Energy Performance Analysis of an Air-Conditioning System with Heat Pump Chillers Controlled by Inverters

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ABSTRACT

This paper presents energy performance analysis of an air-conditioning system with heat pump chillers controlled by inverters. The inverter is attached to the chillers' compressor, and controls the number of revolutions of the motor. As a result, the efficiency of the chiller in a partial load can be largely improved more than in a full load. Although the operation hours of chillers become long, energy consumption in chillers is reducible. The energy performance is verified by direct measurement and a model-based simulation analysis of a small office building and the air-conditioning system existing in Tokyo. In the measurement, the energy efficiency of the chillers and primary pumps using inverters is compared with ones using no inverters, and the result that the former efficiency is higher than the later is obtained. In the simulation, three cases are carried out. The first is the case that no inverters are used in the air-conditioning system, the second is that the inverters are installed in only chillers, the third is that the inverters are installed in both the chillers and the pumps. Though the operation hours of chiller and primary pump in the second case are longer than the first case, the utilization of inverters can cut down the energy consumption. Furthermore, the third case enhances the energy saving compared with the second case. Consequently, the energy conservation effectiveness of chillers controlled by inverters is clarified in this paper.

Introduction

Frank J. Lenarduzzi and Steven S. Yap (1998) studied applying inverter to an existent fixed-speed centrifugal chiller and cooling tower. And Thomas Hartman studied applying inverter to centrifugal chiller plants in a design stage and effective operation of it. These studies, however, targeted a large size chiller and not targeted middle size chiller in average office building. We are now researching on optimal operations of HVAC&R systems to reduce the energy consumptions. Applying inverter to an air-conditioning system in average office building is one of effective solutions of this.

Controlling fans and pumps in a building air-conditioning system by inverters is an important method for realizing building energy saving. Controlling motors of fans and pumps by inverters makes the efficiency of building energy saving in a partial load higher compared with controlling them by movements of valves and dampers. In particular, the cost of inverters is getting lower recently, and the technology is becoming popular. Since the number of hours of a full load is about 5 percent of total operation hours in a year, the technology is very effective for building energy saving. However, on the other hand, the inverters are not usually installed in chillers of a building air-conditioning system, the chillers are basically operated in a full load because the efficiency in a partial load is lower. This is a factor which impedes the push forward with more energy savings and to optimize the operations of whole air-conditioning system. A study on the energy effects of controlling chillers by inverters is presented in this paper. The energy performance is investigated based on direct measurement and the model-based simulation analysis.

Characteristics of Heat Pump Chillers Controlled by Inverters

First, a clarification of the characteristics of heat pump chillers controlled by inverters is needed. Actually, when introducing inverter control into chillers and when chillers are operated in a partial load, it may cause mechanical troubles of the chillers such as that the refrigerant stops circulating. We experimented using two chillers with inverters to investigate the energy efficiency and if the problem occurs or not. The specification of two chillers is described in Table 1. Figure 1 shows the characteristics of the chillers in partial loads obtained as a result of the experiment. Here, partial load rate stands for the rate of the quantity of heat the chiller produces in a partial load. And electric power rate stands for the rate of the electric power the chiller consuming in a partial load. In the cooling operation, it can be understood that the partial load operation is more efficient than the full load one. However, there is a slight difference between the characteristics of two chillers.

Table 1. Specification of Chillers

	Chiller A	Chiller B
Chiller type	Air source heat pump chiller (closed screw type)	Air source heat pump chiller (reciprocating type)
Rated refrigerating capacity	58.6kW	46.7kW
Rated electric power	23.7kW	17.1kW
Electric capacity of inverters	5.5kW×2EA and 7.5kW×2EA	7.5kW×2EA

