ENERGY SAVING EFFECT OF HIGH-EFFICIENCY TECHNOLOGIES IN INDUSTRIAL COOLING PLANT SYSTEM

Tatsuya FUKUZAKI[1], Yasunori AKASHI[2], Masato MIYATA[3] and Shohei SUEYOSHI[1]

1 Graduate School of Human-Environment Studies, Kyushu University,
Fukuoka 812-8581, Japan
2 Faculty of Human-Environment Studies, Kyushu University
3 Building Research Institute

ABSTRACT

This paper is concerned with energy saving effect of high-efficiency technologies in an industrial cooling plant system. In this paper, the cooling plant system introduced into a semiconductor facility is targeted, and the energy saving effect is studied by simulations. The system has turbo chillers with variable speed drive, heat recovery screw chillers with variable speed drive, assembled cooling towers, and also new control strategies for energy saving. The results of the simulations show that using these high-efficiency technologies can cut down the annual electric power consumption by about 30%.

INTRODUCTION

The industrial sector consumes about half of the energy used in Japan. In recent years, energy consumption and CO2 emission in semiconductor facilities producing integrated circuits, liquid crystal display, etc. is gradually increasing in proportion to increase of the amount of products. In these facilities, the cooling loads for air conditioning occur through a year because the internal heat generation is very large compared to one in an office building. It is therefore important to largely reduce the energy consumed in the cooling plant system. In the industrial cooling plant system targeted in this paper, various advanced technologies for saving energy are being introduced. This paper focuses on the industrial cooling plant system that uses high-efficiency technologies, and quantifies the energy saving effect by simulations.

OUTLINE OF COOLING PLANT SYSTEM

Figure 1 shows a schematic diagram and Table 1 shows the design parameters of the cooling plant system. The system mainly consists of turbo chillers with variable speed drive (turbo-chillers), heat recovery screw chillers with variable speed drive (screw-chillers), assembled cooling towers and pumps for cooling water and chilled water. The system operates 24 hours a day, 365 days a year.

There are seven turbo-chillers in the system, which are two turbo-chillers for 5°C chilled water (R5-1 and R5-2, low temperature system) and five ones for 9°C chilled water (R9-1 to R9-5, high temperature system) because the production area needs 5°C chilled water and 9°C chilled water respectively. Figure 2 shows the performance curve of the turbo-chiller for 9°C chilled water. Conventional turbo chiller reaches highest efficiency as the partial load rate approaches 100%, but the COP (Co-efficient of Performance) of these turbo-chillers including ones for 5°C chilled water becomes higher at the time of the operating partial load. The maximum COP of the turbo-chiller for 9°C chilled water reaches close to 22.0 when the cooling water inlet temperature is 13°C and the partial load

