consumption of the building over a period of eight years during which the HVAC&R system was operated, and (b) problematic issues that arose during system operation in order to identify the energy-saving effects of the system found when energy management of the building is continuously practiced. In this HVAC&R system, about 25% of electric power consumption for wintertime could be saved by checking the system operation during the first two years. After that, the electric power consumption gradually increased due to the system deterioration until 2004, but it decreased again by properly dealing with the problems.

1. INTRODUCTION

In recent years, different energy saving methods are being employed aggressively in office buildings. According to some reports, the performance of HVAC&R systems installed in buildings has improved significantly[1,2]. However, there are only a few cases in which the initial performance was maintained over a long period of time and is being verified continuously. To ensure energy saving, it is crucial to properly operate HVAC&R systems by practicing quality management in the design, construction, operation, and maintenance of buildings and facilities. Continuously carrying out energy management throughout the life of a building can bring about the level of reliability required by building owners and/or users for the performance of HVAC&R systems. In Japan, however, the operation and maintenance of HVAC&R systems are com monly performed by system operators hired in buildings. In fact, a scheme for continuous energy management during system operation and maintenance has not been established yet.



(a) Building section (b) Building plan (unit:mm)

Fig. 1 Building section and plan

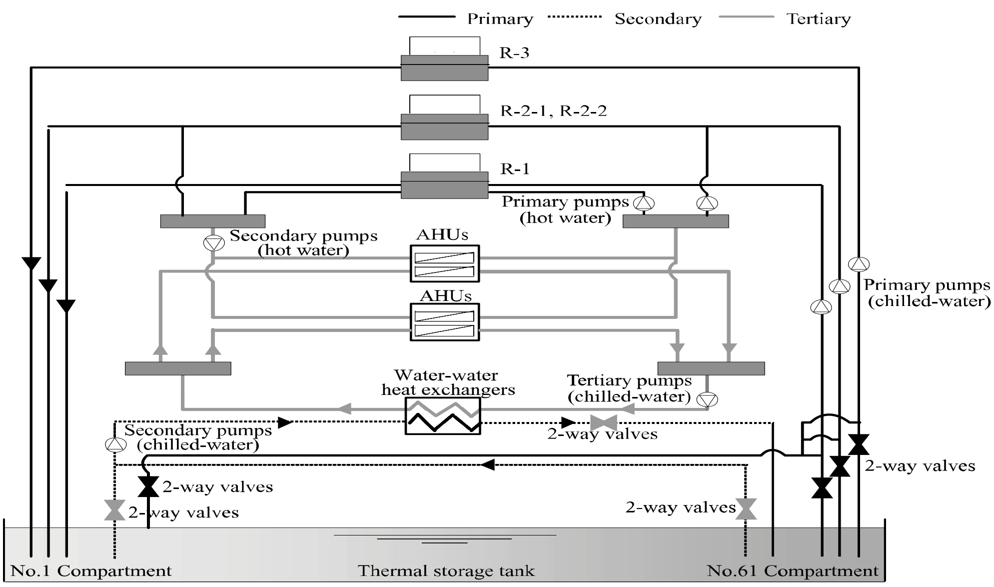


Fig. 3 Schematic of the HVAC&R system

Tab 1 Design parameters of the HVAC&R system

Component	Specifications
Exhaust heat recovery type air-source chiller (R-1: 1 unit)	(Non exhaust heat recovery mode) Capacity: 330kW(cooling), 227kW(heating) Electric power: 150kW(cooling), 113kW(heating) (Exhaust heat recovery mode) Capacity: 320kW(cooling), 456kW(heating) Electric power: 140kW
Heat pump type air-source chiller (R-2-1: 1 unit, R-2-2: 1 unit)	Capacity: 372kW(cooling), 227kW(heating) Electric power: 138kW(cooling), 124kW(heating)
Cooling only chiller (R-3: 1 unit)	Capacity: 372kW(cooling) Electric power: 138kW(cooling)
Primary pump (chilled-water) (4 units)	(R-1) Water flow rate: 57.6m3/h, Electric power: 30kW (R-2-1, R-2-2, respectively) Water flow rate: 64.8m3/h, Electric power: 30kW (R-3) Water flow rate: 64.8m3/h, Electric power: 30kW
Secondary pump (chilled-water) (4 units)	Water flow rate: 54.0m3/h, Electric power: 7.5kW
Tertiary pump (chilled-water) (4 units)	Water flow rate: 54.0m3/h, Electric power: 18.5kW
Primary pump (hot water) (3 units)	(R-1) Water flow rate: 50.4m3/h, Electric power: 5.5kW (R-2-1, R-2-2, respectively) Water flow rate: 32.4m3/h, Electric power: 5.5kW
Secondary pump (hot water) (4 units)	Water flow rate: 28.8m3/h, Electric power: 11kW
Water-water heat exchanger (plate type) (4 units)	Capacity: 512kW
Thermal storage tank (1 unit)	Volume: 1500m3

