Retro-Commissioning and Improvement for District Heating and Cooling System Using Simulation

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Abstract: In order to improve the energy performance of a district heating and cooling (DHC) system, retro-commissioning was analyzed using visualization method and simulation based on mathematical models, and improved operation schemes were proposed according to simulation analysis results. The first part of this paper describes the system performance through visualizing the current operation modes. The second part introduces the retro-commissioning analysis for the system using mathematical models of each component. The third part studies the energy and cost performance of several improved operation proposals using simulation. The results are as follows.1) The carpet plots of current operation modes can be generated automatically and they are useful to check whether the operation is proper or not. 2) The total system simulation model was constructed. The simulation error of the total energy consumption was 1.5% and the percentage of root mean square error (%RMSE) was 16.3%, which show that the simulation is accurate enough to study the performance of proposed operation.3) System simulations for proposed operation schemes were performed. The simulation results show that the system operation with the optimal temperature set point of cooling water at 22oC can improve the total energy coefficient of the heat pump and cooling tower by 2.2 %. Another proposal is that if the return water temperature from users can be kept at the designed value, which is 13±1□ compared with the current average value of 10.5□, the total energy consumption can be reduced by 9.5%, and energy cost can be reduced by 11.6%.

1. INTRODUCTION

District Heating and Cooling system have been applied since 1970's because it can reduce harmful waste exhaust and improve energy efficiency compared with traditional local heat and cooling system. However it is reported that the system Coefficient of Performance (COP) is often less than 1 because of delivering energy consumption, equipments oversize etc. which make high energy efficiency cannot be achieved[1)]. Therefore, it is important to operate a DHC system reasonably or optimally. So it is necessary to develop enhanced operation mode to improve energy efficiency as well as keeping the heating and cooling operation normal.

In order to apply the Retro-Commissioning for an existing DHC system, firstly, the simulation model of each component was developed and the simulation accuracy was verified using measured data. Secondly, the model of each component and control model were connected to form the simulation model of the whole heat source system. Finally, several proposals for reducing the energy consumption were analyzed using simulation.

2. PROFILE OF THE DHC PLANT

The DHC plant is located in Osaka, Japan. It is in charge of heating and cooling an office building and a building with welfare facilities since November 1992. Figure-1 shows the system diagram of the plant. Table-1 shows the profile of main equipments. The required supply temperature of chilled water is 6±1ºC and the design value for return temperature is 13±1ºC. The average system COP in 2004 was 1.89, which is a common value of most DHC systems[2)].

The total electric consumption, water temperature, flow rate, and pressure, etc. are measured by the Building Energy Measurement System(BEMS) once one hour. Because these data are not enough for developing models, 9 points of the electric power of heat source equipments and variable water volume pump, 20 points of the current of

