ENERGY CONSERVATION EFFECT OF HEAT SOURCE SYSTEM FOR BUSINESS USE BY THE ADVANCED CENTRIFUGAL CHILLERS

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Abstract: The high-performance centrifugal chillers have been effective technology to reduce CO_2 gas and save energy by application to the heat source system for the air-conditioning since 2000. The Chillers have been installed in the latest clean rooms of semiconductor, flat-screen display and high-density storage media plants.

The high-performance centrifugal chiller, which is controlled by the inverter and has maximum COP 21.9, has been developed in Japan and it contributes to energy conservation of industrial heat source systems. This report describes that the high-performance centrifugal chillers are extremely effective to reduce energy consumption of heat source systems for air-conditioning. 50% of total energy consumption can be reduced by the new planning and operating method in the heat source systems for air-conditioning and 60% of annual energy consumption can be reduced in the centrifugal chillers, the heat source machines.

The high- performance data of centrifugal chillers are based on actual test measurements. This report also describes new performance-estimation method of cooling towers, which is indispensable for new planning and operating method, and it is verified by the comparison to the actual measurement data of a simple heat source system.

Key Words: ***Centrifugal chillers, Cooling towers, Variable speed, Actual measurement, Simulation, Energy conservation***

1 INTRODUCTION

Centrifugal chillers are large capacity heat source applicable for 350 to 35,000kW cooling capacity. In recent years, the high-performance centrifugal chiller has been developed in Japan and a lot of installation cases and energy saving effects have been reported. The conventional centrifugal chillers had high performance at the maximum capacity and performance degrade in part-load range and different cooling water temperatures. The performance of the new centrifugal chiller indicates high COP values in wide capacity range. Those COP value curves have features to follow thermodynamic characteristics, though the cooling capacity depends on cooling water temperatures.

About 60 to 70% of centrifugal chillers are operated as heat source equipment of industrial heat source systems in Japan. Large-scale semiconductor plants and flat-screen display plants have been constructed these several years and the high-performance centrifugal chillers are installed in heat source facilities of clean rooms of those plants, considering the energy saving effect. These industrial heat source systems have large cooling capacity and energy consumption, therefore, it is very active to research and report about the industrial heat source system high-performance and energy conservation point of view and such a high COP value is exactly remarkable.

On the other hand, the research regarding high-performance and energy conservation is insufficient in the heat source system for air-conditioning cooling purposes of business use. There is the feature that cooling capacity fluctuates widely depending on climate conditions and the chillers are operated at part-load during most of the operating hours. This report verifies the reduction effect of consumption energy about an actual cooling-load data of a large office building by focusing on the estimation method of the cooling tower performance and using the actual performance characteristic of the high-performance centrifugal chiller. This report also proposes the effective planning and control method of the heat source system based on its analysis.

2 HIGH-PERFORMANCE CENTRIFUGAL CHILLERS

The high-efficiency compressor, the high-performance heat exchangers and the high-level arithmetic control are essential parts of the high-performance centrifugal chillers. The high-efficiency centrifugal compressor, an aerodynamic machine, is realized by the improvement of aerodynamic performance of impellers and static channels, and reduction of mechanical losses at the bearings and gears. Additionally, the latest centrifugal chiller has the first and second inlet guide vanes to implement the optimal control, therefore, it has the unchanged high-performance characteristic even the operation point leaves the rated point.

2.1 Performance characteristic tests

The cooling capacity of the testing chiller is 1864kW. (See table1.) The testing chiller equips the inverter mottor drive and can implement both tests of variable and fixed speed control. Fig. 1 shows the flow diagram of the testing centrifugal chiller.

The verification results are indicated by COP and the calculation formula is as follows;

$$COP = \frac{Q}{E} \qquad \ldots\ldots(1)$$

$$Q = (tin - tout) \cdot \gamma \cdot \lambda \cdot F1 \ldots\ldots(2)$$

$$E = Einv + Ectl \qquad \ldots\ldots(3)$$

Q ; Cooling capacity[kW],
tin ; temperature of entering chilled water [℃]
$tout$; Chilled water leaving temperature[℃],
γ ; Specific weight of water[kg/m^3]
λ ; Specific heat of water ; [kJ/kg・K],
$F1$; Flow rate of water ［m^3/s］
E ; Electric power consumption [kW],
$Einv$; Electric power consumption of inverter [kW]
Emt ; Electric power consumption of main motor [kW]
$Ectl$; Electric power consumption of control panel [kW]

Table1; Specific values of testing machines

Item		Unit	Value	
Speed control of compressor		-	Fixed	Variable
Refrigerant		-	HFC134a	
Cooling capacity		kW (Rt)	1864 (530)	
Chilled water	Temperature	℃	14in / 7out	
	Flow rate	m^3/h	229.0	
Cooling water	Temperature	℃	32in / 37out	
Electric power consumption	Motor input	kW	295.8	
	Inverter input	kW	-	304*
	Control box	kW	1.1	
COP		-	6.30	6.13*

The cooling capacity is derived by formula (2) and the specific heat and gravity value are obtained based on the average temperature of chilled water entering and leaving. The electric power consumption of the variable speed machine is the summation of the electric power consumption of the inverter (*Einv*) and control panel (*Ectl*). The electric power consumption of the inverter panel consists of the consumption power of the main motor, inverter control panel, inverter cooling fan and electric power loss in the inverter panel and the electric power consumption of the control panel consists of the consumption power of various parts, control motor of inlet guide vanes, hot gas bypass valve, expansion valve, control board and relays in control panel, oil pump, oil heater.