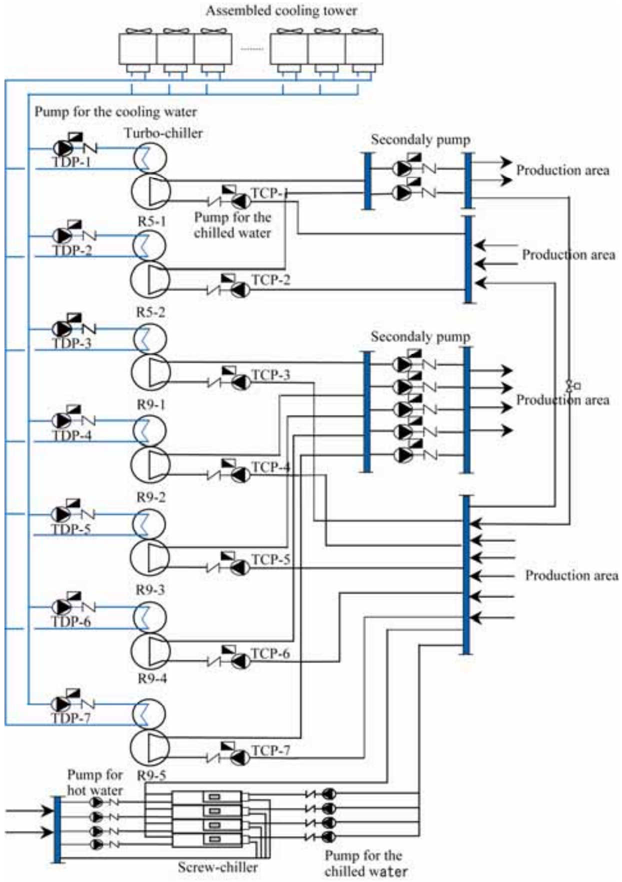

Figure 1 Schematic diagram of the cooling plant system

Table 1 Design parameters of the cooling plant system

Equipment	Design parameters	Num
Turbo-chiller (the low temperature system, R5-1, 2)	Cooling capacity: 2109.8 kW (600 USTR) Chilled water flow rate: 296.4 m^3/h (11 - 5°C) Cooling water flow rate: 432.0 m^3/h (32 - 37°C) Electric power consumption: 412 kW	2
Turbo-chiller (the high temperature system, R9-1, 2, 3,4,5)	Cooling capacity: 5450.0 kW (1550 USTR) Chilled water flow rate: 588.0 m^3/h (17 - 9°C) Cooling water flow rate: 1092.0 m^3/h (32 - 37°C) Electric power consumption: 869 kW	5
Screw-chiller(HSR-1, 2, 3, 4)	Cooling capacity: 457.1 kW (130 USTR) Heating capacity: 563.0 kW (160 USRT) Chilled water flow rate: 49.2 m^3/h (17 - 37°C) Quantity of warm water flow: 48.6 m^3/h (32 - 37°C) Electric power consumption: 112 kW	4
assembled cooling tower (ten cells)	Cooling capacity: 8871.6 kW (2523 USTR) Cooling water flow rate: 1525.8 m^3/h (32 - 37°C) Air volume: 1014000 m^3/h Electric power consumption: 7.5 × 10 kW	3
assembled cooling tower (nine cells)	Cooling capacity: 8913.8 kW (2535 USTR) Cooling water flow rate: 1533.1 m^3/h (32 - 37°C) Air volume: 912600 m^3/h Electric power consumption: 7.5 × 9 kW	1
Pump for cooling water (controlled by inverter, R5-1,2)	Cooling water flow rate: 450.0 m^3/h Electric power consumption: 45.0 kW	2
Pump for cooling water (controlled by inverter, R9-1,2,3,4,5)	Cooling water flow rate: 1140.0 m^3/h Electric power consumption: 110.0 kW	5
Pump for chilled water (controlled by inverter, R5-1,2)	Chilled water flow rate: 336.0 m^3/h Electric power consumption: 30.0 kW	2
Pump for chilled water (controlled by inverter, R9-1,2,3,4,5)	Chilled water flow rate: 690.0 m^3/h Electric power consumption: 55.0 kW	5
Pump for chilled water (HSR-1,2,3,4)	Chilled water flow rate: 49.2 m^3/h Electric power consumption: 5.0 kW	4
Pump for warm water (HSR-1,2,3,4)	Chilled water flow rate: 48.6 m^3/h Electric power consumption: 5.0 kW	4

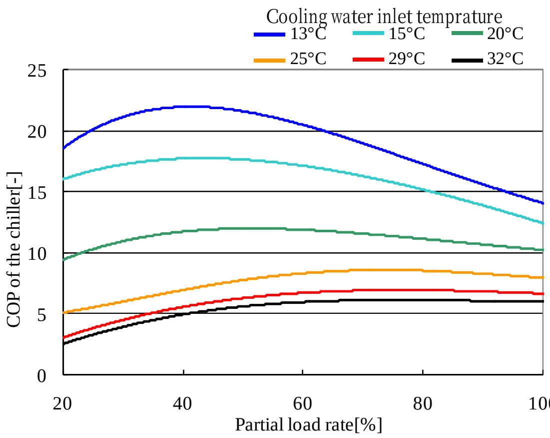

Figure 2 Performance curve of the turbo-chiller for 9°C

rate is about 40% (see Figure 2). The partial load rate when the turbo-chiller indicates the maximum COP changes according to the cooling water inlet temperature.

There are four screw-chillers with heat recovery in the system, which generate 9°C chilled water. The number of the screw-chillers in operation is controlled by the heating loads which the screw-chillers deal with. This study targets only cooling plant system, but actually there is a heating system and the heat is mainly produced by boilers (the heating system is not illustrated in Figure 1). The return chilled water and the hot water (about 30°C) from the production area flow into the screw-chiller, and the refrigerant takes the heat from the hot water at the condenser and moves it into the chilled water at the evaporator, so the screw-chiller reduces the loads of the chiller itself and the boiler. The inverter output of the screw-chiller is controlled by the hot water outlet temperature, and the chilled water and the hot water flow rates of the screw-chiller are constant.

The assembled cooling tower is different from conventional cooling tower. The assembled cooling tower is made by connecting each cooling tower with pipes. The lower limit cooling water temperature generated by the assembled cooling tower is controlled by open air conditions for chiller's mechanical safety in winter season, but it originally aims to cool the cooling water to near the wet-bulb temperature of open air. The fan speed in the cooling tower is controlled by inverters, as are the pumps for chilled water and cooling water.

SYSTEM SIMULATION MODEL

Figure 3 shows the system simulation flow. We could not obtain the detail information about indoor air conditioning