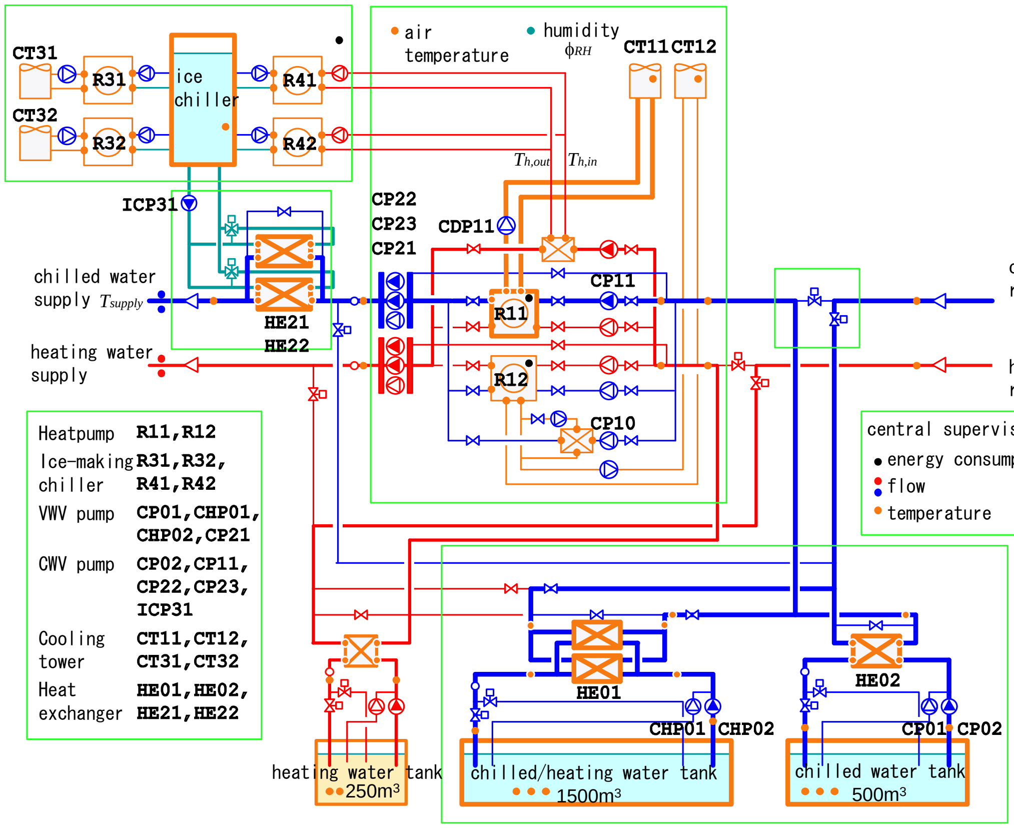


Fig.1 system diagram of the heat source system

Tab.1 Profile of the main equipments in the DHC

Heat source	Name	Capacity[RT]	Number of chiller
Water cooled centrifugal heat pump with heat recovery for cooling mode	R11	700	1
Water cooled centrifugal heat pump	R12	700	1
Air cooled ice chiller with heat recovery	R41,R42	37	2
Water cooled screw ice chiller	R31,R32	75	2
Heat storage tank		Capacity[m^3]	Number of tank
Chilled water tank		500	1
Chilled/heating water tank		1500	1
Heating water tank		250	1
Ice strage tank		150	1

constant water volume pump, and 1 point of the inlet temperature of chilled water were measured additionally.

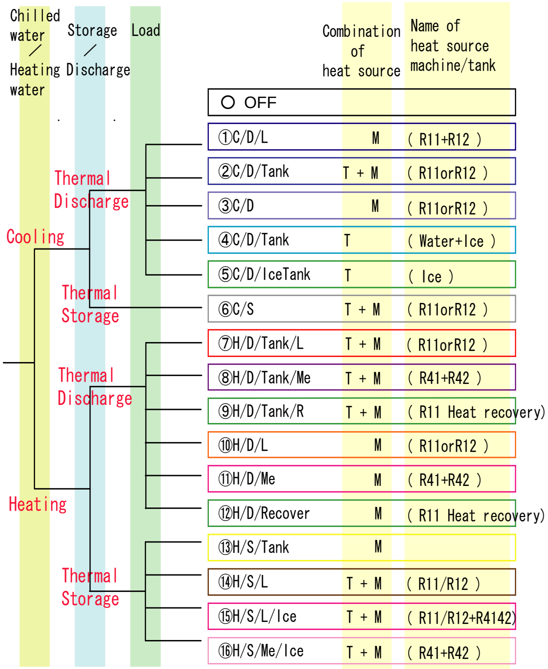
3. OPERATION MODE VISUALIZATION

As one method of commissioning, visualization technology is used to make operation mode easy to recognized[3]. The authors developed a tool to visualize judge operation mode using the data collected by BEMS. This tool can help users to detect faults, understand current operation, find problems of energy efficiency, and understand the limit of operation modes.