Figure 1. Characteristics of Chillers Controlled by Inverters

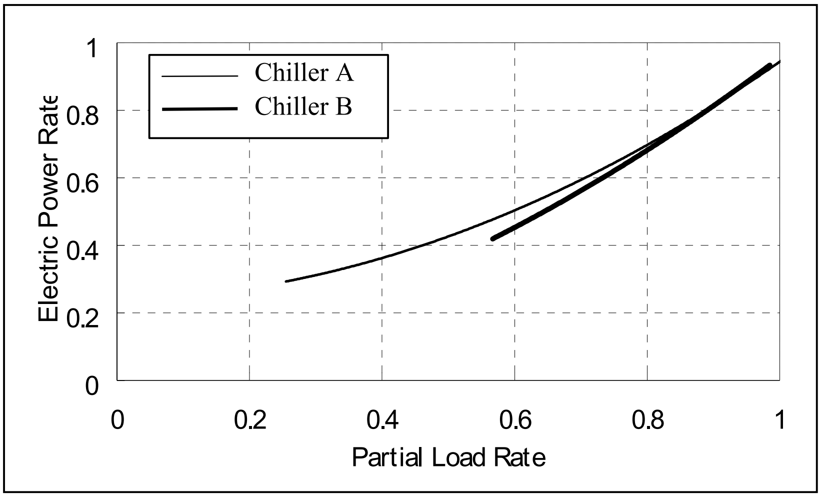


Figure 2 shows the efficiency of two chillers in partial loads. Here, chiller COP stands for the rate of the quantity of heat to the heat equivalent of the electric power of the chiller:

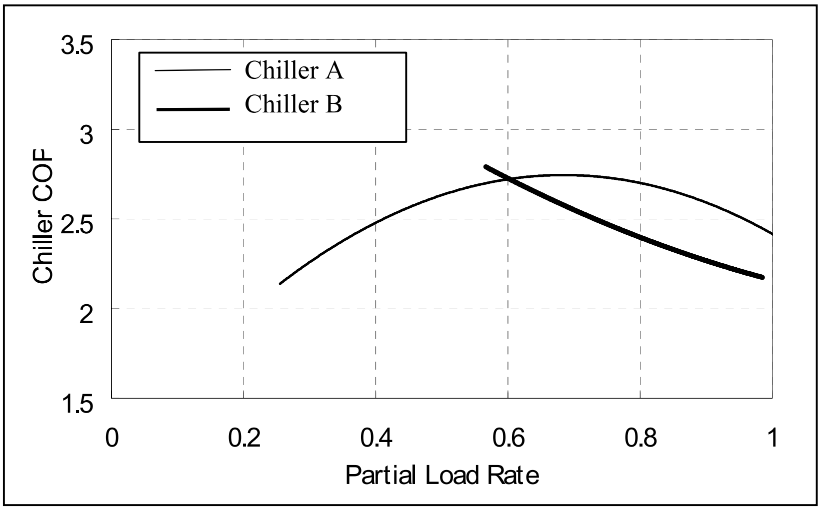
$$COP_c = \frac{Q_c}{E_c} \quad (1)$$

where COP_c, the chiller COP, Q_c, the quantity of heat produced by the chiller and E_c represents the heat equivalent of the electric power consumption of the chiller. The rate value of COP_c of the chiller A is about 2.4, but the value reaches the highest one, about 2.7, when the partial load is about 0.6. The rate value of COP_c of the chiller B is getting higher as the partial load becomes lower. In the ranges with on lines, the experiments are not conducted due to avoid mechanical trouble as mentioned before. In these experiments, there was no problem with the circulation of refrigerant. Conclusions of this chapter are noted below:

- Partial load operation by inverter can increase the efficiency of the chiller by 10-30 percent.
- The difference of efficiency is made by the difference of chillers.
- When partial load rate is above 0.3, the chiller can be operated normally.
- Although the operation hours of chillers become long, it is thought that energy consumption in chillers is reducible.

The chiller A is installed in the building air-conditioning system conducted the measurement, which is described in the next chapter.

Figure 2. Chiller COP in Partial Loads Operation



Measurement Survey

In the preceding section, it was shown clearly that chillers could be operated efficiently by inverter control as well as pumps or fans. In this chapter, a direct measurement survey to investigate the effect on site is presented. The period of the measurement survey was October 21-25, 2002, and it was carried out in an office building and system existing in Tokyo. Figure 3, the photograph of the building, Table 2, the outline of the building, Table 3,