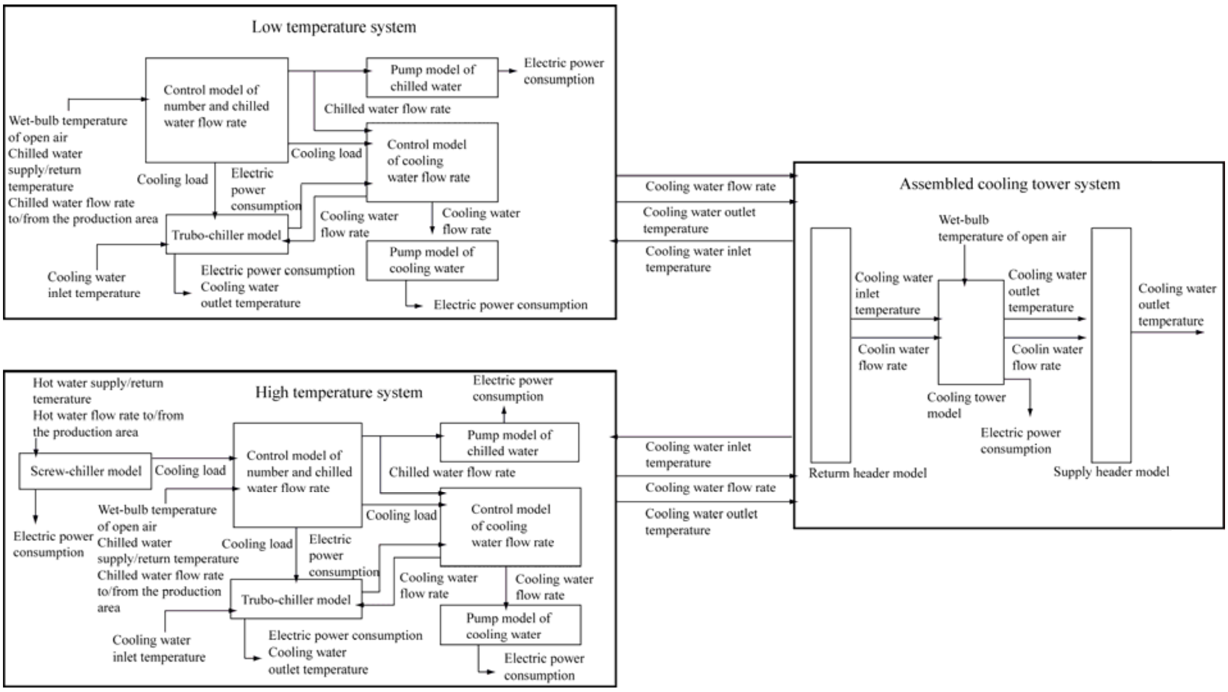

Figure 3 System simulation flow

(secondary system) of the production area due to the secrets, so we target only the cooling plant system excluding the secondary pumps. In the system simulation, the measured data of the chilled/hot water supply temperature, the chilled/hot water return temperature and the chilled/hot water flow rate to/from the production area, which are strictly controlled, can be used as the inputs. The measured open air temperature and humidity are also input in the simulation. The system simulation flow is as follows:

1) The partial load rate of the screw-chiller can be calculated because the number of the operating screw-chillers is set by the actual control logic and the total heating load calculated using the measured hot water supply/return temperature and the flow rate to/from the production area. The partial load rate is actually the heating side one of the screw-chiller, but the measured data show that the value is almost the same with the cooling side one. Therefore, the electric power consumption of per screw-chiller can be calculated by the partial load rate and the measured hot water outlet temperature using the performance curve given from manufacturer.
2) The total cooling load of the turbo-chiller for 5°C chilled water (low temperature system) is calculated using the measured chilled water supply/return temperature and the flow rate to/from the production area. The total cooling load of the turbo-chiller for 9°C chilled water (high temperature system) can be calculated in the similar way with the low temperature system, but it is necessary to subtract the cooling load of the screw-chillers from it. The partial load rate of the turbo-chiller for 5°C chilled water or 9°C chilled water can be also calculated respectively using the actual control logic and the total cooling load as the same way with the screw-chiller, and the electric power consumption of per turbo-chiller is calculated by the partial load and the cooling water inlet temperature using the performance curve given from manufacturer. The cooling water inlet temperature is assumed to be the same with the cooling water outlet temperature of the assembled cooling towers calculated at the previous time step. If more than one turbo/screw-chiller moves, the cooling loads are distributed evenly to each turbo/screw-chiller. In the simulation, the changes in efficiency of the chiller according to the changes of the chilled water flow rate are not considered because of the small influences.
3) The number of the operating chilled water pumps is the same with the number of the operating screw-chillers and turbo-chillers. The chilled water flow rate of the screw-chiller is constant and the one of the turbo-chiller is variable. The chilled water flow rate of per turbo-chiller is calculated by the number of the operating turbo-chillers and the measured chilled water flow rate. On the other hand, the cooling load at the condenser is assumed to be sum of the thermal equivalent of the chiller electric power consumption and the cooling load at the evaporator, and the cooling water flow rate of the turbo-chiller is

calculated by the ratio of the cooling load at the condenser in the rated one. Finally, the electric power consumption of the pumps can be calculated using those water flow rates.

4) The cooling water outlet temperature of the assembled cooling tower is assumed to be the same with the set value decided by the conditions of open air. The cooling water inlet temperature of the assembled cooling tower is calculated by the cooling water outlet temperature, the cooling load at the condenser and the cooling water flow rate (the cooling load and the cooling water flow rate are mentioned above), and the fan air flow rate in the assembled cooling tower is decided so that the cooling load in the assembled cooling tower can be satisfied with the cooling load at the condenser of the turbo-chiller. Based on the fan air flow rate, the electric power consumption is calculated by the same model of the pumps. The cooling water outlet temperature in the assembled cooling tower becomes the cooling water inlet temperature in the turbo-chiller of the next calculation step.

