APPLICATION OF OPTIMIZATION METHOD TO ACTUAL CENTRAL AIR CONDITIONING SYSTEMS

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ABSTRACT

To minimize the total power consumption of a central air conditioning system, optimal control variables are necessary. A simulation of a central air conditioning system and its components are modeled. Modeling of air conditioning equipment required optimization, and power consumption formulas are created from experimental data. Optimal control is applied to the actual central air conditioning systems. The effectiveness of optimization and accuracy of optimization calculations are verified. Prediction of air conditioning load is required for the optimization calculation. Load prediction formulas are created and the accuracy is verified. Optimization calculation is applied to general central air conditioning system. The behavior of optimization calculation results and the necessity of various trends of initial values are verified.

INTRODUCTION

In a central air-conditioning system, energy-saving operations are often carried out by means of local operation control such as an air carrier system, water transfer system, etc. However, as a whole central air-conditioning system, the energy use may possibly increase. In this respect, performing optimal control operations not just locally but for the entire central air-conditioning system is important. For optimization of an air-conditioning system, Kikuchi et al., 2000 have performed a study for modeling an air-conditioning system with optimization based on the penalty method and quasi-Newton method. Mr.Brandemuehl et al., 2009 described a method of near-optimal operation and optimization. However, there are very few examples applied to a central air conditioning system. In this respect, the present study describes the modeling of an air-conditioning system and the application of optimization, the general-purpose application of a general air conditioning system. When the simulation of the central air conditioning system is performed, sensible heat loads of objective areas and initial values of control variables are necessary and the method of generating this data is described.

STUDIED CENTRAL AIR-CONDITIONING SYSTEM

In order to construct a virtual system, which will be a reference standard for general-purpose use of the optimization program, it is necessary to understand how the equipment, instruments, and devices and combined to compose the entire air-conditioning system. Based on the data sheet for the completed facility of "Heating, Air Conditioning and Sanitary Engineering "published by the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, the general central air-conditioning system for the present study is shown in (Fig. 1). Water-cooled chillers or external air handling units are exempt in the present study. A bypass is installed as a passage way for cold water to adjust the required flow rate.

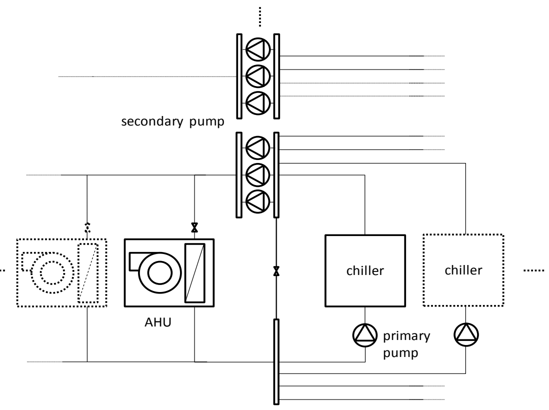

Fig. 1 Central air conditioning system

OPTIMIZATION CALCULATION METHOD

Using a simulation program, a control variable to minimize power consumption is obtained by a sequential quadratic programming method in the non-linear programming with restriction. An optimal solution is attempted in order to find the constrained minimum of a scalar function of several variables starting at an initial estimate. The optimized calculation program can be divided into four modules: a program using a sequential quadratic programming method to perform the optimization calculation, a program to indicate the constraints (restrictive conditions) in the optimization calculation, a program to solve the performance function (electric power calculation formula), and a simulation program of the air-conditioning system using the heat balance equation of each component (See Fig. 2). The optimal solution can be found by repeatedly solving the simulation program for the air-conditioning system by changing control variables according to the sequential quadratic programming method.