In case of the fixed speed machine, the electric power consumption of the main motor (*Emt*) substitutes for the electric power consumption of inverter (*Einv*) in formula (3)

2.2 Accuracy of verification tests

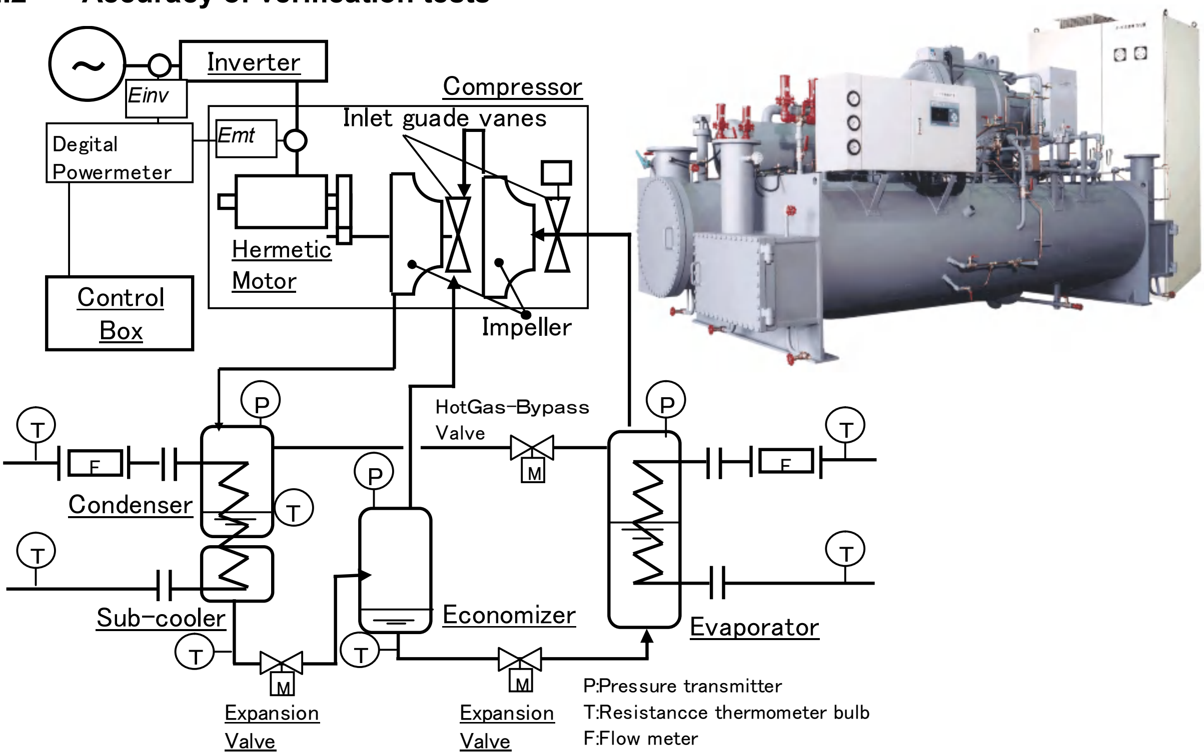


Figure 1: Appearance and Flow diagram of testing centrifugal chiller

The uncertainty of COP value is important in the energy saving evaluation of heat source systems because centrifugal chillers account for large percentages of the consumption energy.

The uncertainty of COP value is derived from formula (4) in accordance with ASME applicable criteria. The uncertainty comprises of the accuracy of each measurement sensor and converter, and they are propagated independently. The uncertainty of COP value in formula (1) depends on the relative accuracy of each measurement value of chilled water entering temperature, chilled water leaving temperature, chilled water flow rate, chilled water specific heat, chilled water density, electric power consumption. When the centrifugal chiller is operated at a constant chilled water flow rate, the temperature difference between the chilled water entering and leaving is small at the part load and the uncertainty will be increased because the denominator of first and second item of right-hand side in formula (4) will be small. The temperatures are measured by the resistance-thermometer bulb thorough converters and receivers in the actual testing machine. (See fig.1.) Therefore, the sensors to measure the chilled water entering and leaving temperature are put in the constant-temperature zone, which is kept at 10.5℃±0.1℃, together with a reference thermometer and each thermometer is adjusted. The water flow rates are measured by orifices through differential pressure transmitters and receivers. And the orifice diameter and pipe internal diameter are also measured. The Zero point adjustment is implemented by the differential pressure open. As a consequence of above careful processes to eliminate the uncertainty in measurement, the range of uncertainty is reduced to ±2.64%～±5.98% from ±3.61%～±8.49% at 100%～40% part load range. The variable speed machine includes the relative accuracy of the inverter power consumption and the uncertainness is bigger than that of the fixed speed machine.

$$\frac{\delta COP}{COP}=\left[\left(\frac{\delta T_{in}}{T_{in}-T_{out}}\right)^2+\left(\frac{\delta T_{out}}{T_{in}-T_{out}}\right)^2+\left(\frac{\delta F1}{F1}\right)^2+\left(\frac{\delta \gamma}{\gamma}\right)^2+\left(\frac{\delta \lambda}{\lambda}\right)^2+\left(\frac{\delta E}{E}\right)^2\right]^{0.5} \quad \text{……(4)}$$

$\frac{\delta COP}{COP}$; relative accuracy of COP, $\frac{\delta T_{in}}{T_{in}-T_{out}}$; relative accuracy of entering water temp