SYSTEM MODELING AND ACCURACY VERIFICATION

Modeling the turbo-chiller

The models of the turbo-chillers are shown below. The inputs are the cooling load, the cooling water inlet temperature of the chiller and cooling water flow rate, and outputs are the electric power consumption of the chiller and the cooling water outlet temperature of the chiller. The COP of the chiller is calculated by using formulas1 and 2. Using this value and formulas 3 and 4, the electric power consumption and the cooling water outlet temperature of the chiller is calculated. The parameter '*a*' is found from the performance curve and it is different depending on the chilled water outlet temperature and cooling water inlet temperature.

$$r_q = \frac{Q_c}{Q_{cr}} \tag{1}$$

$$\eta_{COP} = f_i(r_q) = k_{T_{wic}} \sum_{n=0}^{6} a_{n,i,T_{wic}} {r_q}^n \tag{2}$$

$$E_r = \frac{Q_c}{\eta_{COP}} \tag{3}$$

$$T_{woc} = T_{wic} + \frac{Q_c + E_r}{V_{wc} \cdot \gamma \cdot \lambda} \tag{4}$$

η_{COP} : COP of the chiller[-], k : Compensating rate for each temperature [-], a_n : Parameter [-], r_q : Partial load rate[-], E_r : Chiller electric power consumption [kW], Q_c : Cooling load[kW], Q_{cr} : Rating cooling capacity[kW], T_{woc} : Cooling water outlet temperature [°C], T_{wic} : Cooling water inlet temperature [°C], V_{wc} : Cooling water flow rate [m^3/h], γ : Specific gravity of water [kg/m^3], λ : Specific heat of water [kJ/kg · K]

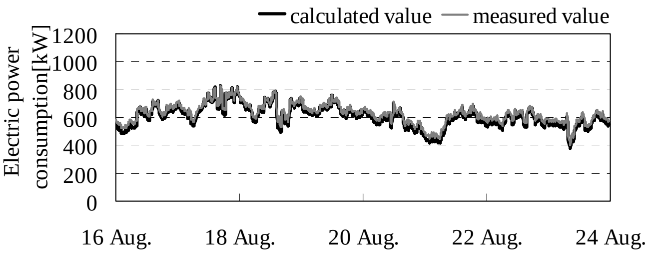

Figure 4 Result of the accuracy verification (Turbo-chiller)

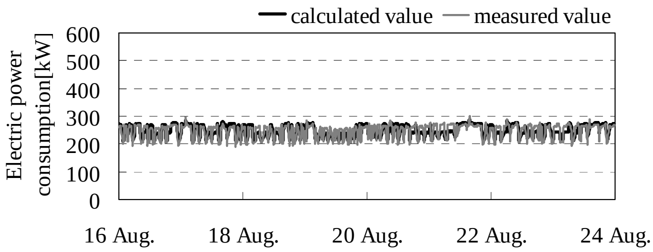

Figure 5 Result of the accuracy verification (Screw-chiller)

To verify the accuracy of the model, we compare the calculated values and the measured values taken at 15 minutes intervals from the 16th - 23rd August 2007. The measuring error of measurement equipment is small because the subject of this paper is an industrial building and the system is managed accurately. Figure 4 shows the results of comparing the calculated values with the measured values. The average error in the electric power consumption of the chiller is about 4%, and the Root Mean Squared Error (RMSE) is about 5%.

Modeling the screw-chiller

The models of the screw-chillers are shown below. The inputs are the heating load and the hot water outlet temperature, and the outputs are the electric power consumption of the chiller and cooling load. The partial load rate is calculated by using the formula 5. It is assumed that the cooling side partial load rate is the same as the heating side one, and using the formulas 6 and 7, the cooling side COP of the chiller and cooling load are calculated. Using these values and formula 8, the electric power consumption is calculated. The parameter '*b*' is found from the performance curve and it is different depending on the hot water outlet temperature.

$$r_{qs} = \frac{Q_h}{Q_{hrs}} \tag{5}$$

$$\eta_{COPs} = f(r_{qs}) = l_{T_{woh}} \sum_{n=0}^{3} b_{n,T_{woh}} {r_{qs}}^n \tag{6}$$

$$Q_{cs} = r_{qs} \cdot Q_{crs} \tag{7}$$

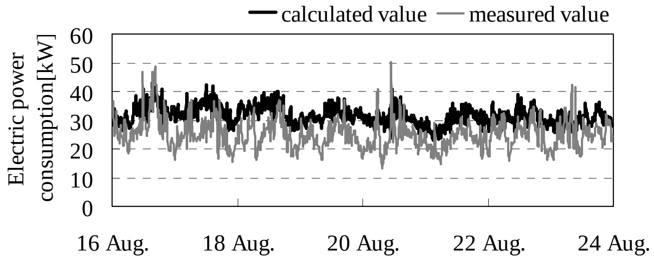

Figure 6 Result of the accuracy verification (Assembled cooling tower)

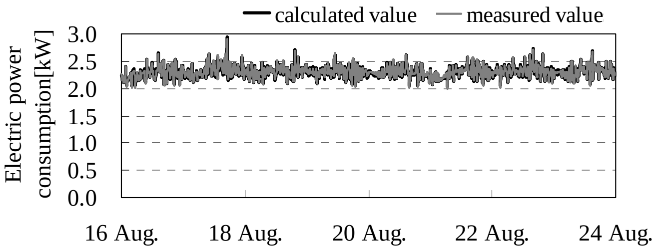

Figure 7 Result of the accuracy verification (Pump for chiller chilled-water)