Fig. 2 Building appearance

The building and the HVAC&R system mentioned in this paper were constructed eight years ago and had been investigated in detail for the first two years after building completion[4,5]. During investigations, a fault in thesystem control setting was detected based on a measurement and simulation analysis; and, the system COP (coefficient of performance) improved significantly as a result of correcting the fault. Afterwards, however, the deterioration of system components appeared [3].

The purpose of this study is to identify the energy saving effects found when energy management of the HVAC&R system is continuously implemented. This paper describes changes in the electric power consumption and problematic issues arising in the use of the HVAC&R system observed in the period starting from building completion to the present as the initial study stage.

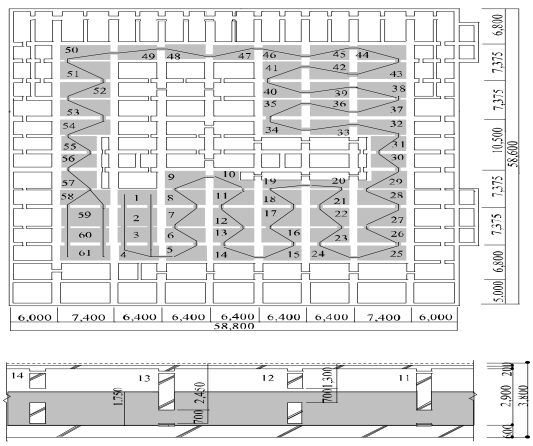
2. OUTLINE OF HVAC&R SYSTEM

Figure 1 shows the building section and plan (a middle floor); and, Figure 2 shows the building appearance. This office building, which was constructed in Oita City in June 1997, has a total floor area of approximately 30,000 m2. Figure 3 is a schematic of the HVAC&R system; and, Table 1 lists the design parameters of the system. The building uses a water thermal storage system with high temperature differentials (Figure 4). In Japan, buildings are generally built upon a double slab (a space is created between the lowest floor slab and the foundation slab) to increase earthquake resistance; and, the space can be used as a water thermal storage tank as well. The thermal storage tank stores chilled-water to meet year-round cooling loads by not only outdoor air temperature, solar radiation, etc. but also internal heat generation in normal workspaces and computer rooms. For heating in the winter, three chillers, not including the R-3 chiller, are operated by multiple control units according to the heating loads. The exhaust heat recovery type air-source chiller (R-1) stores chilled-water in the thermal storage tank while simultaneously recovering heat.

The thermal storage tank is composed of 61 compartments in total. The No. 1 compartment has lower temperature water overall; and, the No. 61 compartment contains higher temperature water overall. During the heat charging mode, mixed water from the No. 1 and No. 61 compartments is sent to all of the chillers; and, the chilled-water produced by the chillers is returned to the No. 1 compartment. During the heat discharging mode, mixed chilled-water from the No. 1 and No. 61 compartments is supplied to the AHUs (air-handling units) via the water-water heat exchangers; and, the water is returned to the No. 61 compartment. The mixing ratio of water from the No. 1 and No. 61 compartments is controlled by the PI (proportional- plus-integral) control of the two-way valves installed in the pipes transporting the water from the compartments. In this way, the primary inlet water temperature of the chillers (during the heat charging mode) and the secondary inlet water temperature of the heat exchangers (during the heat discharging mode) can be maintained at preset values. On the other hand, the flow rate of the water transported from the thermal storage tank to the heat exchangers during the heat discharging mode is controlled by the PI control of the two-way valves installed in the secondary pipes of the heat exchangers. In this way, the tertiary outlet water temperature of the heat exchangers can be maintained at a preset value. Control of the operation of the chillers depends on the preset value (one-day-curve) of the thermal storage rate. That is, the number of chillers to be operated is determined by comparing the preset value to the actual thermal storage rate value at respective points in time in order to maintain the difference between those values within a certain range (Figure 5).