3.1 Classification and Judgment of Operation Mode

The operation mode means the combination of operating state of each component. It is classified into 16 modes according to 1) which of heating and cooling is the main purpose of current operation, 2) thermal storage or thermal discharge 3) magnitude of load(Figure-2). Whether heating or cooling is the main purpose of operation is determined by whether the 1500m3 tank is storaging hot water or chilled water. Heat storage or heat discharge is determined by time. Magnitude of load is determined by 1)combination of thermal storage tanks and heat source equipment, 2) which equipment is running, 3) operation mode of heat source machines(cooling/heating/heat recovery), 4) which tank is discharging heat. Operation mode judgment results using the data obtained from BEMS are shown in Figure-3. In order to check the accuracy of the mode recognition, the judgment results were compared with operation log. The operation state of the system, such as on-off of heat source machines or state of heat storage tanks is recognized correctly.

3.2 Problems Revealed by the Operation Mode Visualization



Notes : C:Cooling, D:Thermal disccharge, H:Heating
L:Large heating/cooling load, M:Heating source machine
Me:Medium heating/cooling load, R:Heat recovery
S:Thermal storage, T:Thermal storage tank

Fig.2 Classification of operation mode

From the visualization chart of operation mode, the following items that seem unreasonable are picked out for further analysis. 1)Operation mode changed from mode □□ to mode □□ every other day. 2) Thermal storage was conducted during the period when it ought not to run thermal storage mode. 3) Heat recovery operation was seldom conducted. 4) Heating pump is operated at cooling mode during the period that heating is main demand. The verification results for the former mentioned issues are as follows. 1) Because ice have to be used to make supply water temperature match required value of 5.5 ºC , during small load period the ice-storage mode is operated every two days.2)In winter, when heating water is required after 18 o'clock, R41 and R42 are operated at ice-making with heat recovery mode. It is necessary to compare the ice-making with heat recovery mode with heating mode to determine which mode is proper. 3) During the plant design phase, the heating load was large so that heat recovery mode was designed. However the load situation has changed later and not so much heating water is required. So the heat recovery operation is seldom conducted. 4) During the period of switching main operation mode of water tank between heating and cooling, because of the weather conditions' influctuating, the phenomena mentioned above appear.

The judgment and visualization of the mode of operation are useful for finding faults in operating. Thus, the operating points that might be faulty can be detected easily for further analysis.

4. MODELING OF HEAT SOURCE SYSTEM

4.1 Modeling of heat source equipments and model validate

The heat source equipments modeling and validating process is as follows. 1) Develop model using characteristic curve proposed by manufacturers. 2) Compare model simulated data with specification data. 3) For the purpose of simulating current performance of the DHC plant, the measured data were used to revise the coefficients fitted using specification data. The details about the modeling are described in reference 3.

4.2 Modeling Of DHC Plant System

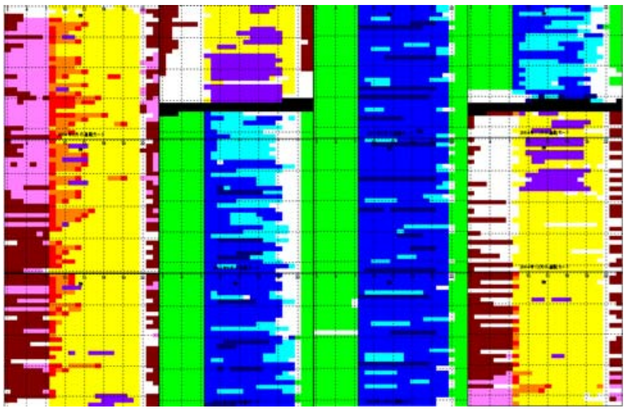


Fig.3 Operation mode recognition

The system model consists of sub system block, formed from components and equipment model, and control block, which send command to equipments according to operation modes. (Figure-4). When operation mode is inputted to block A, A sends detailed commands such as cooling/heating, on/off etc. to each subsystem, such as block B. B sends command, such as on/off, set point value etc. to components and equipments.