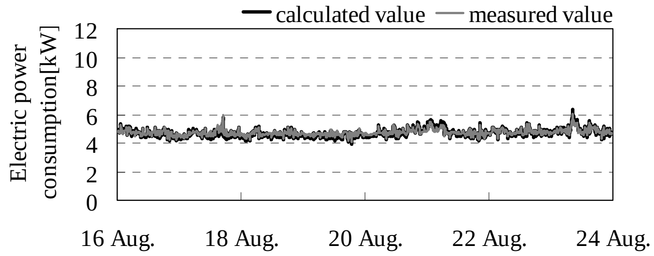

Figure 8 Result of the accuracy verification (Pump for cooling-water)

$$E_s = \frac{Q_{cs}}{\eta_{COPs}} \tag{8}$$

r_s : Partial load rate[-], Q_h : Heating load[kW], Q_{hrs} : Rating heating capacity[kW], η_{COPs} : COP of the chiller[-], l : Compensating rate for each hot water outlet temperature [-], b_n : Parameter [-], T_{woh} : Hot water outlet temperature [°C], Q_{cs} : Cooling load [kW], Q_{crs} : Rating cooling capacity[kW], E_s : Chiller electric power consumption[kW]

Figure 5 shows the result of accuracy verification. The average error in the electric power consumption of the screw-chiller is about 1%, and RMSE is about 6%.

Modeling the assembled cooling tower

The models of the assembled cooling towers are shown below. The inputs are the wet-bulb temperature of open air, the cooling water inlet temperature, cooling water flow rate, and the set value of the cooling water outlet temperature. Outputs are the electric power consumption of the fan and the cooling water outlet temperature. The fan air flow rate is calculated by using the formulas 9 and 10. Using this value and the formula 11, the electric power consumption of the fan is calculated. The parameter '*c*' is found from the actual measurement value.

$$dQ_{ct} = K_{ct}(h_{sa} - h_a)A_{ct}dZ = K_{ct}(h_{sa} - h_a)dV_{ct} \tag{5}$$

$$dQ_{ct} = g_{ct}dh = -c_w w_{ct} d\theta_{ct,w} \tag{6}$$

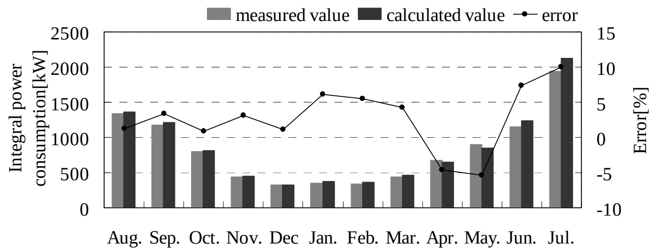

Figure 9 Result of the accuracy verification of the system

$$E_{ct} = \sum_{n=1}^{5} c_n g_{ct}{}^n \tag{7}$$

Q_c : Cooling production [kJ], h_{sa} : Enthalpy of saturated air [kJ/kg], h_a : Enthalpy of cooling tower air [kJ/kg], dZ : Height [m], g_{ct} : Design air mass flow rate [kg/s], c_w : Specific heat of water [kJ/kg・s], w_{ct} : Cooling water flow rate [kg/s], K_{ct} : Unit conductance [kW/ m^2・dh], A_{ct} : Area [m^2], V_{ct} : Volume of cooling tower [m^3], $\theta_{ct,w}$: Temperature of cooling water[°C], h : Enthalpy [kJ/kg], E_{ct} : Fan electric power consumption [kW], c_n : Parameter [-]

Figure 6 shows the results of the accuracy verification. The average error in the electric power consumption of the fan is about 26%, and RMSE is about 32%. The calculated value tends to reach a value that is larger than the actual measurement value.

Modeling the pump

The models of the pumps for chilled water and cooling water are shown below. The input for the pump is the chilled water flow rate or the cooling water flow rate, and the output is the electric power consumption of the pump. The rotational speed is calculated from the formula 16. Using this value and the formulas 12 – 15, the efficiency and the pressure head are calculated. The electric power consumption of the pump is calculated from the formula 17. The parameter '*ach*' and '*aη*' are found from the performance curve and the parameter'*d*' is found from the actual measurement value. The each parameter is different depending on the types of the pump.

$$C_p = k_{ch}(a_{ch,0} + a_{ch,1}C_p + a_{ch,2}C_p{}^2 + a_{ch,3}C_p{}^3 + a_{ch,4}C_p{}^4) \tag{12}$$

$$\eta_p = k_\eta(a_{\eta,0} + a_{\eta,1}C_p + a_{\eta,2}C_p{}^2 + a_{\eta,3}C_p{}^3 + a_{\eta,4}C_p{}^4) \tag{13}$$

$$C_p = \frac{m_p}{\rho_a r_p D^3} \tag{14}$$

$$C_h = \frac{1000\ p_p}{\rho_a r_p{}^2 D^2} \tag{15}$$

$$r_p = \sum_{n=0}^{2} d_n m_p^n \tag{16}$$

$$E_p = \frac{m_p P_f}{\eta_p \rho_a} \tag{17}$$

Table 2 List of simulation cases

	Equipment				Control			
	Chiller		Cooling tower		Control of the chilled water flow rate in the chiller		Lower limit value of the cooling water outlet temperature	
	Turbo-chiller	Constant turbo-chiller	Assembled cooling	Individual cooling tower	Variable	Constant	13°C	24°C
Case 0	-	○	-	○	-	○	-	○
Case A-1	-	○	○	-	-	○	-	○
Case A-2	○	-	-	○	-	○	-	○
Case A-3	○	-	○	-	-	○	-	○
Case B-1	○	-	○	-	○	-	-	○
Case B-2	○	-	○	-	-	○	○	-
Case B-3	○	-	○	-	○	-	○	-