3. HVAC&R SYSTEM OPERATION

Figure 6 shows a record of data collection carried out and problems arising since the building was constructed. The entire term is roughly classified into three periods. In Period 1, the HVAC&R system was operated using the initially- designed operation strategy; and, exhaustive research of the system was carried out for the purpose of verification. In Period 2, operation of the HVAC&R system improved temporarily, as a result of the use of findings from research carried out in Period 1. However, further system faults occurred over time in the second half of Period 2. Because research like that carried out in Period 1 was not implemented in Period 2, the system operators dealt solely with the data stored in the BEMS (building energy management system). As in Period 1, in Period 3, countermeasures for the faults revealed in Period 2 were carried out as part of the research process



(a) Plan (b) Section

Fig. 4 Water thermal storage tank (unit:mm)

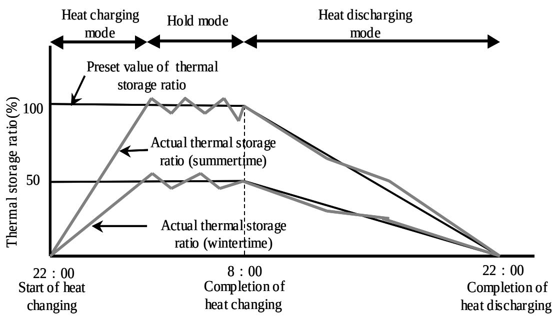


Fig. 5 Outline of the preset value of the thermal storage ratio

3.1 Period 1

Figure 7 shows the initially-designed preset values of the HVAC&R system. The inlet water temperature of the chillers was set at 12°C (degrees Celsius). The secondary inlet water temperature of the heat exchangers was set at 9°C; and, their tertiary outlet temperature was set at 10°C. Creating a gap of 2K between the primary outlet water temperature of the chillers (7°C) and the secondary inlet water temperature of the heat exchangers (9°C) results in a higher thermal storage efficiency as compared to that of a conventional thermal storage tank. Further, the water temperature difference in the thermal storage tank was set at 10K, differing from the 5-7K difference conventionally found. Through cost estimation, it was found that this thermal storage tank contributed to an initial cost reduction of about 4.4% and a running cost reduction of about 8.2%, as compared to the costs incurred when using a conventional thermal storage tank.

In the first year of Period 1, for both summer and winter, the preset value of the thermal storage ratio was. the exhaust heat recovery operation of the R-1 chiller stopped in the wintertime when the actual thermal storage ratio reached 100%. As a result, the system did not perform as expected. In the second year of Period 1, the preset value for wintertime was changed (to the maximum value of 50%); and so, system performance in the wintertime improved significantly. the same (Figure 5). Because the maximum preset value of the thermal storage ratio for summertime is 100%, Furthermore, a more efficient operation strategy was examined. In the summer of 1999, two different field tests were carried out. Test 1 was conducted to study the effectiveness of increasing the thermal storage water temperature to improve the chiller COP. Test 2 was conducted to study the effectiveness of increasing the difference between the inlet and outlet temperatures of the heat exchangers to reduce the electric power consumption of the pumps. Figure 8 shows the system performance appeared gradually over time, but went unnoticed. In November 2004, the preset values changed during testing. As a result of these tests, system performance improved slightly; and, it was confirmed that changes in operation strategy did not have a negative effect on the indoor air temperature or humidity.

3.2 Period 2 and Period 3

In Period 2, the HVAC&R system was operated, making use of the findings gained in the research carried out in Period 1. In the beginning, however, the importance of energy management was not realized sufficiently. Degradations in compressor of the R-1 chiller finally stopped, and problems emerged. In response, we immediately implemented an analysis of the stored data and met with the system operators in Period 3, the period during which the countermeasures were taken.