The operation staff's commands can be divided into two types. One is operation policy such as operation mode etc., and another is detailed operation

Tab.2 Comparison of average energy consumption of subsystems and equipments

Subsystems and equipments		Rated value [kW]	Average enerry consumption Measurement [kW]	Simulation [kW]	Error [%]	%RMSE [%]
Subsystem	Chiller system	607.0	346.5	353.5	2.0	21.6
	Derivering system	141.0	67.5	69.1	2.4	14.6
	Heat strage system	75.0	18.5	20.0	8.5	21.9
	Ice strage system	410.7	135.7	134.0	-1.3	45.7
	Whole heat source system	1233.7	568.2	576.7	1.5	16.3
Main equipment	Chiller R11	457.0	243.8	246.4	1.1	28.0
	Secondary pump CP21～CP23	130.0	65.8	67.4	2.4	15.0
	Chilled/heating water tank pump for discharge CHP0	30.0	6.9	7.4	6.5	32.4
	Chilled/heating water tank pump for storage CHP0	30.0	6.9	6.8	-0.2	16.1
	Ice chiller R31	118.0	36.3	34.8	-4.3	43.8
	Ice chiller R32	118.0	39.0	36.8	-5.6	46.1
	Ice thermal strage tank pump for dicharge ICP3132	18.5	4.8	6.4	31.7	152.9