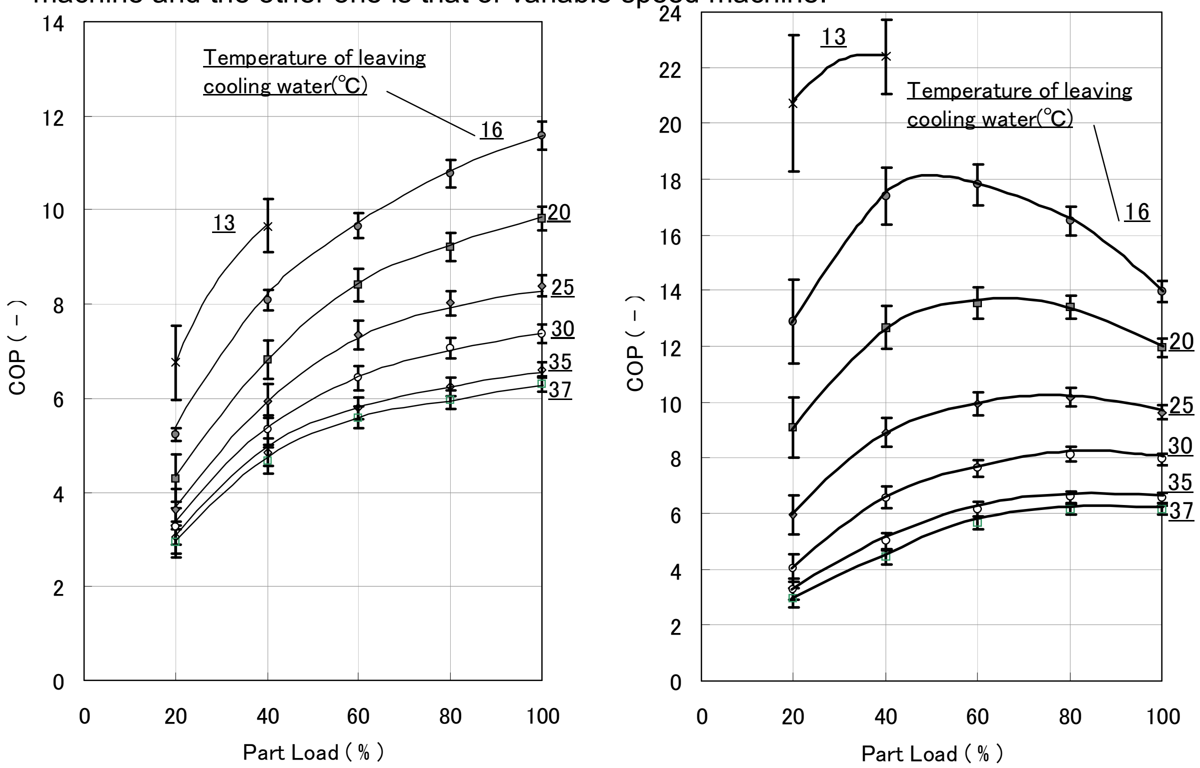
$\frac{\delta T_{out}}{T_{in}-T_{out}}$; relative accuracy of leaving water temp, $\frac{\delta F1}{F1}$; relative accuracy of flow rate

$\frac{\delta \gamma(Ts)}{\gamma}$; relative accuracy of specific weight, $\frac{\delta\lambda(Ts)}{\lambda}$; relative accuracy of specific weight

$\delta E/E$; relative accuracy of electric power consumption

2.3 Measured performance

Fig. 2 shows the COP value curves, the test result of the testing machine (table. 1) based on the cooling water temperature and cooling capacity. The left graph is that of fixed speed machine and the other one is that of variable speed machine.



Performace curves of the centrifugal chiller (Fixed rotated speed)

Performace curves of the centrifigual chiller (Variable rotated speed control)

Figure 2: Performance curves of the centrifugal chillers

On the premise that cooling water flow rate is constant, when the COP value characteristic is shown in full load ranges, it is general to arrange the data in the cooling water leaving temperature. However, when the performance of heat source system is evaluated, the cooling water flow rate differs depending on the design and operating method, therefore, the performances are shown in cooling water leaving temperature and part load rate. Additionally, the said uncertainty is indicated with each error-bar as acceptable range of the true values. The plotted values are indicated in table 2 and 3.

In the fixed speed machine, the COP value becomes higher as the cooling water leaving temperature becomes lower and the part load rate becomes higher. In the variable speed machine, the COP value becomes higher as the cooling water leaving temperature becomes lower, however, the maximum COP value point exists at each cooling water leaving temperature. For the conventional design and operation methods, chillers were planed to operate at the highest performance point with keeping the maximum load. But the variable speed machine has the different part load rate with maximum COP values at each temperature of cooling water leaving and the previous method is insufficient. It means that new planning and operating method is required

The existing centrifugal chillers started to be installed in the middle of 1990's and had COP value 4.9.

Table2: COP of fixed speed centrifugal chiller (latest)

Cooling Load	Uncertainness (%)	Temperatures of leaving cooling water (℃)						
		37	35	30	25	20	16	13
100% 1864kW	±2.62	6.32	6.62	7.39	8.40	9.85	11.6	-
80% 1491kW	±3.17	5.99	6.27	7.08	8.04	9.24	10.8	-
60% 1118kW	±4.09	5.61	5.81	6.44	7.36	8.43	9.69	-
40% 746kW	±5.97	4.69	4.87	5.34	5.96	6.85	8.11	9.67
20% 373kW	±11.7	2.95	3.05	3.29	3.64	4.31	5.24	6.76

Table3: COP of variable speed control centrifugal chiller (latest)

Cooling Load	Uncertainness (%)	Temperatures of leaving cooling water (℃)						
		37	35	30	25	20	16	13
100% 1864kW	±2.64	6.13	6.56	7.95	9.62	11.9	14.0	-
80% 1491kW	±3.18	6.13	6.59	8.13	10.2	13.4	16.5	-
60% 1118kW	±4.10	5.67	6.16	7.62	9.93	13.6	17.8	-
40% 746kW	±5.98	4.43	5.02	6.58	8.90	12.7	17.4	22.4
20% 373kW	±11.7	2.96	3.27	4.05	5.94	9.09	12.9	20.7

Table4: COP of fixed speed centrifugal chiller (conventional)

Cooling Load	Temperatures of leaving cooling water (℃)						
	37	35	30	25	20	16	13
100% 1864kW	4.90	5.78	5.15	6.52	-	-	-
80% 1491kW	4.78	5.59	5.00	6.32	-	-	-
60% 1118kW	4.21	4.95	4.42	5.59	-	-	-
40% 746kW	3.18	3.74	3.33	4.19	4.50	-	-
20% 373kW	1.67	1.98	1.76	2.22	2.38	-	-

3 Estimation model of cooling tower performance

The proper calculation method of the cooling tower performance is indispensable to evaluate the heat source system for business use, which is influenced greatly by climate conditions. However, in the past performance estimation of the cooling tower has not been implemented properly in many simulation models of heat source systems. Therefore we have developed the simulation model and compared the results of it with actual measurement data for verification.