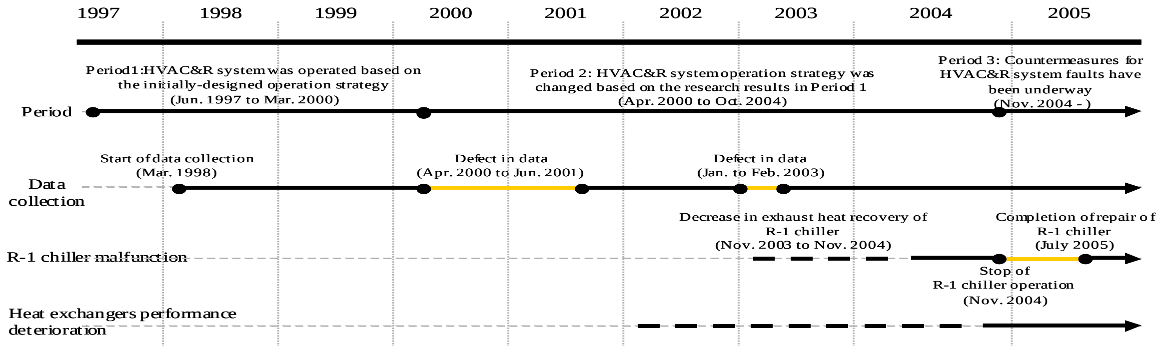


Fig. 6 Record of data collection and problems arising since building const

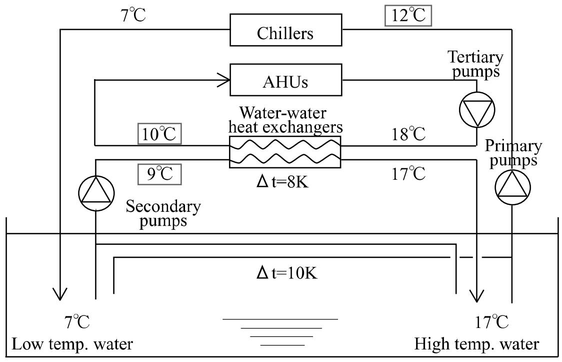


Fig 7 System preset values (initially-designed)

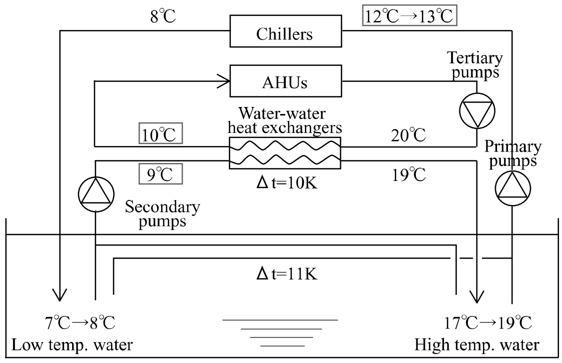
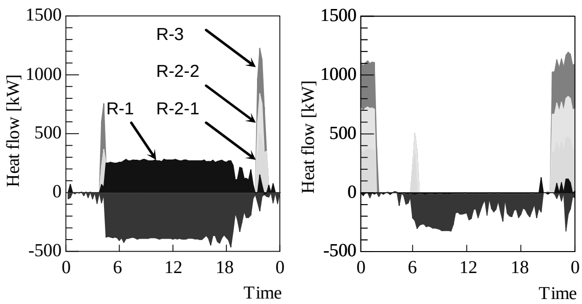


Fig 8 System preset values changed by the Tests



(a) Feb. 19, 2002 (b) Feb. 17, 2004

Fig 9 Heat flow produced by the chillers in the wintertime

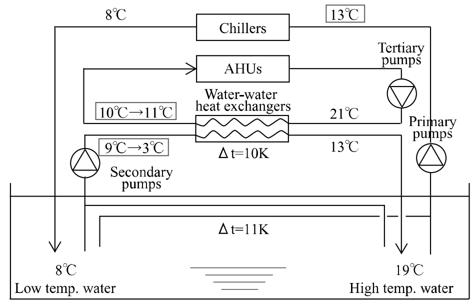
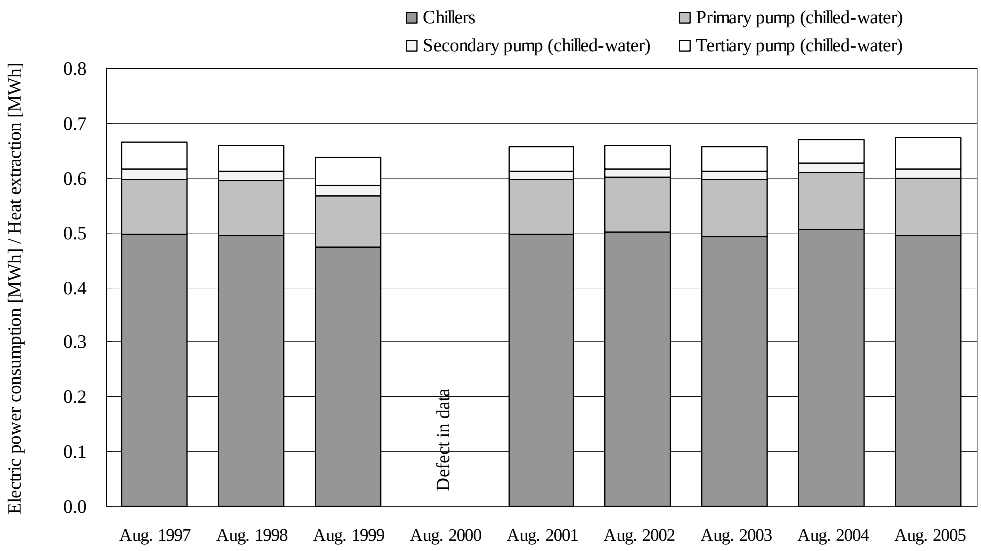