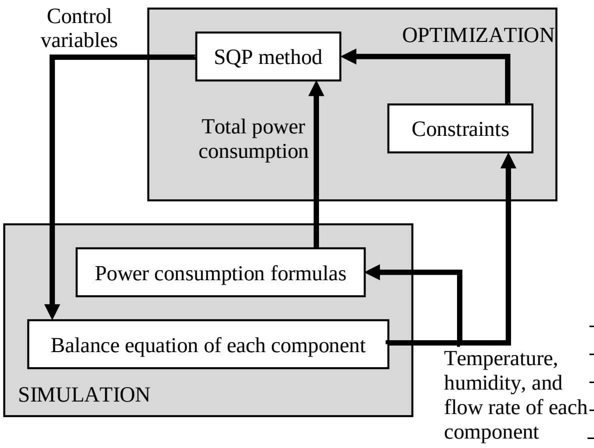

Fig. 2 The flow of optimization

EXPERIMENTAL APPARATUS FOR THE CENTRAL AIR CONDITIONING SYSTEM

To determine the general-purpose optimization calculation method, a simple and small-scale experimental facility shown in Fig. 3 and detailed in table 1 is used in the present study. The facility consists of one air-cooled heat pump chiller, one secondary pump, two air-conditioners, and one-room air handling units for each of the air-conditioning systems. By measuring the leaving water temperature, the chiller is controlled by an inverter. By measuring the exit pressure, the pump and fan are controlled by an inverter. At three-way valve and tank serve as the bypass shown in Fig. 1. The temperature, humidity, and flow rate of each component were measured in an prior experiment. In addition, the power consumption models of components are created from the data of the prior experiment. Comparing to the following experiment, power consumption models are verified.

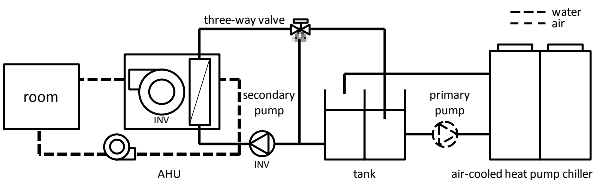

Fig. 3 Experimental facility

Table 1 Outline of experimental facility

	rated power consumption	rated capacity	rated flow rate(capacity)
chiller	7.63[kW]	25[kW]	72[L/min]
pump	2.2[kW]	35[m]	72[L/min]
fan	2.2[kW]	600[pa]	4960[m^3/h]
tank			400[L]

MODELING AND MODEL ACCURACY

Based on the experiments and the table of equipment, instruments, and devices, the actual performance characteristics for each component of the air-conditioning system were investigate. Based on the data, models of the air-conditioning system including chillers, pumps, coils, and fans were prepared. Table 2 shows the resulting models.

Table 2 Component models

chiller	$J_1=a_0*(a_1*r_c^2-a_2*r_c+a_3)*(a_4*(a_5-T_a)+a_6)*(a_7*(a_8-T_o)+a_9)$
pump	$J_2=rnp_p^3*(b_0+b_1*(Q_2/rnp_p)-b_3*(Q_2/rnp_p)^2)+b_4$
fan	$J_3=rnp_f^3*(c_0*(Q_3/rnp_f)^2-c_1*(Q_3/rnp_f)+c_2)+c_3$
a, b, c : parameters	

Air-cooled heat pump chiller

For the chiller, the power consumption was expressed by a quadratic function of the power load factor (Fig. 4). The ratio which were the calculated electric power value and measured electric power value obtained by this relational expression was corrected using outdoor air temperature and outlet water temperature as the primary function. The outlet water temperature was determined by the inlet water temperature, flow rate, and load factor. When the calculated electric power and the measured electric power were compared,the accuracy (Fig. 5) was found to be not very high.

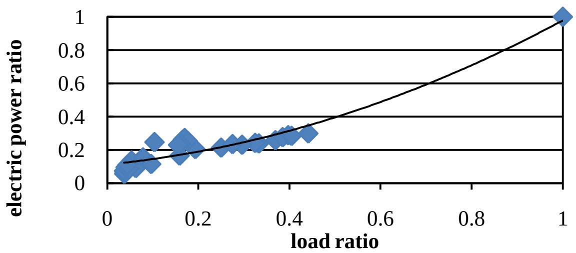

Fig. 4 Regression of chiller power consumption

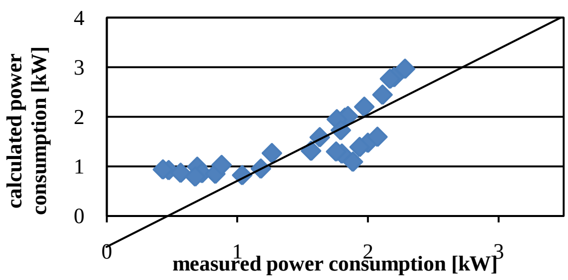

Fig. 5
Accuracy of chiller's power calculation formula

Fan and pump

For the fan and pump, an electric power calculation model was prepared. Based on the rule of similarity, a relational expression of the flow rate to rotation number ratio and fan electric power to rotation number ratio cubed was determined (Fig. 6 and, Fig. 8). This expression was corrected by the measured value. For the fans, the temperature difference between outlet and inlet caused by heating was taken into account. For the pump, the effect from heating was neglected. When the results of the experiment were compared with the calculated values, a high coincidence was found (Fig. 7 and Fig. 9).