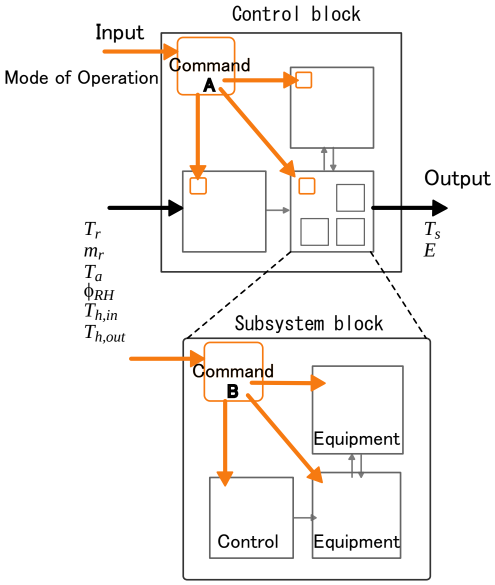


Fig.4 Modeling of DHC plant system

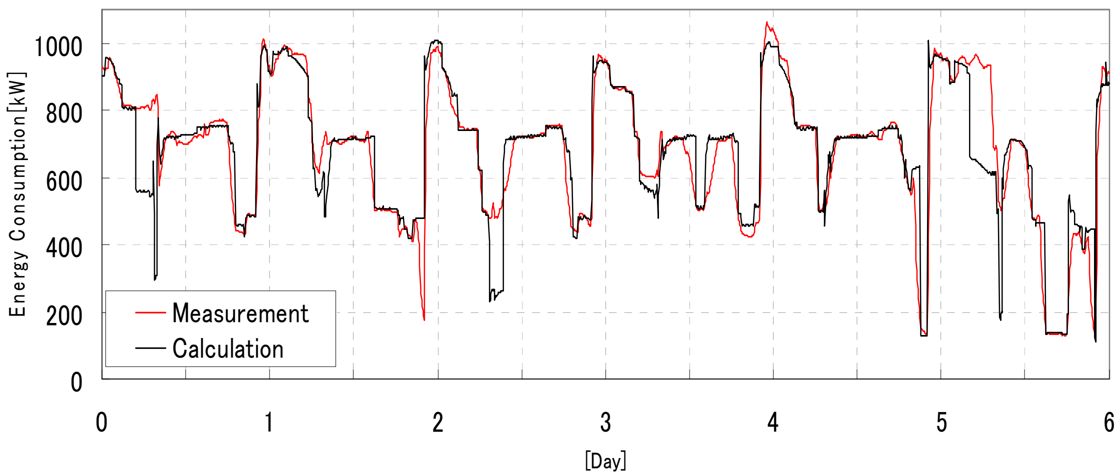


Fig.5 Comparison of simulated energy consumptions with measured data

Tab. 3 Object and items suitable for optimization

Type	Optimization item
1)Control set point	○Entrance temperature of cooling water to chiller, Outlet temperature of chilled water from chiller, Temperature from heat storage tank for thermal discharge, Threshold for change the number of running pumps
2)Operation mode	○Change of the criterion for determin operation mode
3)Adaptaton to user side	○Change of water flow rate to make chilled water return temperature match design value
4)Retrofit of equipment	Install of vibration of piping, Making of pump inverter, Install cooling tower fan inverter
5)Retrofit of pipe	Make chilled water for thermal storage not pass socondary pump

Tab. 4 Comparison of energy consumption at a different cooling water temperature

Period	Average outside air temperature Dry-bulb [℃]	Average outside air temperature Wet-bulb [℃]	Item	Cooling water temperature at the limit of chiller 22℃	24℃	26℃	28℃	30℃
8/18 ～ 10/18	24.5	19.9	Chiller R11 Average energy consumption[kW]	217.0	219.7	223.9	228.9	238.0
			Cooling tower CT11 Average energy consumption [kW]	17.2	15.2	12.9	10.4	8.9
			Sum(chiller＋cooling tower) [kW]	234.1	234.9	236.8	239.4	246.9
			Rate of increase of energy consumpyion[%](R11＋CT11)	-2.2	-1.8	-1.1	0.0	3.1
			Rate of increase of energy consumpyion[%](whole system)	-0.9	-0.8	-0.5	0.0	1.3
			COP of chiller[-]	4.3	4.2	4.1	4.0	3.9
① 9/2 ～ 9/6	26.3	23.0	Chiller R11 Average energy consumption[kW]	285.7	286.1	288.7	296.7	305.8
			Cooling tower CT11 Average energy consumption [kW]	22.0	21.2	18.9	15.2	12.7
			Sum(chiller＋cooling tower) [kW]	307.7	307.4	307.6	311.9	318.5
			Rate of increase of energy consumpyion[%](R11＋CT11)	-1.4	-1.5	-1.4	0.0	2.1
			Rate of increase of energy consumpyion[%](whole system)	-0.7	-0.8	-0.8	0.0	1.2
			COP of chiller[-]	4.3	4.3	4.2	4.1	4.0
② 9/27 ～ 10/1	22.1	16.7	Chiller R11 Average energy consumption[kW]	178.4	183.9	188.9	195.5	200.8
			Cooling tower CT11 Average energy consumption [kW]	13.2	10.5	9.0	7.4	6.5
			Sum(chiller＋cooling tower) [kW]	191.6	194.4	197.9	202.9	207.3
			Rate of increase of energy consumpyion[%](R11＋CT11)	-5.6	-4.2	-2.5	0.0	2.1
			Rate of increase of energy consumpyion[%](whole system)	-2.0	-1.5	-0.9	0.0	0.8
			COP of chiller[-]	4.3	4.1	4.0	3.9	3.8

Tab.5 Operation schedule

Operation mode	Schedule 22:00 ～6:59	7:00 ～17:59	18:00 ～19:59	20:00 ～21:59
Original	⑥Cooling / Water and ice thermal storage	②Cooling/ Discharge from ice and water tank + chiller	③Cooling/Chiller	⑥Cooling/ Discharge from ice tank
No ice thermal storage Scenario 1	⑥Cooling/ Water thermal storage ※No ice thermal storage	②Cooling/ Discharge from ice and water tank + chiller ※No ice thermal discharge	③Cooling/Chiller ※No ice thermal discharge	
No ice thermal storage Discharge at evening Scenario 2	⑥Cooling/ Water thermal storage ※No ice thermal storage	②Cooling/ Discharge from ice and water tank + chiller ※No ice thermal discharge	④Cooling/Discharge from water tank ※No ice thermal discharge	