3.1 Estimation model

The open-circulating cooling tower is equipment to cool water by heat exchange with air. It is equipped with quite a lot of resin plates to increase heat transfer areas. Water flows down the surfaces of resin plates and exchanges the heat with air from fans on liquid film surface. In this report, focusing on the evaporative heat transfer surface of falling liquid films to estimate the performance of the open-circulating cooling tower, the estimation model (fig. 3) have been developed to apply to the simulation of heat source systems. The validity was evaluated by applying the estimation model to the measurable simple heat source system.

3.2 Heat source system for validity evaluation

The actual measurement data were used to verify the validity of the estimation model of the cooling tower performance. The actual measurements were implemented for the simple heat source system, which consisted of one unit of centrifugal chiller and one unit of cooling tower, and the actual data were compared with output of the estimation model.

3.3 Validity of calculated temperature of leaving cooling water

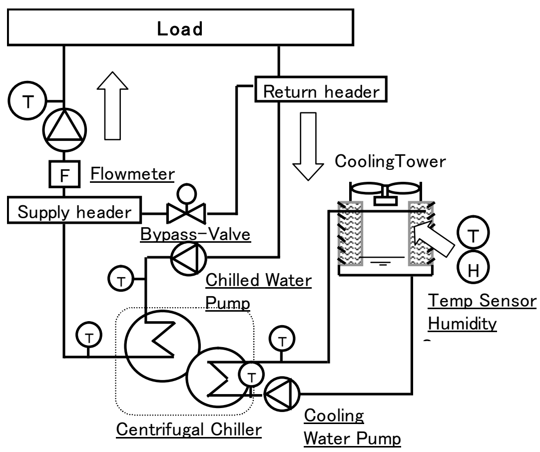
The actual measurement values for the evaluation are that of dry-bulb temperature, wet-bulb temperature, cooling water entering and leaving temperature to cooling tower, chilled water flow rate. And the measurement cycle is one minute.

The calculated value of the cooling water leaving temperature was derived by the said calculation method and compared with the actual measurement value.

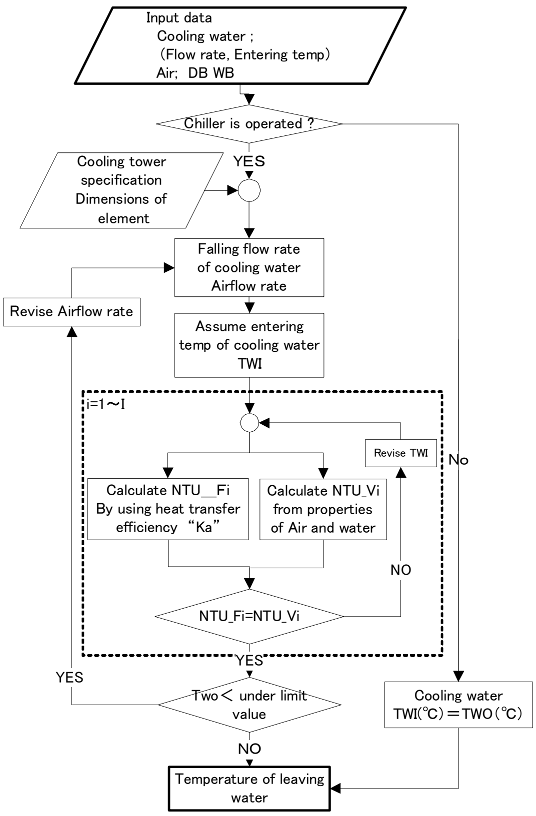
As fig. 4 shows, the actual measurement data were coincident with the calculated value including dynamic trends. However, the difference between measured and calculated value was confirmed when wet-bulb temperature closed to dry-bulb temperature and relative humidity was high, or the load was over the rated cooling capacity.

Fig. 4 also shows the difference between calculated and measured values. The differences are almost below 1℃ within the range of the rated cooling capacity and the peak point has the value of -0.3℃. It means that the calculated values are coincident with the actual measurement values.

Considering the percentage of part load range is higher in business use, this calculation can be evaluated to have enough accuracy for the simulation.

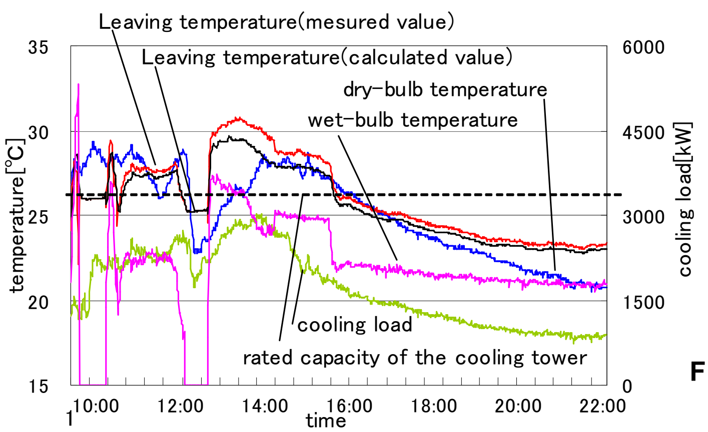


(a) Flow diagram



(b) Calculation flow diagram

Figure 3: Performance prediction of cooling tower



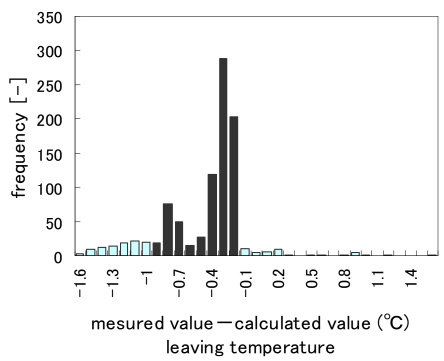
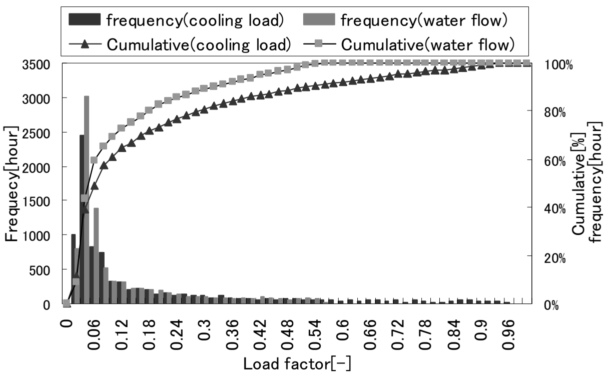