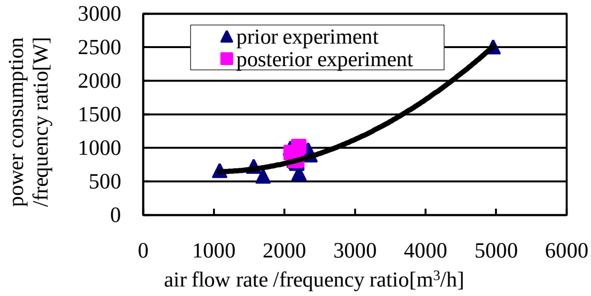

Fig. 6 Power calculation curve of fan

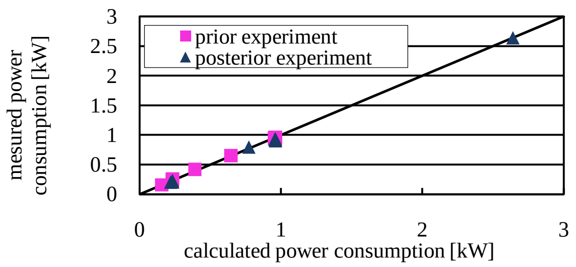

Fig. 7
Accuracy of fan's power calculation formula

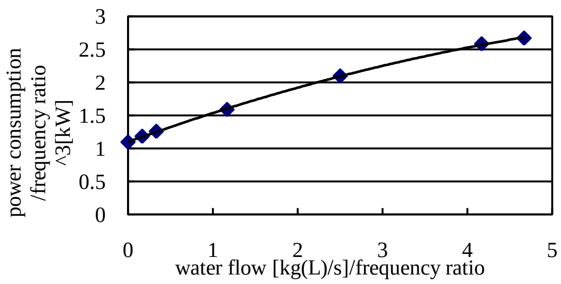

Fig.8 Power calculation curve of pump

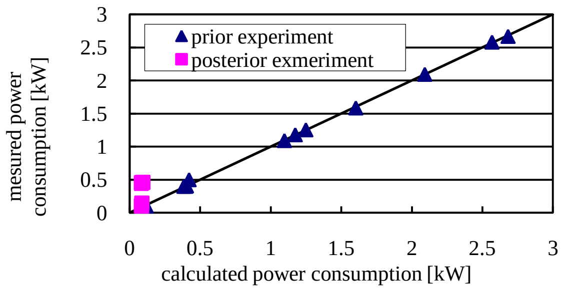

Fig. 9
Accuracy of pump's power calculation formula

Coil

In case of the coil, there was no power consumption, and a balance equation of the inlet-outlet condition was obtained on the water side and on the air side. The heat exchange was calculated from the water equivalent and the heat transfer effectiveness was determined by air flow, water flow and coil characteristic. In addition, when the results of the experiment were compared with the calculated value, good coincidence was found (Fig. 12 and Fig. 13).

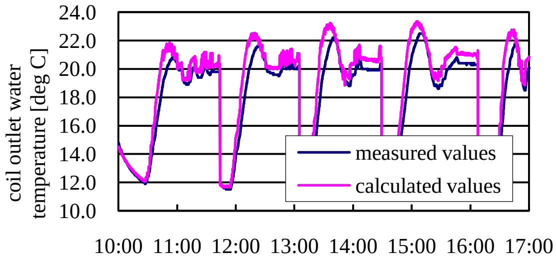

Fig. 12 Measured and calculated values of coil outlet water temperature

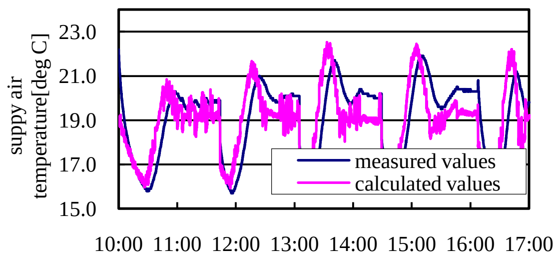

Fig. 13 Measured and calculated values of supply air temperature

EXPERIMENT OF THE CENTRAL AIR-CONDITIONING SYSTEM

General outline of the experiment

To simplify the experiment, a system containing one air handling unit was operated, to verify the process in which power consumption was reduced. Sensible heat load was measured in the first experiment and used to perform the optimization calculation. The second experiment was performed using the optimization calculation result for chiller outlet water temperature, water flow rate, and frequency of pump and fan.