Figure 3. Photograph of Building

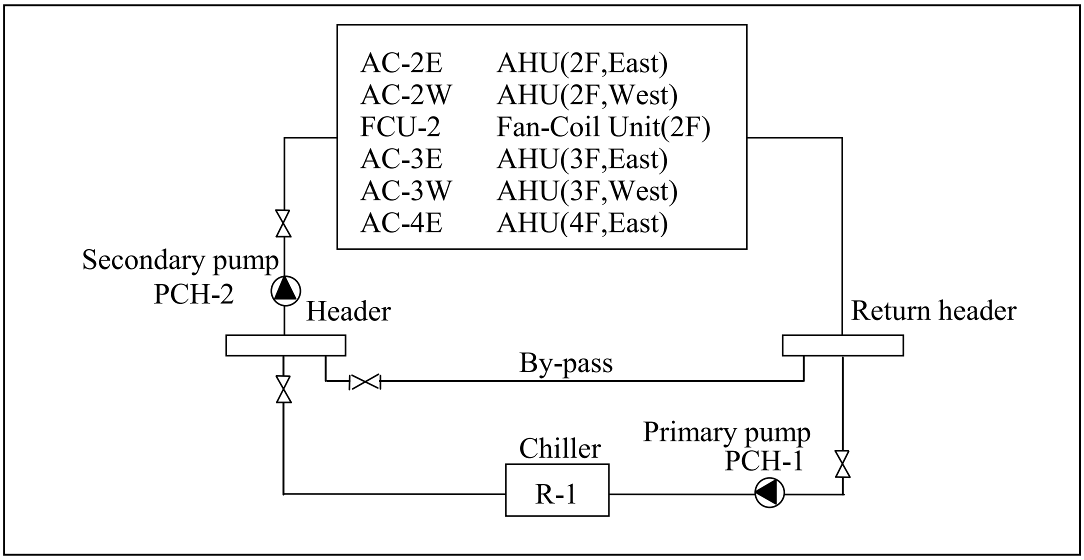
Table 2. Outline of Building

Location	Tokyo
Main use	Office
Structure and stories	Steel structure, 4 stories
Lot area	4353.7m^2
Architectural area	703.97m^2
Total floor area	1697.05m^2
Air-conditioned area	741.76m^2

Table 3. Specification of Equipments

Equipments / Symbol	Specification
Air handling unit(2F,East) / AC-2E Air handling unit(2F,West) / AC-2W	Cooling capacity : 33.72kW Rated electric power : 5.9kW
Fan-Coil Unit (2F) / FCU-2	Cooling capacity : 4.5kW Rated electric power : 0.4kW
Air handling unit(3F,East) / AC-3E Air handling unit(3F,West) / AC-3W	Cooling capacity : 31.39kW Rated electric power : 3.7kW
Air handling unit(4F,East) / AC-4E	Cooling capacity : 36.04kW Rated electric power : 5.2kW
Primary pump / PCH-1	Water flow rate : 7.2m^3/h Rated electric power : 1.5kW
Secondary pump / PCH-2	Water flow rate : 13.2m^3/h Rated electric power : 2.2kW

Figure 4. Schematic of Air-Conditioning System



The Specification of Equipments and Figure 4 shows the schematic of the air-conditioning system. The air-conditioning system consists of an air source heat pump chiller (the chiller A experimented), a primary pump, a secondary pump, five air-handling units, a fan-coil unit, etc. The chiller has four compressors in itself.

(1) Measurement Cases

Two cases were carried out in the measurement survey. The methods of the two cases (Case A and Case B) are shown in Table 4.

Table 4. Measurement Cases

Case	Chiller	Primary pump
A	Controlling the number of driving compressors by outlet water temperature	Full load operation
B	Controlling the number of driving compressors by outlet water temperature + Inverter control by the quantity of secondary water flow (range: 25-50Hz)	Inverter control for the quantity of secondary water flow (range: 30-50Hz)

Case A: operation with no inverters. Case A was carried out in October 21-22. In Case A, in the chiller, the number of driving compressors changes to four- two- zero with inlet water temperature (see Figure 5; For example, if inlet water temperature changes to 16 Celsius degrees (60.8 Fahrenheit degrees) with two compressors driving, driving number of compressors will become 4.). The primary pump passes constant quantity of water flow. If the outlet water temperature of the chiller is less than 4 Celsius degrees (39.2 Fahrenheit degrees), the chiller will stop to avoid freezing.

Case B: operation with inverters. Case B was carried out in October 23-25. In Case B, inverter control is introduced into the chiller and the primary pump. The frequency of the chiller and the primary pump is changed by the quantity of secondary water flow: their capability and electric power change with the frequency. As for the chiller, the frequency is 25Hz when the secondary water does not flow, and the frequency is 50Hz when it flows in the rated value, 12 m^3/h. On the primary pump, the frequency is 30Hz when the quantity of secondary water does not flow, and the frequency is 50Hz when it flows in the rated value, 12 m^3/h (Figure 6). If the outlet water temperature of the chiller is less than 4 Celsius degrees (39.2 Fahrenheit degrees), the chiller will stop to avoid freezing as the same with Case A.