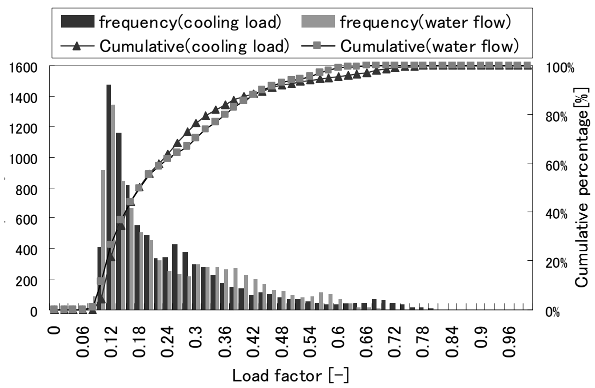
Figure 4: Comparison with the calculated values and the measured values

4 SIMULATION ALGORITHM OF HEAT SOURCE SYSTEM

4.1 Actual load for evaluation

The load of heat source systems for business use consists of the high intensive cooling load in summer time, little load in winter time and low intermittent load in spring and autumn time. Recently some buildings have the constant heating loads of personal computers and server machines throughout the year.
The actual load data of below two buildings were used for the analysis of energy saving effect. The actual data consists of date and hourly data of the chilled water temperature and flow rate throughout the year. Those two buildings are located in same area. Therefore, the data of the Japan Metrological agency at same area and time are used for dry-bulb temperature and humidity. Fig.5 arranges the frequency and cumulative value about cold demands and chilled water flow rate demands.





Building A **Building B**

Figure 5: Accumulated cooling loads

Building A:（Very few load in winter time）.

The cooling load rate has the highest frequency from 2%, annual maximum rate of cooling load, to 4%, and the frequency is 2440 hours, 28% of cumulative hours. And the load rate below 30% accounts for more than 80% of annual cumulative hours. (See fig. 5.) This building has the typical type of load for business use air-conditioning. Since temperature difference between supply and return water is smaller than design value, the number of operating chillers are determined by flow rate demand, that is larger than the number of chillers required by heat load

Building B: (Low base load in winter time).

The cooling load rate has the highest frequency from 10%, annual maximum rate of cooling load, to 12%, and the frequency is 1470 hours, 17% of cumulative hours. And the load rate below 30% accounts for more than 80% of annual cumulative hours as same as building A, however, the base load is over 10%. There is the business load by many computers and servers. Since temperature difference between supply and return water is almost same as design value, the number of operating chiller is determined by heat load.

4.2 Elements of heat source system

Based on some preconditions, the heat source system was planned and it corresponds to the building A and B
(See fig. 6.)
- Consists of only centrifugal chillers

- Two capacity ranges, big and small
 Big type has double capacity of small type (Considering maintenance and backup)
- Consists of 5 to 6 units and apply to low load with high frequency by quantity control
- One set consists of a centrifugal chiller, a cooling tower, a chilled water pump, a cooling water pump

4.3 Simulation procedures

Fig.8 shows the flow diagram of the simulation procedure. First, the number of centrifugal chillers is calculated from the actual load data and cooling water leaving temperatures are assumed from air conditions. The exhaust heat of centrifugal chillers, heat load of cooling towers, is calculated from the performance data of centrifugal chillers. Additionally, the cooling water leaving temperatures of cooling tower are calculated by the said estimation method of cooling tower performance with air condition data and property program.

The calculations are repeated until the first assumption values would be correspondent with calculated values in cooling water leaving temperatures. The air volume to cooling towers is reduced by the moderation control of cooling tower fan when the cooling water leaving temperatures of cooling towers is below 12 ℃, the lower limit temperature. The power of pumps and cooling tower fans are calculated from the required head and if the cooling water flow rate will reduce, the flow rate is proportion to the frequency and power is proportion to the cube of flow rate.

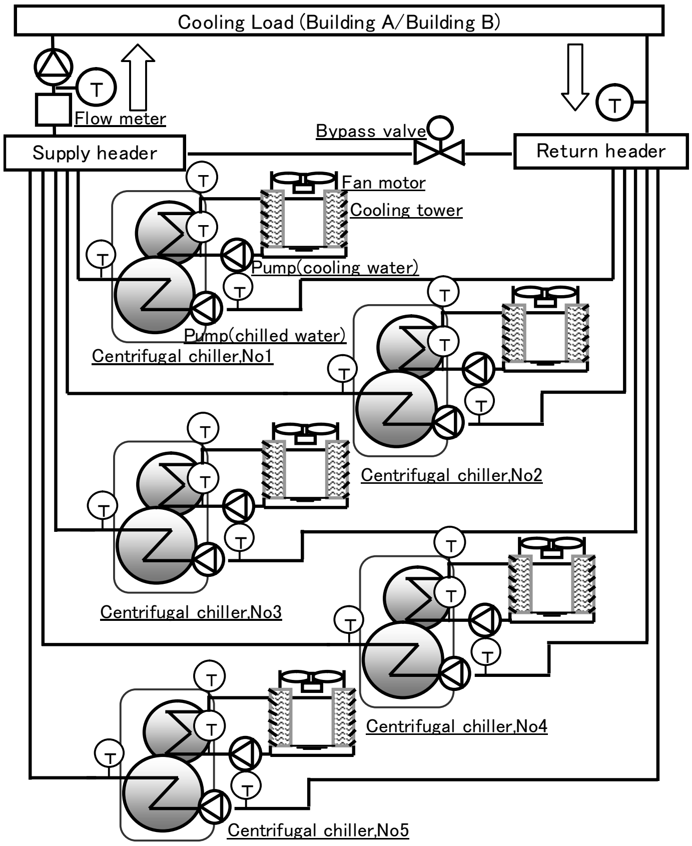


Figure 6: Flow diagram of heat source system

5 ENERGY CONSERVATION EVALUATION

5.1 Cases for evaluation

The effects of energy saving is evaluated by each technical elements as follows;