Results of the experiment

The optimal solution was calculated by taking the experimental room sensible heat load before correcting the control parameters as a given condition, then the experiment was conducted according to the parameters after the correction (Fig. 14, Table 3). On the first day of the experiment, power consumption decreased but not as much as exhibited in the optimized calculation results. This may be due to a lower room sensible heat load (q_c) estimation in the optimization calculation. Therefore, on the second day of the experiment, the calculation was completed with 1.0 kW added to the measured room load before the correction, and the experimental operation and measurements were conducted.

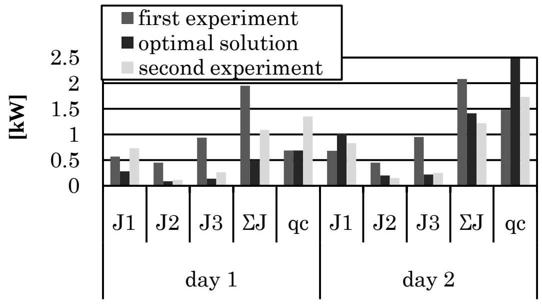

Fig. 14 Power consumption of initial experiment, optimized solution, and optimized experiment

However, the room sensible heat load was not increased significantly, and the power consumption was lower than that of the optimal solution. In addition, because of the optimization calculation results, the chiller outlet water temperature was decreased, and the fan airflow rate and pump flow rate were both exhibited a decreasing trend.

Table 3 Results of demonstration experiment

		Q_1[kg/s]	Q_2[kg/s]	Q_3[m^3/s]
day 1	first experiment	0.05	0.05	0.60
	optimal solution	0.03	0.03	0.12
	second experiment	0.05	0.05	0.31
day 2	first experiment	0.09	0.09	0.60
	optimal solution	0.19	0.19	0.29
	second experiment	0.11	0.11	0.29
		r_c[-]	T_a[deg C]	T_o[deg C]
day 1	first experiment	0.040	9.0	11.9
	optimal solution	0.029	7.0	11.9
	second experiment	0.042	8.0	13.5
day 2	first experiment	0.048	9.2	10.3
	optimal solution	0.109	7.0	10.3
	second experiment	0.044	8.1	8.1

Verification of optimization accuracy

When the room sensible heat load, outside air temperature, return air temperature and return air absolute temperature are regarded as given conditions, the power consumption is determined by $Q_1 \cdot Q_2 \cdot Q_3$. Figs. 15, and 16 show the details of power consumption and chiller exit water temperature when the measured values on the first day are regarded as the given conditions and the value of $Q_1 \cdot Q_2 \cdot Q_3$ is varied near the optimal solution. In the optimization calculation, the three-way valve was considered to be completely opened ($Q_1 = Q_2$). The graph exhibits that the increase and decrease of the fan power consumption due to the change of $Q_1 \cdot Q_2 \cdot Q_3$ and the increase and the decrease of power consumption by the chiller caused by the change of chiller exit water temperature were balanced well. It is also evident that the operation to minimize total power consumption could be obtained from the result of optimization calculation. Further, when the value of $Q_1 \cdot Q_2 \cdot Q_3$ was decreased, chiller could not extract the room sensible heat load unless the chiller outlet water temperature was 7deg C or lower. But 7 deg C is the minimum value of the chiller outlet water temperature.