Table 3 Design parameter of the individual cooling tower

Equipment	Design parameters
Cooling tower (low temperature system)	Cooling capacity: 2717 kW Cooling water flow rate: 468 m^3/h Air volume: 242000 m^3/h Electric power consumption: 5.5 kW
Cooling tower (high temperature system)	Cooling capacity: 6793 kW Cooling water flow rate: 1170 m^3/h Air volume: 625000 m^3/h Electric power consumption: 15 kW

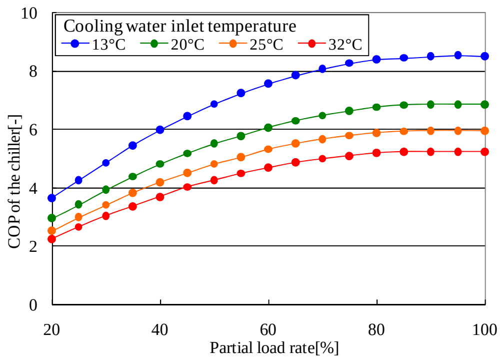

Figure 10 Performance curve for constant turbo-chiller for 9°C

C_h : Dimensionless pressure head[-], C_p : Dimensionless flow rate[-], $a_{ch,0}$,..., $a_{ch,4}$: Fitted coefficients for the equation of C_h-C_p[-], $a_{\eta,0}$,..., $a_{\eta,4}$: Fitted coefficients for the equation of η-C_p[-], k_{ch} : Compensating rate for a_{ch} [-], k_η : Compensating rate for a_η [-], η_p : Efficiency[-], m_p : Mass flow rate[kg/s], ρ_a : Density [kg/m^3], r_p : Rotational speed[1/s], D : Diameter[m], p_p : Pressure head [kPa], d_n : Parameter[-]

Figures 7 and 8 show the results of accuracy verification. The average error in electric power consumption of the pump for chilled water is about 1%, and the RMSE is about 3%. The average error in the electric power consumption of the pump for cooling water is about 0.7%, and RMSE is about 3%.

Accuracy verification of the system simulation model

We constructed a system simulation model by combining the individual equipment models. The accuracy of the system simulation model is verified by comparing calculated values with actual measurement values taken from August 2007 to July 2008. Figure 9 shows the results of comparison of the monthly power consumption. The measured annual power consumption is 9869 MWh and the calculated one is 10207 MWh, so the error is about 3.4%. Therefore, this system simulation model can be deemed to have enough accuracy for verifying the performance of the cooling plant system.

ENERGY SAVING EFECT OF HIGH-EFFICIENCY TECHNOLOGIES

Outline of the case studies

Case studies on energy saving effect of high-efficiency technologies have been performed by simulation programs which we developed as mentioned above. Table 2 shows the simulation cases. Case 0 is the conventional system which consists of turbo-chillers with constant speed drive (constant turbo-chillers) and individual cooling towers. In Case 0, the performance curve for the constant turbo-chiller and the design parameters of the individual cooling tower as showing in Figure 10 and Table 3 are used. The chilled water flow rate is constant in the rated value and the lower limit cooling water outlet temperature of the individual cooling tower is set to 24°C. Case A series is for case studies on the high-efficiency equipment, and Case B series is for case studies on the high-efficiency controls. Case A-1 replaces only the individual cooling towers in Case 0 with the assembled cooling tower. Case A-2 replaces only the constant turbo-chillers with the turbo-chillers in Case 0 with variable speed drive. Case A-3 replaces both of them. On the other hand, CaseB-1 replaces the constant chilled water flow rate in the chiller in Case A-3 with variable one. Case B-2 replaces the lower limit cooling water outlet temperature 24°C of the assembled cooling towers in Case A-3 with 13°C. Case B-3 replaces both of them. Therefore, in Case B-3, all high-efficiency technologies we consider in the simulation are included.

The results of the case studies

1) Energy saving effect of the assembled cooling tower (see Figures 11, 12, 13 and 16)

Energy saving effect of the assembled cooling tower is quantified by comparing the energy consumption of Case 0 with that of Case A-1. The annual electric power consumption

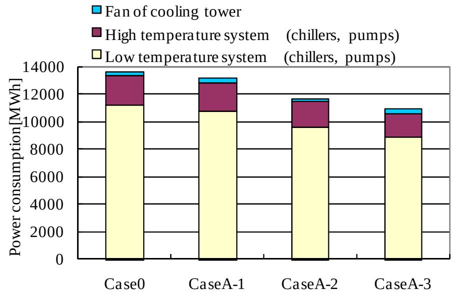

Figure 11 Annual power consumption

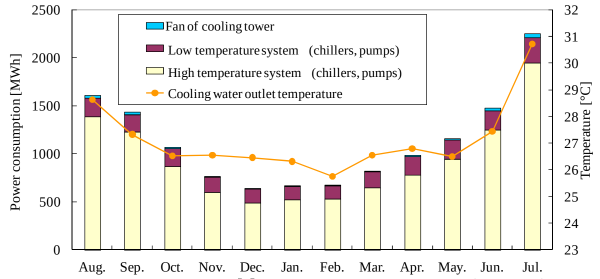

Figure 12 Monthly power consumption (Case 0)