Tab.6 Energy consumption at different chilled water

	Chilled water return temperature 10.05℃	11.5℃	12℃	12.5℃	13℃	13.5℃	14℃
Average flow rate [kg/s]	40.0	80.0	72.2	66.0	60.7	55.7	51.9
Chiller system [kW]	464.8	445.9	449.2	455.0	459.7	462.7	459.7
Delivering system [kW]	80.5	65.5	58.3	52.2	46.3	42.4	41.3
Heat storage system [kW]	17.7	21.3	21.6	21.7	21.6	21.6	21.6
Ice thermal storage system [kW]	149.1	139.9	132.3	124.3	122.4	117.8	131.6
Sum [kW]	712.1	672.6	661.4	653.1	650.1	644.5	654.2
Rate of increase [%]	0.0	−5.5	−7.1	−8.3	−8.7	−9.5	−8.1
COP of chillerR11[−]	4.28	4.34	4.35	4.37	4.34	4.39	4.37

command, such as control set point, experiential change of operation mode, etc. In this research, only the pre-determined operation modes are modeled. The control flow based on the operation criteria used by operation staffs.

4.3 Model Validation

The whole heat source system model was constructed
through combining equipment models. Then the model was used to simulate the total energy consumption of the DHC plant. For the purpose of checking the simulation accuracy, the simulated data were compared with measured data. Sixty days' data from August 18, 2005 were compared. The simulation time step internal is five minutes. Sixty days' comparison results are shown in Figure-5, and the energy consumptions of each subsystem and the main equipments are shown in Table-2. The simulation error of the total energy consumption was 1.5% of average measured data, which shows that the simulation is accurate enough to study the performance of the DHC plant.

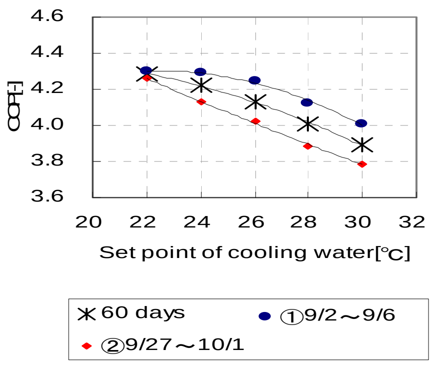
Table-4 Comparison of energy consumption at a different cooling water temperature

5. OPTIMIZATION FOR THE OPERATION OF THE DHC PLANT

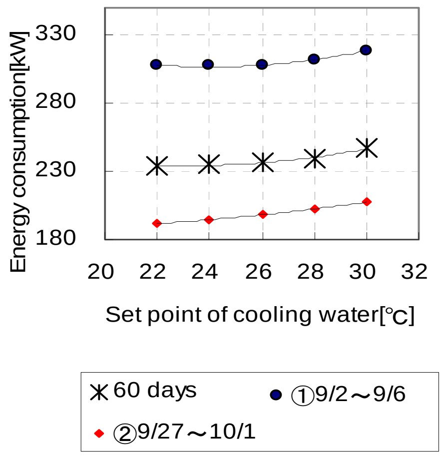
For the purpose of improving the current operation of DHC plant, the DHC system was analyzed to develop optimal operation method. Table-3 shows the items suitable for optimization. The following items, attached with a ○ in Table-3, were analyzed in this paper: 1) Change of temperature set point of cooling water. 2) Check the performance of an operation mode that doesn't use ice thermal storage subsystem because of its low COP. 3) Check the performance of making chilled water return temperature in conformity with design value through changing water flow rate. The optimation objective is to make energy consumption minimum. The measured cooling loads in the summer of 2005 were used for the analysis.

5.1 Optimization For Temperature Of Cooling Water

In the chiller subsystem, if the temperature of cooling water entering the chillers T_C decreases, the COP of the chillers can be increased and the energy consumption of the chillers E_R decreases. However if T_C is lowered, the running time of cooling towers increases and the energy consumed by cooling towers E_{CT} increases. Therefore, it is necessary to decide the optimal cooling water temperature which can make $E_R + E_{CT}$ minimum.