- Up grading to high performance chillers

STEP1; Replace conventional chillers with latest fixed speed machines
STEP2; Replace conventional chillers with latest variable speed machines

- Improvement of system and operation

Technique 1; In addition to step2, operation is improved to make chillers operated at optimum point and introduction of variable-speed chilled water pump and cooling water pump
Technique2; In addition to technique1, increase cooling tower capacity to 120%
Technique3; In addition to technique2, increase cooling tower capacity to 150%

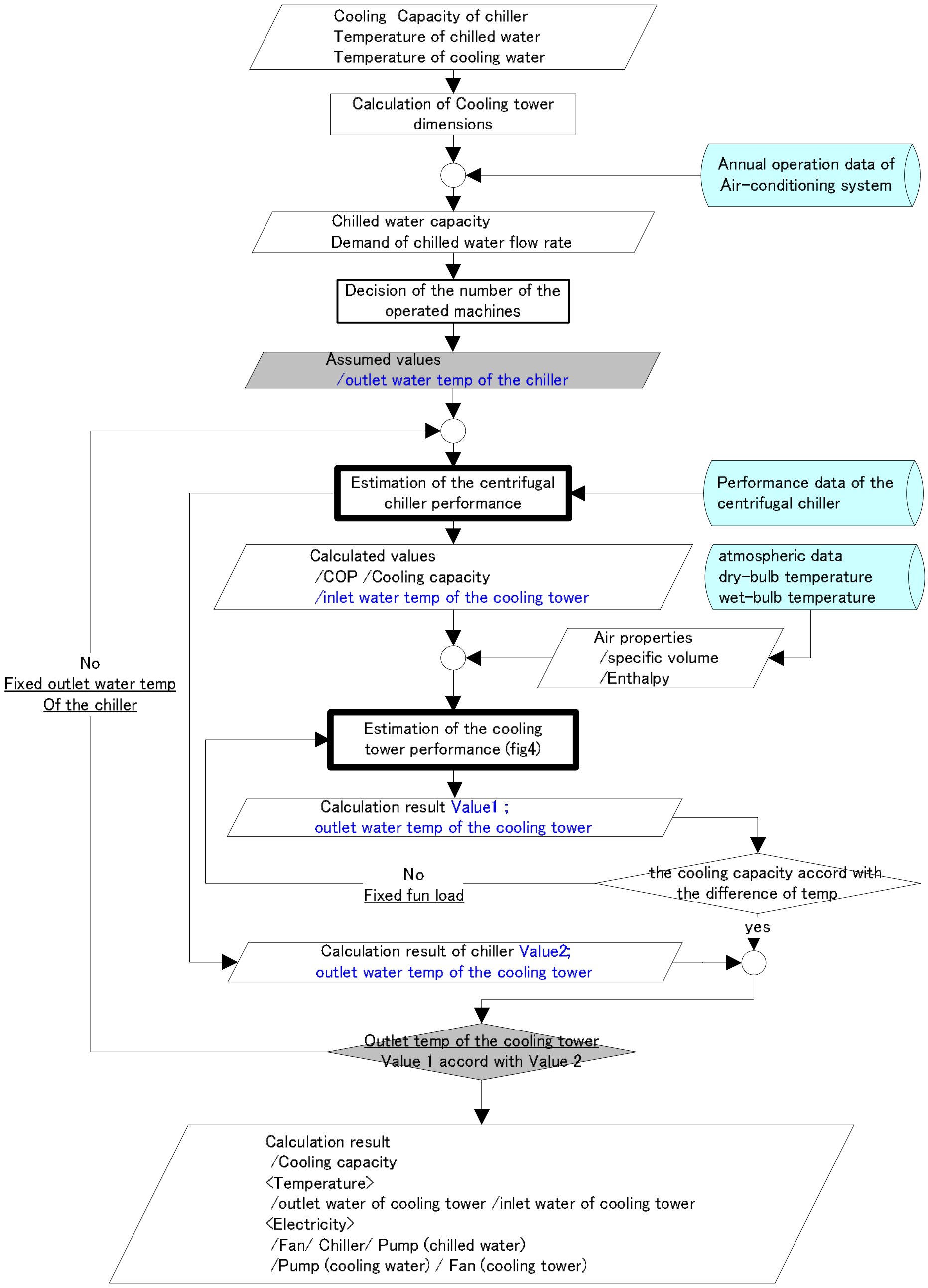


Figure 7: Simulation model flow diagram

5.2 Effects of high-performance chillers

High performance chillers are very effective to reduce energy consumption and the coefficient of performance, the annual out put heat divided by consumption energy, have been improved by 42% / 54% (building A/ building B) for the fixed speed machines and by 85% / 129% for the variable speed machines. It is more effective for building B because it has the base load in winter time. Annual equipment COP value reaches to 7.08/7.70. (Table 5) However, there is no reduction of power consumption for auxiliaries, chilled water pump, cooling water pump and cooling tower, because the preconditions for auxiliaries were same . Consequently, consumption energy percentages of auxiliaries are extremely high in whole heat source system. It increases from 23% to 36% in building A and from 24% to 43% in building B. The consumption power of auxiliaries accounts for same percentage, regardless the load characteristics, in the conventional performance chillers. However, the energy saving of auxiliaries is the considerable subject in high performance centrifugal chillers. Therefore it is obvious that new operation method is necessary for heat source system and auxiliaries. The consumption energy in total heat source system is reduced by 22.6% / 26.6% (building A / building B) in the latest fixed speed machines and by 35.2% / 42.1% in the latest variable speed machines.