Figure 5. Number of Driving Compressors

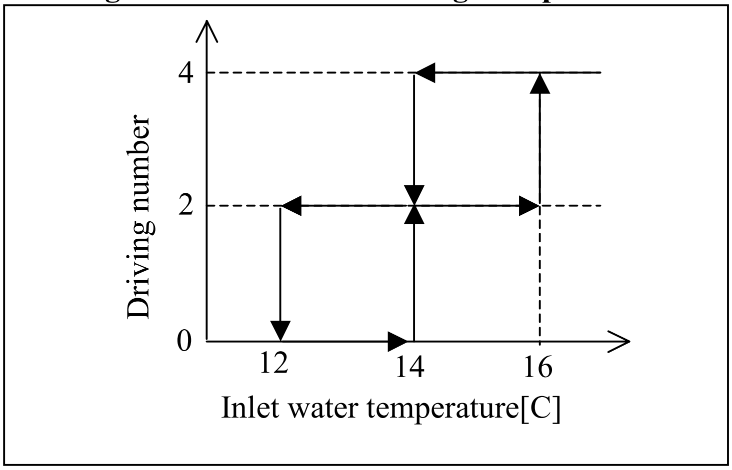
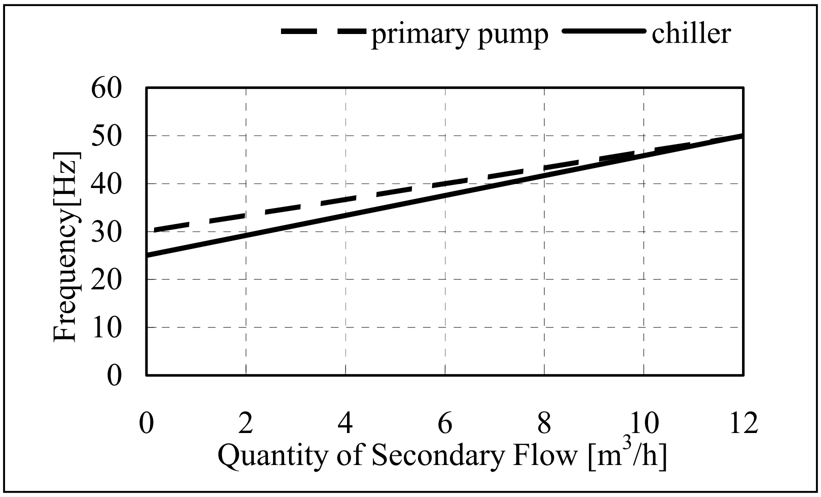


Figure 6. Relation between Secondary Water Flow and Frequency of Inverter Control



(2) Measurement Results

The measurement results are shown in Figure 7 and Figure 8. Since the operation was changed from 18:00 to 24:00 on the 22nd, it has been removed from the measurement data.

The outdoor temperature was low on the 24th and it did not much exceed 15 Celsius degrees (59 Fahrenheit degrees) in the daytime (Figure 7). Therefore, the chiller was hardly operated on the 24th (Figure 8). Since the building cooling load was also low on the other days, the number of driving compressors frequently became zero and the chiller stopped to avoid freezing when the inlet water temperature was less than 4 Celsius degrees (39.2 Fahrenheit degrees). The quantity of heat produced by the chiller changes with the inverter control in Case B. The quantity of primary water flow is sharply cut down in Case B. Table 5 shows the average value per day for each case. However, the data on the 24th was removed from the total. Here, the primary COP shown in Table 5 indicates the energy efficiency of the primary system including both the chiller and the primary pump:

$$COP_p = \frac{Q_c}{E_c + E_p} \quad (2)$$

where COP_p, primary COP, and E_p, heat equivalent of electric consumption of the primary pump. Case B is compared with Case A, the chiller COP is improved from 3.04 to 3.54, and the primary COP is improved from 2.06 to 2.98. Since the climate conditions are different between Case A and Case B, it can not be strictly compared, however the effect of chiller and primary pump controlled by inverters is very large. Compared with Case A, quantity of electric consumption in system is reduced by 6 percent in Case B. Because the rate of electric consumption in chiller and pumps to in fans is small on account of too low cooling load, it is hard to reflect energy-cutting in chiller and primary pump on the whole.