(a)



(b)

Fig. 6 Comparison of COP(left) and energy consumption(b) at different cooling water temperature

Presently, T_C set point is 28□, which is controlled by the number of four cooling tower fans and a bypass route between supply and return water. Cooling water temperature set point $T_{C,S}$ is the variable to be optimized. The measured cooling amount produced by the chiller Q_e and wet-bulb temperatures of outside air T_{wb} are input conditions. Constraint condition is that cooling water temperature can change between 22℃ to 31℃ according to the chiller's manual. The energy consumption of $E_R + E_{CT}$ summed up through the analysis period should be minimum when the cooling water temperature is setted at the optimal value.

Two months from August 18th through October 16th, 2005 is chosen for the analysis because during this period, there are days with high outside temperatures and large cooling loads and days with low outside temperatures and small loads. The analysis result for this period is that the optimal cooling water temperature $T_{C,S}$ is 22℃. Compared with 28℃, the current set point, COP of the chiller can be improved from 4.0 to 4.3, $E_R + E_{CT}$ can decrease by 2.2%, which is 0.9% of the total energy consumption of the DHC plant.

The minimum solution of $E_R + E_{CT}$ is hourly different depending on the wet-bulb temperature and cooling load. Therefore the characteristic of $E_R + E_{CT}$ changing according to $T_{C,S}$ is compared between a period when wet-bulb temperature is high and a period when wet-bulb temperature is low, as shown in Figure-6 and Table-4. In the period when wet-bulb temperature is high and cooling load is large, the temperature of cooling water can not decrease to the lower limit 22℃, and the energy saving rate is smaller about 1.5%. The optimal cooling water temperature is 24℃. In the period when wet-bulb temperature is low and cooling load is small, 22℃ is the optimal cooling water temperature and the energy saving rate is higher about 5.6%. Because the optimal cooling water temperature depends on cooling load and outside air wet-bulb temperature, it is necessary to search for the optimal cooling water temperature once an hour or once a day in the future research.

5.2 Analysis On Changing Operation Mode

As case study that doesn't use ice thermal storage tank is analyzed because the COP of ice thermal storage system is low, about 1.6. Five weekdays are analyzed from August 22nd to 26th, 2005, which are ordinary days of summer operation. Table-5 shows the schedule of three operation modes. The energy consumption of the whole system decreases by 18.2% when no-ice thermal storage mode is performed. However, as shown in Figure-7, in several periods chilled water supply temperature T_S exceeds 7℃, which is upper limit of supply water temperature because the terminal Air Handling Units (AHU) are refrigerant evaporation condensation type and they cannot work if chilled water temperature is higher than 7℃. Two reasons are considered for this phenomenon. 1) On the day when cooling loads are large, only running water thermal storage and chiller cannot keep T_S lower than 7℃ because of the insufficient chiller capacity. The time exceeding 7℃ is average 1.6h/day in average. It is possible to decrease this time if the efficiency of water thermal storage tank is increased. 2) During the period from 18:00 to 22:00 when cooling loads are smaller than the lower limit of chiller starts up, chilled water is cooled down only by thermal storage tank so that the temperature cannot be cooled lower than 7℃. This time is 1.5h/day in average.