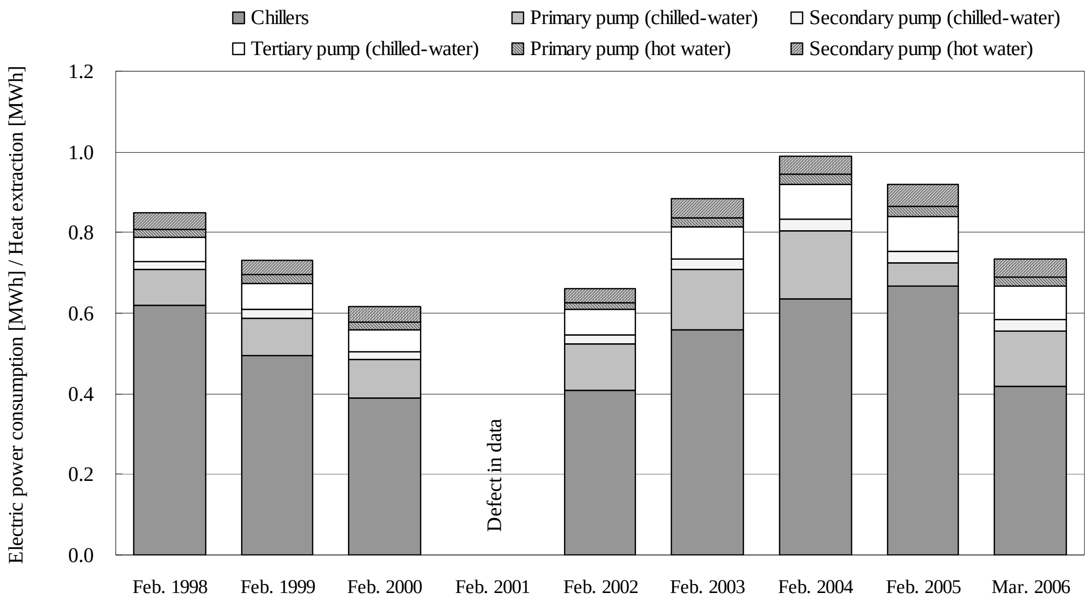
Fig. 10 System preset values when we met with system operators

Figure 9 shows the heat flow produced by the chillers in the winters of 2002 and 2004. The positive heat flow is heating and the negative is cooling. The R-1 chiller functions to recover exhaust heat and simultaneously create both chilled-water and hot water, as shown in Figure 9(a). However, in the winter of 2003, the amount of exhaust heat recovered by the R-1 chiller started to decrease gradually over time; and, in February 2004, the R-1 chiller recovered very little exhaust heat, as shown in Figure 9(b). For heating operation during the winter, the R-2-1 and the R-2-2 chillers were operated solely. For heat charging in the thermal storage tank, the R-2-1, the R-2-2 and the R-3 chillers were operated.

Figure 10 shows the preset values of the HVAC&R system found when we met with the system operators. Two settings were found to have been changed by the operators (when they were changed is unknown). First, the setting for the tertiary outlet water temperature of the heat exchangers was changed from 10°C to 11°C. Second, the setting for the secondary inlet water temperature of the heat exchangers was changed from 9°C to 3°C, which means that the control for mixing the water from the



(a) Summertime



(b) Wintertime

Fig. 11 Monthly integrated values of the electric power consumption per unit of heat extracted