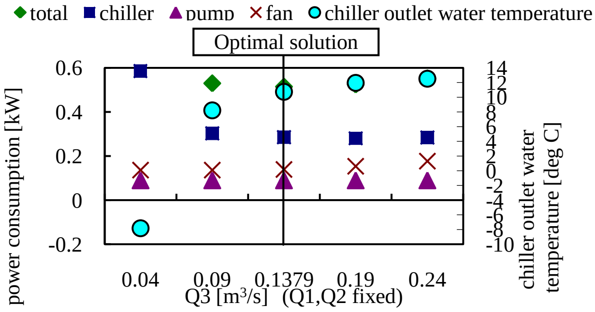

Fig. 15 Power consumption near optimal point

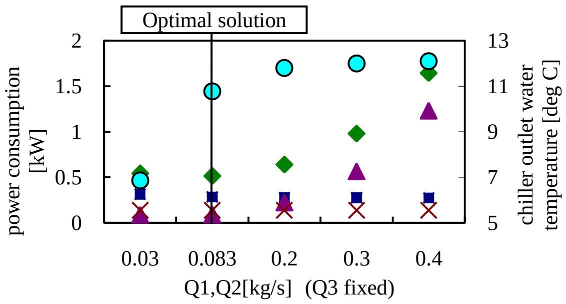

Fig. 16 Chiller outlet water temperature near optimal point

PREDICTION OF LOAD

To simulate a central air conditioning system, determining the sensible heat load of an objective room is necessary. Sensible heat load can be determined by using previous measured data or using prediction data. In this section, the method of predicting load is described. From the regression formula (Figs. 17 and 18) of outside air temperature, the standardized load (i.e., a value obtained by subtracting the heater load from the room sensible heat load), and the outside air temperature based on weather forecast, the predicted values of the sensible heat load in each room were calculated.

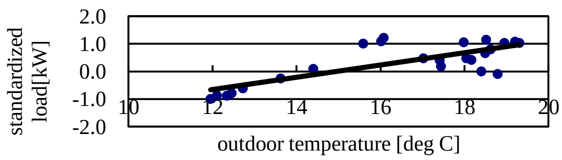

Fig. 17 Regression of room A load

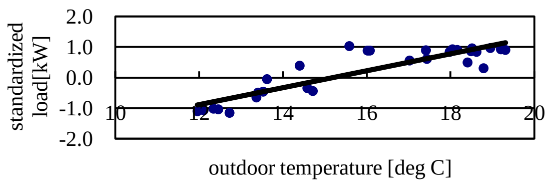

Fig. 18 Regression of room B load

Considering the outside air temperature and the load used in the experiment, a 15 minute period where the load stabilized was selected and the average load during the period was calculated for 29 cases. The predicted load value was different from the measured values (Fig. 19).

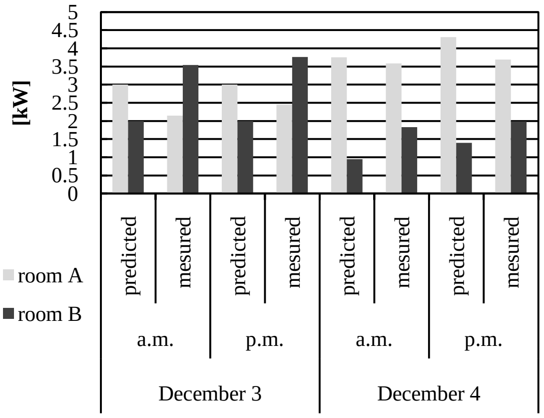

Fig. 19 Comparison of predicted and measured load

However, rather than vaguely predicting the load, a more valid and reasonable approach is to predict the value according to the regression formula. In addition, adopting the load from the standard operation case seen in the first half of the experiment obtains a value that is closer to the actual load.

STUDIED SYSTEM

By utilizing the results obtained in the small-scale experiments and the optimization simulation, a large-scale virtual system was constructed to investigate the behavior of the optimization calculation. Efforts were made to establish a methodology for performing accurate and reliable optimization calculations.

Generalization of optimization program

Preparing the optimization calculation program for each individual building is not realistic or practical. Therefore, preparing a program in which the optimization calculation can be performed simply by entering the features of an air-conditioning system (such as the number of AHU, etc.) and the given conditions (such as room temperature, outside air temperature, etc.) was necessary. An optimization calculation program was prepared where the maximum system was limited to 100 rooms for each air handling unit, including one chiller, 20 pumps, and 50 air handling units for each pump (Fig. 1). As described above, the calculation would be performed when the features of the air-handling unit and the given conditions are provided (Table 4).

Table 4 Fixed parameters and input variables of optimization program

fixed parameters	chiller	rated ability , rated water flow
	pump	piping resistance , characteristic curve , number of units
	coil	coil conductance
	fan	ducting resistance , characteristic model , number of units
	room	number of rooms
input variables	outdoor temperature , room temperature , sensible heat load of room	

Determination frequency of pump and fan

In the optimization calculation, the two-way valve is always completely opened in the case where one air handling unit is dedicated to one pump. A proportional relationship between pump flow rate and frequency exists. However, when a system has multiple air handling units, the two-way valve is not always completely opened. Except for one two-way valve, two-way valves can be restricted to satisfy the requested flow rate (Fig. 20) because the values of the before-and-after differential pressure of each air handling unit are coincident with each other. The frequency of the pump was determined from the resistance of each pipe and from characteristic curves of the pumps (Fig. 21). The same applies to the frequency of the fan.