Figure 7. Outdoor Temperature and Humidity

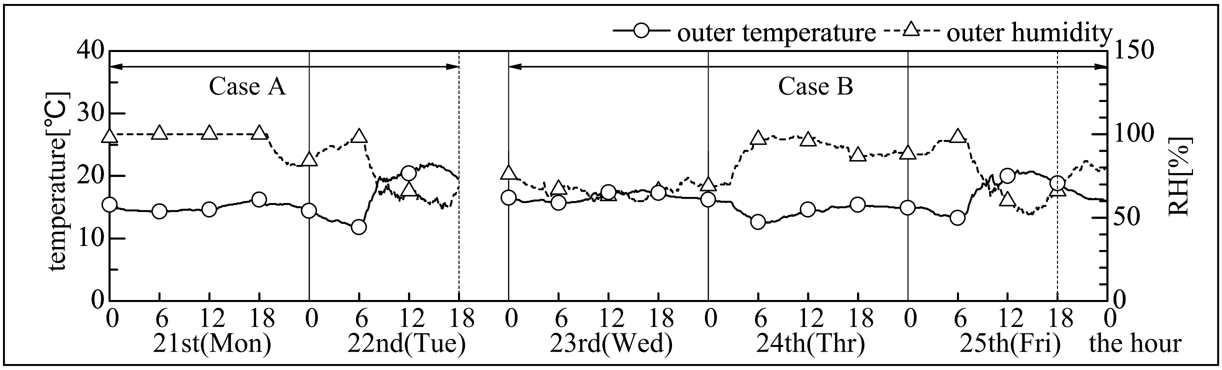


Figure 8. Actions of Chiller and Primary Pump

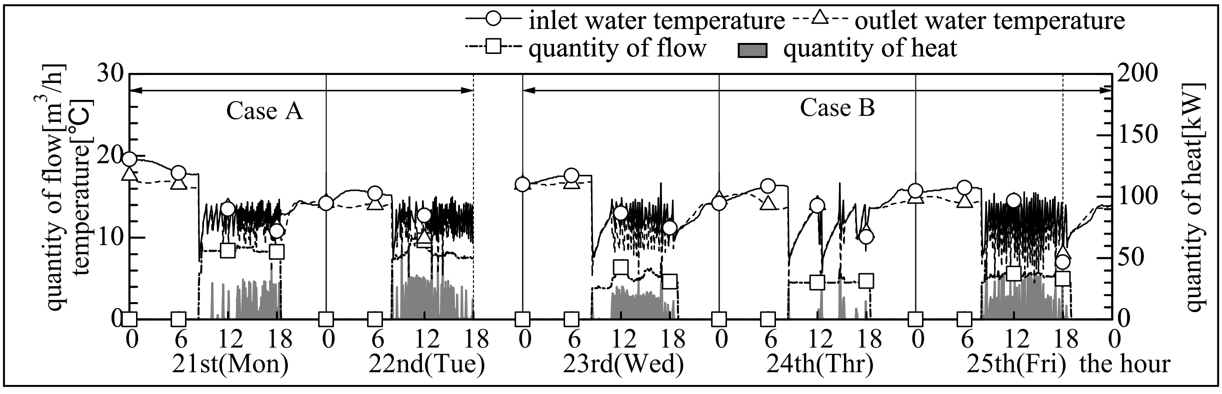


Table 5. Average Values per Day in Measurement Survey

	Case A	Case B
Quantity of heat removed by AHU (building cooling load)[kWh]	93.5	90.3
Quantity of heat produced by chiller[kWh]	116.3	107.9
Quantity of electric consumption in chiller[kWh]	38.2	30.5
Quantity of electric consumption in primary pump[kWh]	18.3	5.7
Total quantity of electric consumption in AHU[kWh]	117.1	125.5
Quantity of electric consumption in system[kWh]	181.8	170.4
Chiller COP	3.04	3.54
Primary COP	2.06	2.98

Simulation

A model-based simulation is conducted in the long term in order to confirm the effect of inverter control because the results mentioned in the preceding section are obtained from the measurement in the limited several days of mild-climate.

(1) Outline of Simulation Model

The simulation program used in this study is remodeled based on a Japanese representative simulation program, HASP (Heating and Air-conditioning Simulation Program). The conditions such as building and system design, operational strategies, etc. are basically matched with the measurement written in this paper. The calculation period is from April to November in the cooling term, and the time interval is one minute. The air-conditioning system is operated in 8am to 7pm, and not operated on Saturdays, Sundays and national holidays. The set point of room temperature is 24 Celsius degrees (75.2 Fahrenheit degrees) in April, May, October and November, and is 26 Celsius degrees (78.8 Fahrenheit degrees) in the other months. In the calculation, the characteristics of the chiller A in Figure 1 is used in the case of calculating on chiller controlled by inverter. If the outlet water temperature of chiller is less than 4 Celsius degrees (39.2 Fahrenheit degrees), the chiller will stop for at least 10 minutes to avoid freezing. The heat generation with operations of pumps and fans and the heat loss from with pipes and ducts are taken into consideration in the simulation.

(2) Simulation Cases

Three cases were carried out in the simulation. The difference between three cases is shown in Table 6. Case 1 is the same as Case A and Case 3 is the same as Case B in the measurement survey. And in Case 2 the inverters are installed only in the chillers.