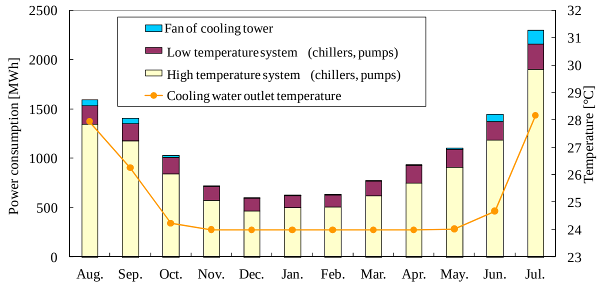

Figure 13 Monthly power consumption (Case A-1)

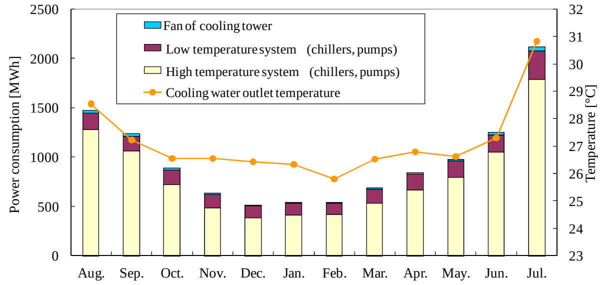

Figure 14 Monthly power consumption (Case A-2)

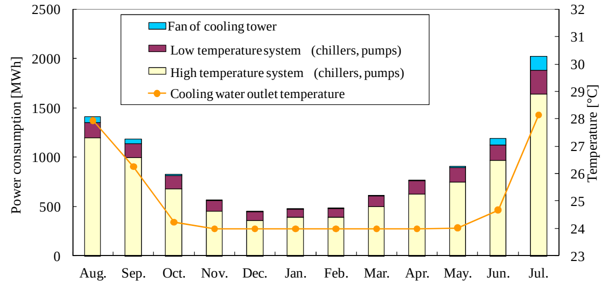

Figure 15 Monthly power consumption (Case A-3)

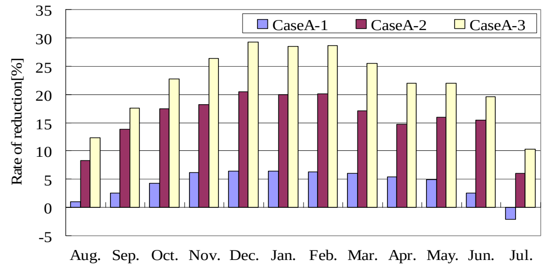

Figure 16 Rate of reduction of power consumption

of Case 0 is about 13,600 MWh and that of Case A-1 is 13,200 MWh - a reduction in electric power consumption of about 400 MWh. The monthly average cooling water outlet temperature of cooling tower in Case A-1 is lower than that in Case 0 from 2°C to 4°C. The monthly electric power consumption except for July in the whole system is reduced from 2% to 6% because the electric power consumption of the turbo-chillers is reduced by dropping the cooling water inlet temperature. In July, the 2.1% electric power consumption increases over the one of Case 0 because of the large increase of the power consumption of the assembled cooling tower.

(2) Energy saving effect of the turbo-chillers with variable speed drive (see Figures 11, 12, 14 and 16)

We examined the energy saving effect of the turbo-chillers with variable speed drive by comparing Case 0 with Case A-2. The annual electric power consumption of Case A-2 is about 11,700MWh - a reduction in electric power consumption of 1,900MWh (14%). The cooling water outlet temperature of the cooling tower is the same in Case 0 and Case A-2, however, in winter the electric power consumption can be reduced by about 20% because the turbo-chillers with variable speed drive shows a high COP in winter in which the cooling water inlet temperature of the chiller becomes low.

(3) Energy saving effect of the high-efficiency equipment (see Figures 11, 12, 14 and 16)

We examined the energy saving effect of the assembled cooling towers and the turbo-chillers with variable speed drive by comparing Case 0 with Case A-3. The annual electric power consumption of Case A-3 is 10,900 MWh - a reduction in electric power consumption of 2,700 MWh (20%). Case A-3 shows a high reduction rate similar to Case A-2 in winter because Case A-3 has the turbo-chillers with variable speed drive, and the monthly electric power consumption can be reduced by a maximum of 30%.

(4) Energy saving effect of the variable chilled water flow rate (see Figures 17 and 18)

We examined the energy saving effect of the variable chilled water flow rate for the chiller by comparing Case A-3 with Case B-1. Figure 18 shows the monthly electric power consumption of pumps for chilled water. They are reduced by variable controls of the pumps, and a reduction in the annual electric power consumption is about 400 MWh (4.0%).