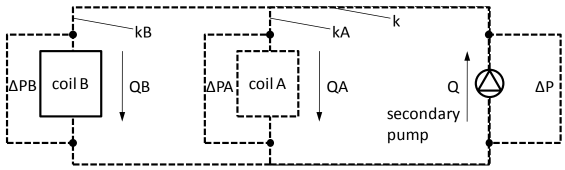

Fig. 20 System diagram of chilled water

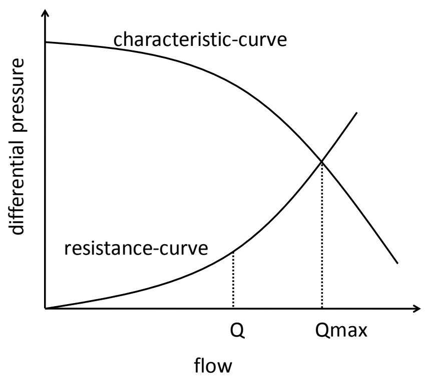

Fig. 21 Determination frequency of pump and fan

Optimization calculation

In the present study, the optimization calculation was performed using the sequential quadratic programming method, while its accuracy is not certain. Under such circumstances, clarifying whether the value obtained by the optimization calculation would indicate the minimal solution under a certain setting condition (Table 5, Fig. 22) was necessary. The air-conditioning load is assumed to be 120W/m^2 and each 30kW AHU covers 250m^2. This case has 6 AHUs for a total air-conditioning load of 180kW. A chiller is selected to cover 80% of the total air-conditioning load.

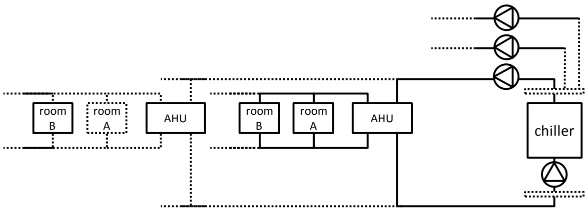

Fig. 22 Assumed central air-conditioning system

Table 5 Capacity of virtual system

	number of units	rated capacity	rated power consumption	rated flow
chiller	1	150[kW]	45[kW]	7.15[L/s]
secondary pump	3	30[m]	1.5[kW]	4.17[L/s]
fan	6(each 2)	500[pa]	1.5[kW]	3.33[m^3/s]
room	18(each 3)	-	-	-

The control variables of the optimization are supply water temperature and supply air temperature. With the supply air temperature fixed at the optimal solution (Tables 6 and 7), the values of power consumption were compared when the supply water temperature was increased or decreased near the optimization calculation value.

Table 6 Result of optimization

		AHU1			AHU2		
		room1	room2	room3	room1	room2	room3
pump1	air flow [m^3/s]	0.06	0.18	0.18	0.07	0.07	0.07
pump frequency [Hz] 14.97	fan frequency [Hz]	7.88			4.92		
	water flow [L/s]	0.39			0.21		
pump2	air flow [m^3/s]	0.19	0.23	0.23	0.08	0.09	0.09
pump frequency [Hz] 26.56	fan frequency [Hz]	10.26			5.56		
	water flow [L/s]	0.86			0.16		
pump3	air flow [m^3/s]	0.10	0.12	0.12	0.11	0.12	0.12
pump frequency [Hz] 27.97	fan frequency [Hz]	10.24			5.42		
	water flow [L/s]	0.85			0.16		

Table 7 Control variables of optimization result

control variables [deg C]	supply air temperature		supply water temperature
	AHU1	AHU2	
pump1	13.42	14.13	
pump2	14.58	15.01	10.45
pump3	14.61	15.02	

In Fig. 23, the optimization calculation result shows the local minimum value.