Table 6. Simulation Cases

<table>
<tr><th>Case</th><th>Chiller</th><th>Primary pump</th></tr>
<tr><td>1</td><td>Controlling the number of driving compressors by outlet water temperature</td><td>Full load operation</td></tr>
<tr><td>2</td><td rowspan="2">Controlling the number of driving compressors by outlet water temperature
+
Inverter control for the quantity of secondary water flow (Figure9)</td><td>Full load operation</td></tr>
<tr><td>3</td><td>Inverter control for the quantity of secondary water flow (Figure9)</td></tr>
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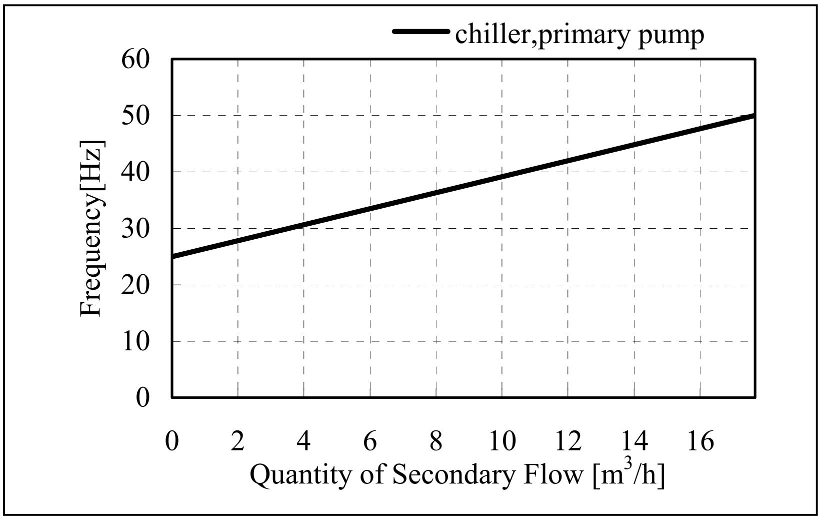
Figure 9. Relation Between the Secondary Flow and Frequency of Inverter Control



(3) Simulation Results

Actions of chiller and primary pump. Actions of the chiller and primary pump of each case are shown in Figure10. The chiller in Case 2 and Case 3 is clearly operated in a partial load in May. Compared with Case 1 and Case 2, the quantity of primary water flow is decreased drastically in Case 3 in May because there is much time that the chiller stops or is operated in a low partial load. The graphs of August show that the chiller can be also operated in a partial load in August.