Tab 2 Monthly mean COP values of the chillers and of the system

(a) Summertime

	Monthly mean COP values of the chiller [-]					Monthly mean	Average outdoor
	R-1	R-2-1	R-2-2	R-3	Average	of the system [-]	air temperature
Aug. 1997	2.12	2.42	2.33	2.54	2.35	1.50	27.74
Aug. 1998	2.06	2.42	2.27	2.51	2.32	1.52	29.25
Aug. 1999	2.38	2.52	2.37	2.56	2.46	1.57	27.38
Aug. 2000				Defect in data			
Aug. 2001	2.15	2.34	2.50	2.62	2.41	1.52	28.28
Aug. 2002	2.17	2.42	2.29	2.43	2.34	1.52	28.65
Aug. 2003	2.20	2.46	2.34	2.48	2.38	1.52	27.32
Aug. 2004	2.17	2.47	2.35	2.12	2.28	1.49	26.04
Aug. 2005	2.33	2.55	2.46	2.23	2.40	1.49	26.60

(b) Wintertime

	Monthly mean COP values of the chiller [-]					Monthly mean of the system [-]	Average outdoor air temperature
	R-1	R-2-1	R-2-2	R-3	Average		
Feb. 1998	2.60	2.55	2.63	2.96	2.65	1.18	9.64
Feb. 1999	4.19	1.96	1.99	0.21	3.85	1.37	7.62
Feb. 2000	4.37	2.34	2.84	3.28	3.73	1.62	6.40
Feb. 2001	Defect in data						
Feb. 2002	4.69	2.69	2.65	2.85	3.91	1.51	8.95
Feb. 2003	3.27	2.82	Not worked	2.89	3.06	1.13	7.36
Feb. 2004	2.71	2.75	2.74	2.84	2.74	1.01	7.00
Feb. 2005	-	2.25	2.30	2.88	2.38	1.09	5.89
Mar. 2006	5.56	2.43	2.56	2.36	3.69	1.36	9.98

No. 1 and No. 61 compartments were stopped. It was guessed that these changes made by the system operators caused the deterioration of the performance of the heat exchangers; and, from August 1 to October 18, 2005, a field test (Test 3) was carried out to confirm this hypothesis. In Test 3, the secondary inlet water temperature of the heat exchangers was reset from 3°C to 10°C, and the secondary outlet water temperature of the heat exchanger was expected to be 20°C. However, after the values were reset, it was about 18°C and the difference was reduced to 8K. This fact shows that the performance of the heat exchangers degraded due to deterioration caused by adhesion of scales, etc.

4. ELECTRIC POWER CONSUMPTION

4.1 Summer

Figure 11(a) shows the monthly integrated values for the electric power consumption of the HVAC&R system per unit of heat extraction rate of the system; and, Table 2(a) lists the monthly mean COPs of the chillers and the system in the summer. In August 1999, the system's electric power consumption decreased slightly as a result of operation strategy changes (Figure 8), as compared to that of 1997 and 1998. In the summer, exhaust heat recovery by the R-1 chiller was not activated. Therefore, the impact of the R-1 chiller's malfunction on system performance was less.

4.2 Winter

Figure 11(b) shows the monthly integrated values for the electric power consumption of the HVAC&R system per unit of heat extraction rate of the system; and, Table 2(b) lists the monthly mean COPs of the chillers and the system in the winter. In February 2000, compared to that of 1998 and 1999, the system's electric power consumption decreased significantly as a result of changing the preset value of the thermal storage rate as mentioned above. Afterwards, however, degradation of the R-1 chiller's performance by the functional fault resulted in a decrease of the COP values for the R-1 chiller and the system. In February 2005, the R-1 chiller's compressor finally broke down, resulting in the suspension of the R-1 chiller's operation. This brought about further decreases in the other COP values. The R-1 chiller did not run in 2005; therefore, the electric power consumption in February 2005 was less than that of February 2004 because electric power consumption for the primary pumps was not necessary. After repair of the R-1 chiller was completed in July 2005, system performance was regained as shown in the data for March 2006 shown in Figure 11(b).

5. CONCLUSIONS

This paper summarizes changes in the operation strategy used for the system, problems that emerged in the system, and trends in the electric power consumption of the HVAC&R system using actually measured data for a period of eight years since the building construction. In this study, the importance of carrying out continuous energy management for the HVAC&R system, including the quick detection of system deterioration, was recognized. In this HVAC&R system, about 25% of electric power consumption for wintertime could be saved by checking the system operation strategy during the first two years. After that, the electric power consumption gradually increased due to the system deterioration until 2004, but it decreased again by dealing with the problems.

6. ACKNOWLEDGEMENTS

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