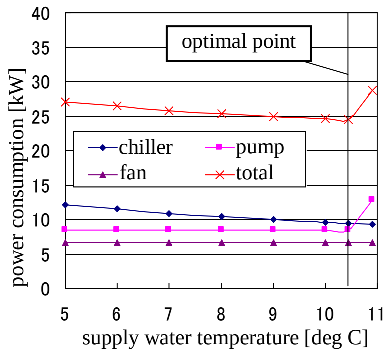

Fig. 23 Power consumption and supply water temperature

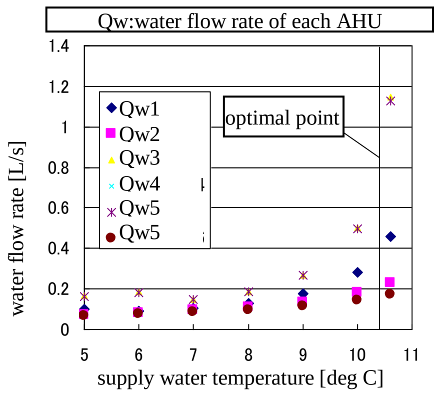

Fig. 24 Water flow rate and supply water temperature

When the supply water temperature was increased from the optimization point, the power consumption of the pump increased and the optimal point was obtained before the pump power consumption increased significantly. Also, when the supply water temperature was changed, there was no change in the air flow volume, while the cooling water flow rate changed (Fig. 24). For the cooling water flow rates 3 and 5, i.e., the flow rates of air handling unit 1 of pumps 2 and 3, the load was higher compared to the other air handling units. As a result, when the supply water temperature was increased, the flow rate increased more.

INITIAL VALUE OF OPTIMIZATION CALCULATION

In order to reliably solve the optimization calculation, determining the initial value is necessary, but not necessarily certain. In this context, the calculation is evaluated for reliably solving the optimization with different initial values. The possibility that the solution could change under the preset conditions described above (Table 5) was also investigated.

Necessity of the initial value to satisfy the constraints

The command of the mathematic simulator MATLAB that generates random numbers was used to generate the optimization control variables of coil inlet water temperature (T_{win}) and supply water temperature (T_{fout}) within the constraints of each parameter (T_{win}: 5–15[°C], T_{fout}: 10–18[°C]) (Fig. 25).

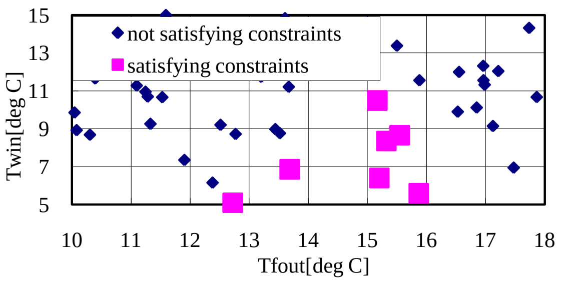

Fig. 25 Distribution of random initial values

Six values of supply air temperature are associated with the number of the air handling units. All units are assumed to be equal in the stage of determining the initial values. Simulations were performed with all of the initial values, and the temperature and humidity of each component, air flow rate, and frequencies were calculated. If all constraints are met in a simulation, the initial values were selected (Fig. 25). Among the 50 cases generated at random, the initial values of 7 cases satisfy the constraints. Regardless of whether the initial values found would meet the constraints or not, an optimization calculation was performed for each of the 50 cases, and the reliable completion of each calculation was evaluated. Here, completion of the optimization calculation signifies that the calculation has been completed, and that a local minimal solution has been found. In all of the 7 cases that satisfied the constraints, the optimization calculations were completed. However, all of the remaining 43 cases, which did not satisfy the constraints, could not complete the optimization calculation. This suggests that if the initial values satisfy the constraints, it is certain that the optimization calculation could be reliably completed, and that selecting the initial value is important for the optimization calculation method in the present study.

Difference of results due to the initial values

When the results of the optimization calculation differ due to the initial values, it cannot be regarded as the optimal solution. Therefore, possible changes in the results of the optimization calculation caused by initial values should be verified.

(1) Random initial values

Among the 50 randomly selected cases, evaluation was performed in the 7 cases where the optimization calculation was completed (Fig. 26 and Fig. 27). Cases 2 through 7 exhibit the same trends. However, Case 1 exhibits a trend different from the other 6 cases. Also, no substantial difference in power consumption is evident between the cases. An evaluation is made as to why the results of the optimization calculation differ according to the initial values. Since the search scalar of the control variable in the optimization calculation is small, the program may regard a local minimal solution, not far from the initial value, as the optimal solution.