Figure 10. Actions of Chiller and Primary Pump

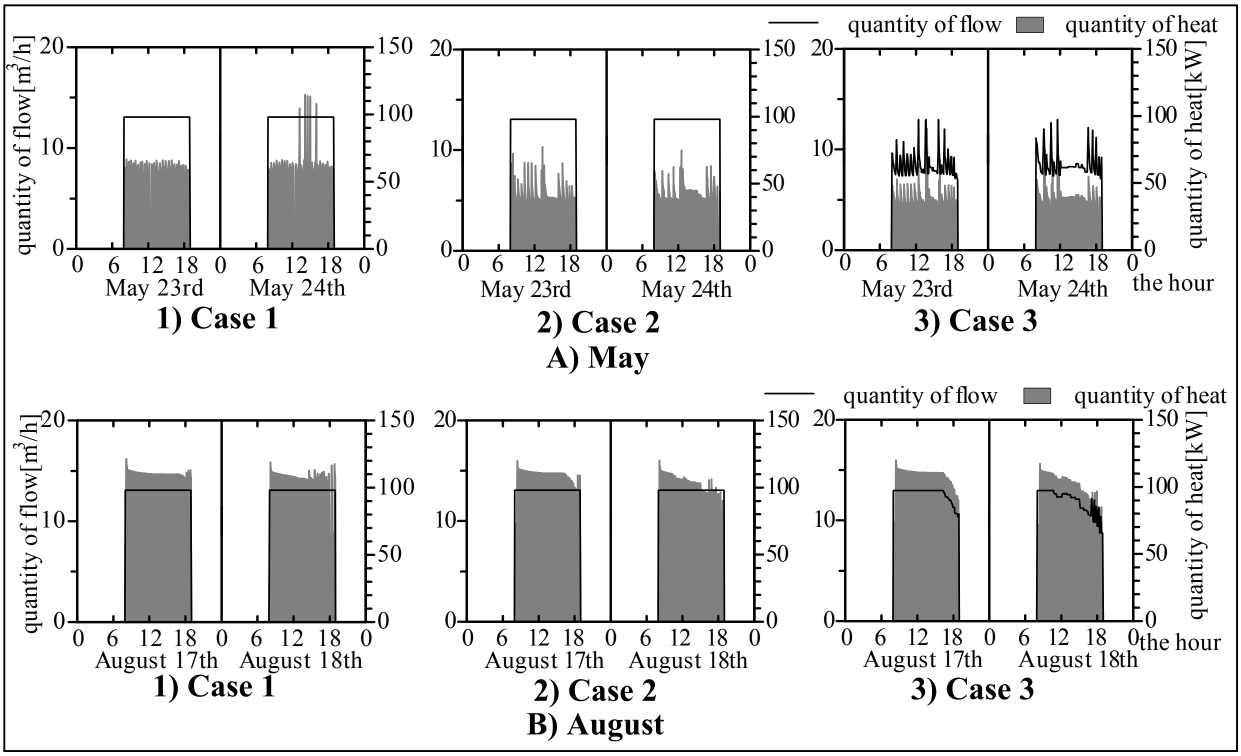
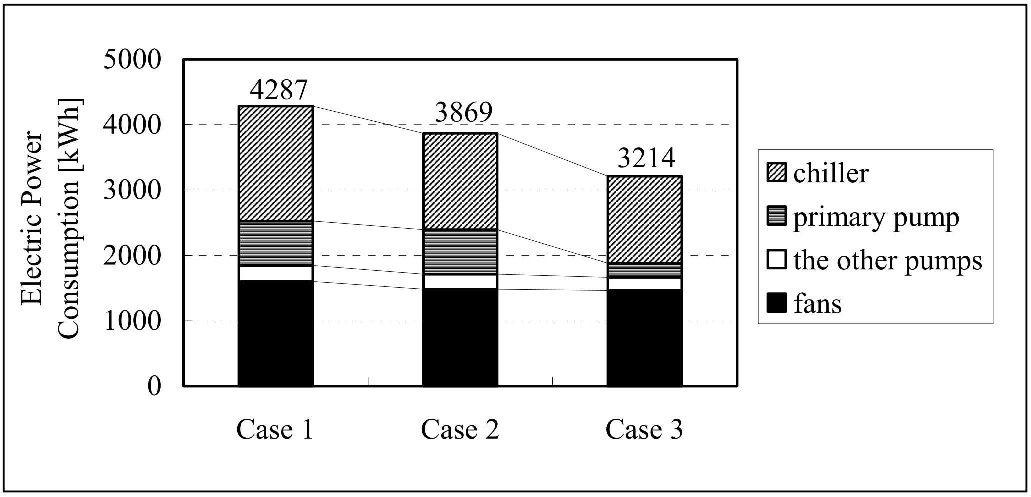


Figure 11. Integral Electric Power Consumption for Each Component in May



Electric power consumption. First, the integral electric power consumption for each component in May is shown in Figure 11. Case 2 introduced the chiller inverter control that cuts down the electric power consumption of the chiller to 83.9 percent and also cuts down the total electric power consumption of the system to 90.3 percent of Case 1. Case 3 introduced the chiller and the primary pump inverter control, and the electric power consumption of the chiller is cut down to 75.8 percent and that of the primary pump is cut down to 31.2 percent of Case 1. In Case 3, the electric power consumption of the primary pump is largely reduced because the waste of the primary water flow was excluded by the inverter control. Accordingly, the electric power consumption of the system of Case 3 is cut down to 75.0 percent of Case 1.

Next, the integral electric power consumption in August is shown in Figure 12. The results are similar with ones in May, and in Case 3 the electric power consumption of the system is cut down to about 87 percent of Case 1. Since in August, the term of the operation in a partial load is shorter than in May, the effect of the chiller inverter control is smaller than in May. However, the chiller inverter control is also an effective method in summer because the quantity of the electric power consumption is larger in August.