(5) Energy saving effect of the lower limit value of the cooling water outlet temperature(see Figures 17, 19 and 20)

We examined the energy saving effect of changing the lower limit value of the cooling water outlet temperature of the cooling tower by comparing Case A-3 with Case B-1. Figure 19 shows the monthly average cooling water outlet temperature of cooling tower and the wet-bulb temperature of open air. Figure 20 shows the monthly electric power consumption. The annual electric power consumption of Case B-2 is 10,500 MWh - a reduction in electric power consumption of 1,000 MWh (9.0%) compared with Case A-3. The cooling water outlet temperature of the cooling tower of Case A-3 is the same as that of Case B-2 in summer, so no change is seen in electric power consumption. From October to May, in Case A-3 the cooling water outlet temperature of the cooling tower steadies at a minimum of 24°C. However, the cooling water outlet temperature declines to 13°C in Case B-2, so the efficiency of the chillers grows substantially and the electric power consumption is reduced.

(6) Energy saving effect of the high-efficiency controls (see Figure 17)

We examined the energy saving effect of both controls by comparing Case A-3 with Case B-3. The annual electric power consumption of Case B-3 is about 9,500 MWh - a reduction in electric power consumption of 1,400MWh. When all the high-efficiency technologies are introduced (Case B-3), the result is that the annual electric power consumption can be reduced by 4,100 MWh (30%) compared with the conventional system.

CONCLUSIONS

We have quantified the energy saving effect of certain high-efficiency technologies by using a system simulation we devised. The conclusions are shown below.

1) We analyzed the energy saving effect of the assembled cooling towers and the turbo-chillers. In the case of introducing only the assembled cooling towers, the annual power consumption can be reduced by 1.2%. Introducing only turbo-chillers, the rate of reduction increases in winter, the monthly power consumption can be reduced by a maximum of 20%, and the annual power consumption can be reduced by 14%. In the case of introducing both, the annual power consumption can be reduced by 20%.
2) We analyzed the energy saving effect of variable control of the chilled water flow rate for the chiller and the lower limit value of the cooling water outlet temperature of the cooling tower as high-efficiency controls. The electric power consumption of the pump for chilled water is reduced by controlling the chilled water flow rate for chiller, and annual power consumption can be reduced by 4.0%. When the lower limit value of the cooling water outlet temperature 24°C of the cooling tower is replaced with 13°C, the power consumption can be reduced by about 9.0% from October to May, though the reduction in power consumption is not seen in summer. In the case of introducing both controls, the annual power consumption can be reduced by 12%. When all the high-efficiency technologies are introduced, the annual power consumption can be reduced by 30% compared with conventional system.

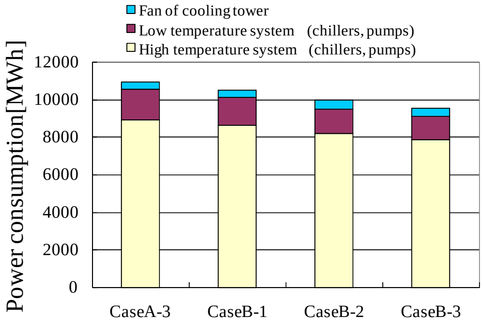

Figure 17 Annual power consumption

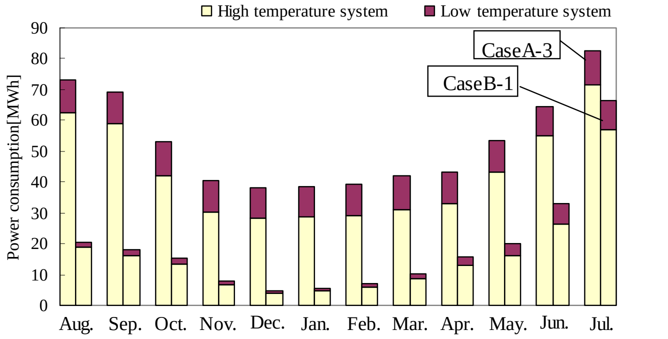

Figure 18 Monthly power consumption of pumps (Case A-3 and B-1)

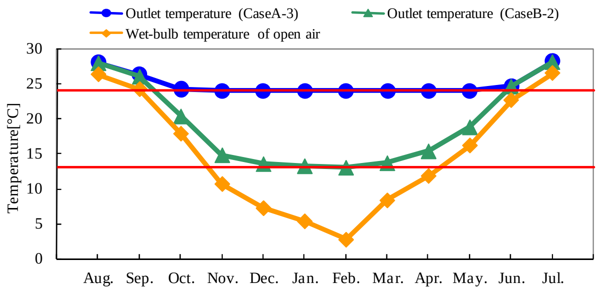

Figure 19 Air wet-bulb temperature and cooling water outlet temperature of monthly average (Case A-3 and B-2)

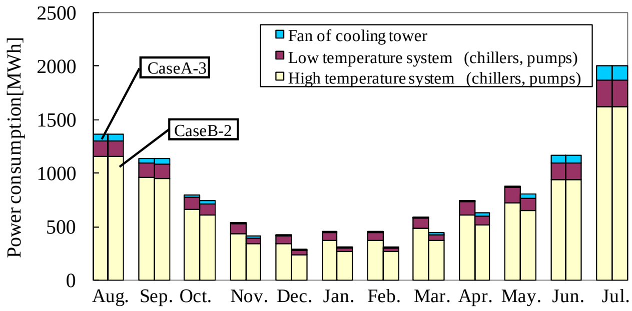

Figure 20 Monthly power consumption (Case A-3 and B-2)