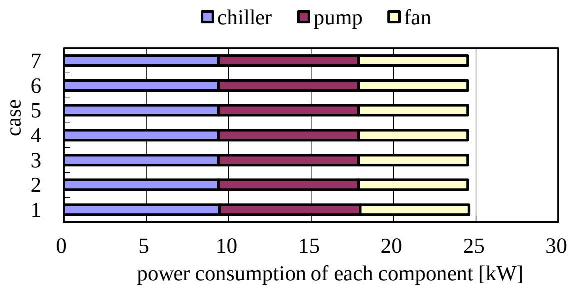

Fig. 26 Power consumption by variant initial values

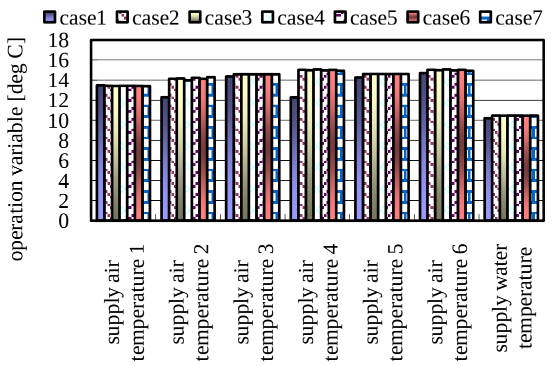

Fig. 27 Initial values and optimization results

(2) Initial values from various searching directions

In the evaluation where the initial value was selected at random, no difference was found in the trends of the optimal solution, while a program was prepared to generate various types of initial values having different behaviors (such as increasing/decreasing water temperature etc). First, the minimum and maximum values of the control range for each control variable were considered as the starting point of the search. Then, only the combination caused by the difference of the starting point in multiple control variables was evaluated. The control variables on the inner side of the loop were changed from the starting point of the search (e.g., the minimum value) to the end (Fig. 28).

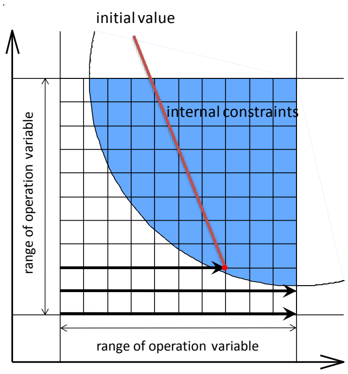

Fig. 28 Image of searching initial values 1

If the constraints could not be satisfied before the end point is reached, the control variable of the loop on the outer side was changed to the end point. This procedure is repeated until the constraints are satisfied and the value at that moment is determined as the initial value. Then, the searching direction is changed and the initial value with a different trend is generated (Fig. 29).

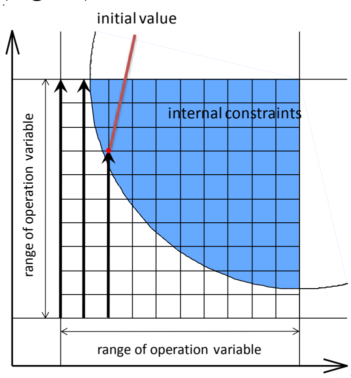

Fig. 29 Image of searching initial values 2

CONCLUSIONS

This paper describes the modeling of an air-conditioning system and the application of optimization. Methods of generating sensible heat loads of objective areas and initial values of control variables are described.

Since the accuracy of the modeling is not necessarily high, obtaining more values through actual measurements is necessary. The load prediction is effective at the time of initial operation where the load immediately before is not known. For the optimization control variable, a plurality of different initial values was generated, while no substantial difference was found in power consumption. When a large change from current operating conditions is required, using an optimization calculation value requiring no other sudden change is practical. Future research is necessary to further investigate methodologies of this kind.

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NOMENCLATURE

T_a : chiller outlet water temperature [deg C]
T_b : chiller inlet water temperature [deg C]
T_c : coil outlet water temperature [deg C]
T_d : coil inlet water temperature [deg C]
T_e : return air temperature [deg C]
T_f : supply air temperature [deg C]
T_g : fan outlet air temperature[deg C]
T_o : outdoor temperature [deg C]
S_1 : coil inlet air absolute humidity [kg/kg(DA)]
Q_0 : chiller water flow [L/s]
Q_1 : water flow [L/s]
Q_2 : water flow [L/s]
Q_3 : air flow [m^3/s]
r_c : chiller load ratio [-]
rnp_p : pump rotational speed ratio [-]
rnp_f : fan rotational speed ratio [-]
q_c : room sensible heat load [kW]
J_1 : chiller power consumption [kW]
J_2 : pump power consumption [kW]
J_3 : fan power consumption [kW]
Σ_J : total power consumption [kW]

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