Figure 12. Integral Electric Power Consumption for Each Component in August

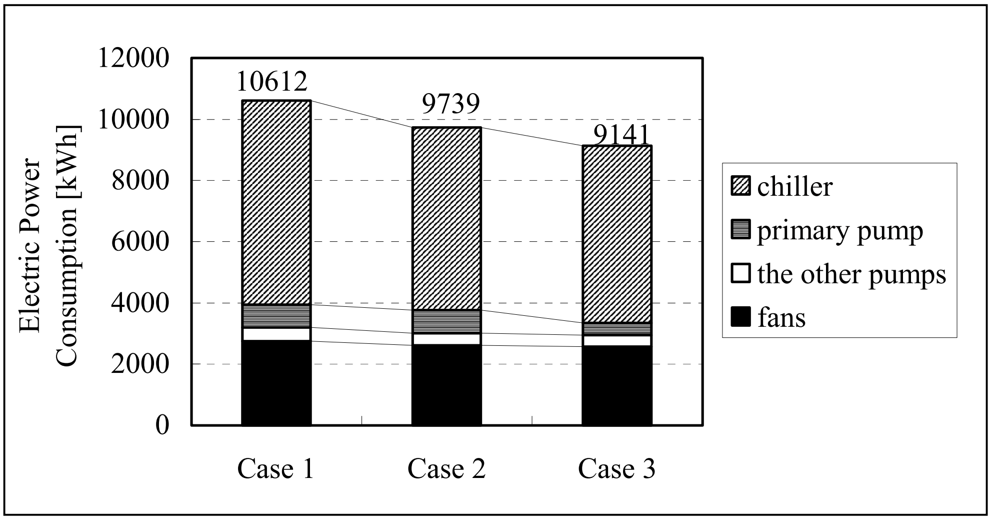
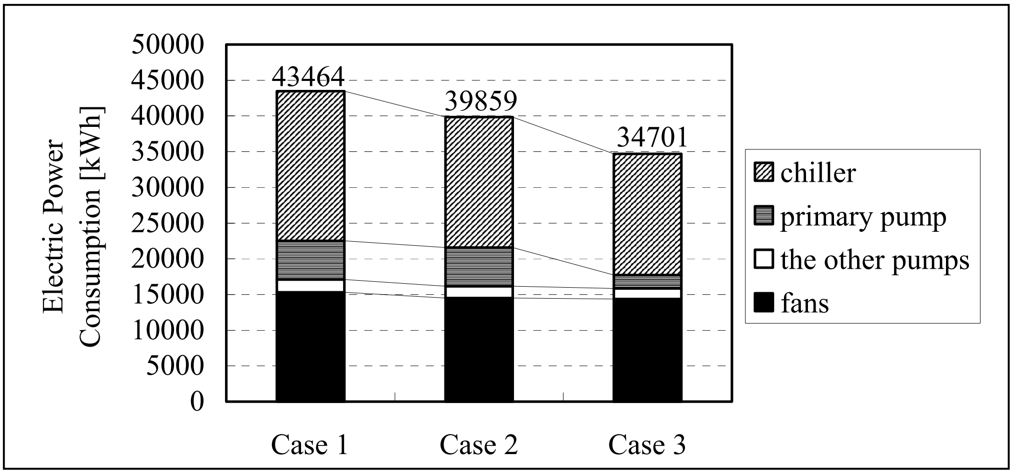


Figure 13. Integral Electric Power Consumption for Each Component in Calculation Period



Finally, the integral electric power consumption in the calculation period is shown in Figure 13. Case 2 can cut down the electric power consumption of the chiller about 87 percent and of the system about 91 percent compared with Case 1. In Case 3, the electric power consumption of the chiller is cut down to 81.1 percent, the one of the primary pump is cut down to 34.1 percent and the one of the system is cut down to 79.8 percent.

Comparing costs. Based on a table of electric power charges of TOKYO ELECTRIC POWER COMPANY, the running cost for April to November is 637,000 yen ($5,444; when one dollar is 117 yen) in Case 1, 583,000 yen ($4,982) in Case2 and 509,000 yen ($4,350) in Case 3. Case 2 can reduce the running cost by 9 percent and Case 3 can reduce it by 20 percent. On the other hand, four inverters of the chiller are taken about 1,800,000 yen ($15,384) in this system; the chiller is composed of four compressors and carried out for measurement survey. Therefore, if the inverter control is used for only cooling, recouping the initial costs takes 33.3 years in Case 2 and takes 14.1 years in Case 3.

Conclusion

In this paper, the effectiveness of controlling chillers by inverters was clarified by direct measurement and a model-based simulation analysis. In the measurement, the efficiency in connection with quantity-of-heat production could be raised greatly by installing inverter control to the chiller and primary pump. In the simulation, the energy-saving effect of the chiller inverter control is about 8 percent from April to November though the operation hours of the chiller and primary pump are longer and energy consumption of the primary pump is larger than not using chiller inverter control. Furthermore when the primary pump inverter control is used together, the energy-saving effect is about 20 percent because energy consumption of primary pump is reduced. As for the running cost, using chiller inverter control can reduce it by 9 percent and using primary pump inverter control together can reduce it by 20 percent.

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