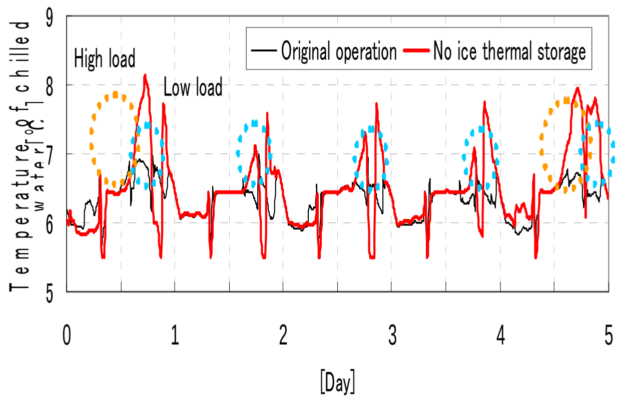
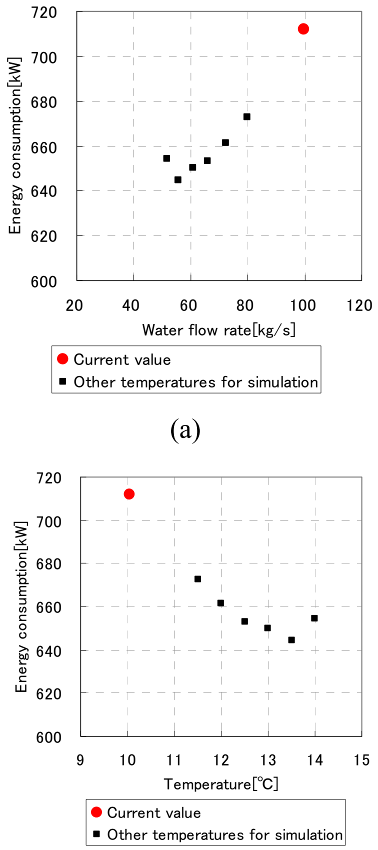


Fig.7 Temperature of chilled water



(b)

Fig.8 Energy consumption of the DHC plant V.S. chilled water return temperature(b) and water flow rate(a)

The simulation shows that if chilled water is cooled only by water thermal storage tank, the chiller water temperature can only be decreased to 7.5□. Moreover, the return chilled water temperature at low cooling load time is low to 8~9□, so the heat storage tank cannot be effectively used because of the small temperature difference between tank water and chilled water. Therefore if the ice thermal storage subsystem is not used, during the small cooling load period when main chiller R11 cannot start up, the required chilled water temperature cannot be achieved. So during this kind period, ice thermal storage system has to be used. But in period other than this situation, it should not use the ice storage system because of its low COP.

5.3 Optimization For Chilled Water Return Temperature

Although the design value for chilled water return temperature is 13±1□, the average of chilled water return temperature was 10.5□ in August 2005. In this section, the influence of chilled water return temperature to energy consumption is analyzed using the measure cooling load in August 2005.

Figure-8 shows the relations between chilled water return temperature and the total energy consumption of the DHC plant. Tabe-6 shows energy consumption at different chilled water return temperature. The heat amount discharged from the thermal storage tank increases as chilled water return temperature goes up. The chiller running time decreases in daytime and increases in nighttime, and total running time decreases become night is cooler than daytime. So that the delivery energy decreased also. The total energy consumption of the DHC plant achieved the minimum value at the temperature of 13.5□, and the total energy consumption can be reduced by 9.5%. That the average of flow rate is 55.7kg/s at 13.5□, compared with the average flow rate 99.6kg/s at the present temperature of 10.5□.

6 CONCLUSIONS

1) The operation of an existing DHC plant was visualized. From visualized chart of operation several problems were detected, and the causes were analyzed.

2) The DHC plant system model was developed and used for Retro-commissioning analysis. The model accuracy was checked through comparing model simulated data with measured data. Simulation was conducted using the models developed. The simulation error of the total energy consumption was 1.5% and the root mean square error (RMSE) was 16.3% of average measured value, which shows that the simulation is accurate enough for analyzing the performance of the DHC system.

3) The following optimization for operation was analyzed using simulation.

□Optimal cooling water temperature is analyzed and the optimal value is 22^{o}C, which can reduce the total energy consumption of the chiller and cooling tower is reduced by 2.2 %.

□The performance of not using ice thermal storage system is analyzed. The energy consumption of the whole system can be decreased by 18.2%. However, about 1.6 hours per day the chilled water temperature cannot be kept lower than 7□, which is upper limitation for supply temperature.

□The optimal chilled water return temperature from users was studied. If the temperature can be kept at 13.5□ the total energy consumption can be reduced by 9.5%.

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