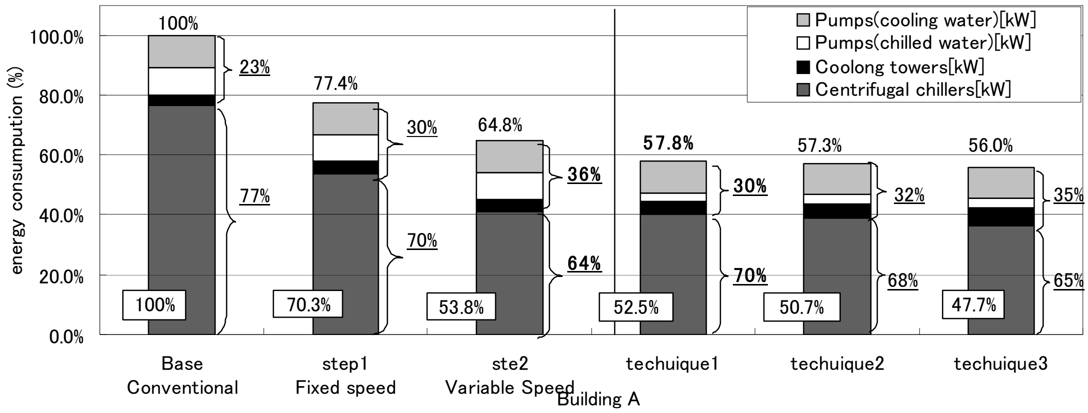
Table5: Energy consumptions of simulation results)

Performance Of for a yaer	Building A		Building B	
	Chiller COP	System COP	Chiller COP	System COP
<u>Base</u> ; conventional	<u>4.98 (100%)</u>	3.81 (100%)	<u>4.97 (100%)</u>	3.77 (100%)
<u>Step1</u> ; Fixed speed	<u>7.08 (142%)</u>	4.92 (129%)	<u>7.70 (154%)</u>	5.10 (135%)
<u>Step2</u> ; Variable speed	<u>9.25 (185%)</u>	5.88 (154%)	<u>11.4 (229%)</u>	6.52 (173%)

Table6: Energy consumed percentage for each machinery

Performance Of for a yaer	Building A				Building B			
	chiller	Pump		Cooling tower	chiller	Pump		Cooling tower
		Chilled water	Cooling water			Chilled water	Cooling water	
<u>Base</u> ; conventional	76.5%	9.1%	10.8%	3.6%	75.9%	9.7%	11.7%	2.8%
<u>Step1</u> ; Fixed speed	53.8%	9.1%	10.4%	4.1%	49.0%	9.7%	11.2%	4.0%
<u>Step2</u> ; Variable speed	41.2%	9.1%	10.4%	4.1%	33.0%	9.7%	11.3%	4.0%
Technique 1	40.2%	3.2%	10.4%	4.1%	32.2%	4.9%	11.3%	4.0%
Technique 2	38.8%	3.2%	10.5%	4.8%	30.9%	4.9%	11.3%	4.4%
Technique 3	36.5%	3.2%	10.4%	5.9%	28.9%	4.9%	11.3%	4.9%

Note) Above all COP values are indicated compared to conventional heat source systems, COP 4.9, as 100% consumption energy.



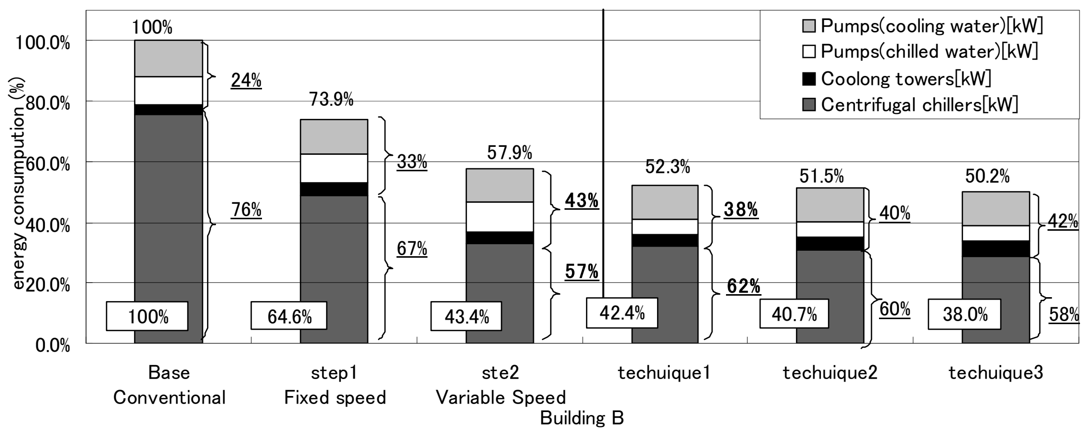
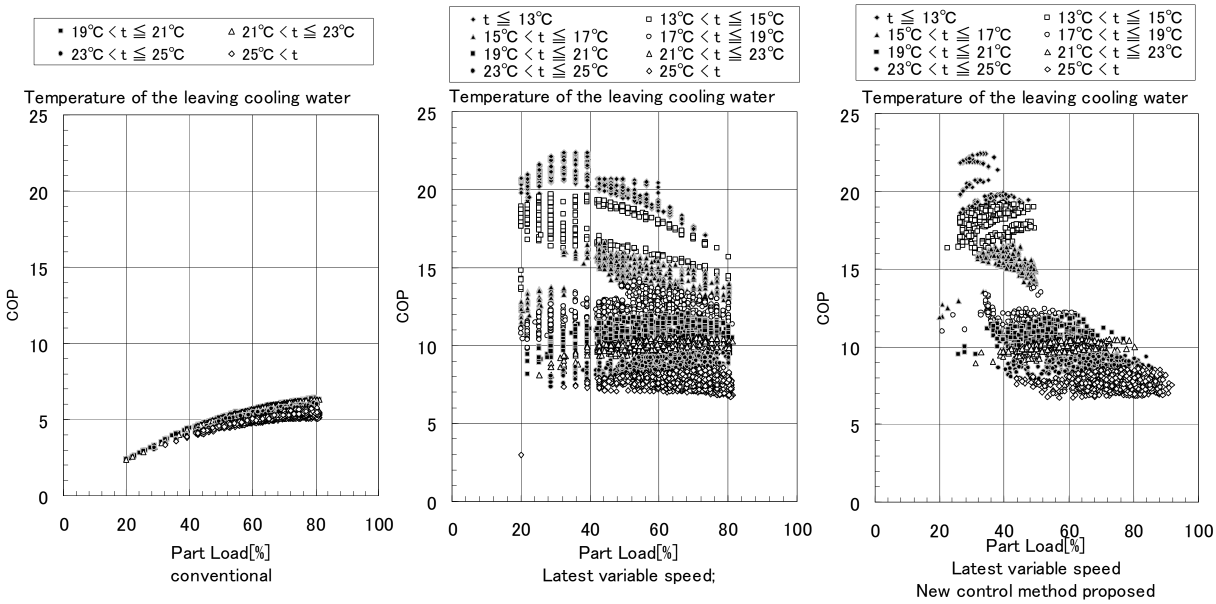


Figure8: Results of simulation

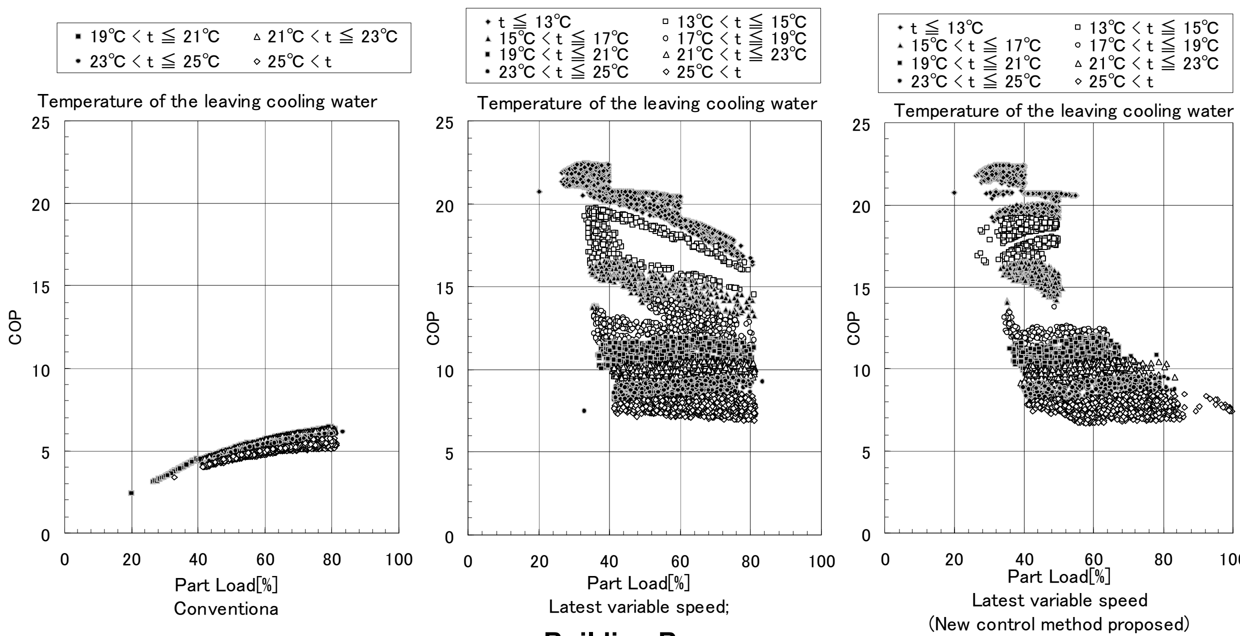
5.3 Effects of improvement of system and operation

In tequnique1, about 60% consumption energy was reduced in the chilled water pump of building A and about 50% consumption energy was reduced in the chilled water pump of building B. And the auxiliary power rate of building A / building B was improved to 30%/38% substantially. The results of Technique 2 and 3 about effects of cooling towers are below 2% consumption energy saving. However, about 10% consumption energy was reduced in the heat source machine unit.

5.4 Effective use of high performance centrifugal chillers



Building A



Building B

Figure9: Change operated points of centrifugal chiller

The high performance centrifugal chillers, heat source machines, contribute extremely to the reduction of consumption energy. This report verified the specific load, building A and B,

but the heat source machines need to correspond to various loads properly. Therefore, the subjects to the previous clause are revaluated in operational point of view of centrifugal chillers.
Based on loads and the chilled water temperatures, operational points are plotted for all models, conventional machines, latest variable speed machine, latest variable speed machine No.1 with new operation method, latest variable speed machine No.2 with new operation method. (See fig. 9) In the conventional machines, even if the operational point has low cooling water temperature, the consumption power reduction is not expected due to the part load rate characteristics and it is only effective to operate around at the maximum load point. In same cooling water conditions, high performance machines are effective to improve COP values extremely in low temperatures of cooling water. Additionally, new operating method improves to find the highest COP value per each cooling water temperature. Consequently, low load operation is most appropriate for the latest variable speed machines in low cooling water temperature. And the operational points of each cooling water temperature overlap with the peak points of COP values. The substantial energy saving is estimated in the building, which has the appropriate load in winter and intermediate season.

6 CONCLUSION

We concluded through the actual data analysis that energy saving technology by the high performance centrifugal chillers of industrial heat source system is also effective in typical air-conditioning heat source system for business use. Compared to the existing heat source machines, the effect is 50% reduction of consumption energy in whole heat source system and 60% reduction only in centrifugal chillers. It is the mistaken perception that high performance centrifugal chillers are suitable for the industrial use, which has high loads in winter and intermediate season, and are not suitable for air-conditioning use, which has high loads mostly in summer.
When we use the high performance centrifugal chillers, we can get enough effects of consumption energy reduction at any loads. However, the performance of latest chillers has been improved depending on the cooling water temperature and the improvement of cooling tower performance increases the effects much more. Additionally, it is indispensable to pay attention to the consumption energy of auxiliaries, chilled water pump, cooling water pump and so on because the consumption energy of chillers was reduced substantially.

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