EVALUATION AND SIMULATION OF COST SAVING OPERATION FOR THERMAL STORAGE HVAC SYSTEM

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ABSTRACT

Three indices are introduced in order to evaluate cost saving operation of chillers using nighttime low electric power rates for thermal storage systems with water tanks. A storage tank discussed here is a multi-connected complete mixing type, which is widely used in Japan. The indices are calculated with some measured data. In this paper, definitions of the indices are described, and one of evaluation results in actual office buildings is shown. Moreover, differences among the indices applied to simulation results are compared under several combinations of chiller capacity, tank capacity and set point temperature in the tank for chiller on/off control. As a result, these indices give us useful information if operation of thermal storage HVAC system can be more economical.

INTRODUCTION

Electric utilities offer financial incentives in the form of specialized electric power rates to encourage customers to shift their on-peak electric energy consumption to off-peak periods using thermal storage systems. One of them is the nighttime (off-peak from 10 p.m. to 8 a.m.) electric power rates, which are applied to systems shifting a part of daytime (from 8 a.m. to 10 p.m.) electric power consumption to nighttime.

Many building owners who install thermal storage system hope to reduce operating costs by utilizing nighttime rates. However, several faults on design, operation and maintenance prevent the owners from saving the operating costs. Though there are some cases that the faults are easily to be corrected such as mistakes in set point, few owners and operators recognize them due to lack of sufficient experience. This causes distrust for thermal storage systems because cost merits are a little. Therefore it is significantly important for the designers and engineers to evaluate the operation of the thermal storage systems on behalf of owners.

The purpose of this study is to investigate whether the proposed indices are effective in evaluating the chiller cost saving operation for various thermal storage HVAC systems. If the indices are effective, they will provide useful information to building owners or operators.

EVALUATION

The indices are introduced to evaluate daily chiller operation. In this paper, 'one day' means the period from 10 p.m. of previous day to 10 p.m. of evaluated day (24 hours), 'nighttime' means from 10 p.m. of previous day to 8 a.m. (10 hours) and 'daytime' means from 8 a.m. to 10 p.m. (14 hours).

Indices for Cost Saving Operation

One of the most popular indices for cost saving operation of thermal storage systems in Japan, 'peak shaving factor', is the ratio of consumed electric power or generated cooling energy in the nighttime against total of it. However, it is not enough to judge the nighttime chiller operation merely from its value because its appropriate value varies according to tank capacity, chiller capacity and cooling loads. This is a reason why additional indices are needed. The concepts of evaluation indices are as follows, and three indices are defined by *Equations (1)* to *(3)*.

1. Whether charged cooling energy in storage tank in the nighttime was maximum or not.
2. Whether charged cooling energy was discharged completely in the daytime or not.

$$S_0 = \frac{Gnight}{Gnight + Gday} \qquad (1)$$

$$S_1 = \frac{Q8 - Q8,req}{Qtank} \quad (2)$$

$$S_2 = \frac{Qover}{Qtank} \quad (3)$$

S_0 is 'peak shaving factor' based on generated cooling energy. This value is useful to estimate the utilization of low electric power rates for a day. However, it may not show the possibility for cost saving operation.

S_1 evaluates whether the nighttime chiller operation is optimal or not. In *Equation (2)*, *Q8,req* represents the required cooling energy in the tank at 8 a.m. in case that the chiller operates ideally in order to utilize the low electric rates in the nighttime, and defined as follow.

$$Q8,req = min(Lday, Qtank, Qc + Qt,y22) \quad (4)$$

In this equation, '*min*' is the operator that chooses the minimum value among three factors. *Lday* is the cooling load integrated during the daytime. *Qtank* is the maximum storable cooling energy in the tank, and it is estimated by whole water volume in the tank and the difference of average temperatures when cooling energy is fully charged and completely discharged. *Qc* is the storable cooling energy when the chiller operates throughout the nighttime (10 hours), and is defined by the chiller capacity (*G*) and by the nighttime cooling load (*Lnight*) as follow.

$$Qc = 10 \cdot G - Lnight \quad (5)$$

Qt,y22 is the remaining cooling energy in the tank at 10 p.m. of previous day when nighttime electric rates are applied. The value is also calculated with measured temperature in several divided tanks of multi-connected storage tank and discharged average temperature used in *Qtank*.

In *Equation (2)*, *Q8* is the actual charged cooling energy in the tank at 8 a.m. when nighttime rates application ends, and it is calculated by sum of the charged energy in the nighttime represented as *Qnight* (= *Gnight* - *Lnight*) and *Qt,y22* mentioned above.

After all, S_1 evaluates whether the actual generated cooling energy in the nighttime was as ideal as follows.

1. If the daily load was very small, chiller should have generated the cooling energy in the nighttime as much as load.
2. If the tank size was very small, chiller should have been operated until the tank was fully charged.
3. If the chiller capacity was very small, chiller should have been operated throughout nighttime.

According to *Equation (2)*, the chiller operation would be said as proper when S_1 is nearly equal to zero. If S_1 is negative, the nighttime operation is insufficient. If S_1 is positive, it means that the nighttime operation was excessive, and will cause the increase in heat losses from tank walls.

S_2 evaluates whether chiller daytime operation is minimized. This index becomes efficient only when S_1 is judged as proper. In *Equation (3)*, *Qover* is fundamentally the amount of cooling energy in the tank at 10 p.m. of evaluated day. However, if chiller capacity is very small against tank capacity and cooling load, the chiller has to start operation before 10 p.m. for the purpose of charging the cooling energy to meet the cooling load next day. Therefore this increased cooling energy in the tank is subtracted from *Qover* so as to prevent S_2 from judging it as excessive operation.

The chiller operation would be said as proper when S_2 is nearly equal to zero. If S_2 is positive, daytime chiller operating time seems too long, and it might cause the reduction of next nighttime operation in some case. By the way, S_2 will not become negative because the *Qover* is defined based on the amount of charged cooling energy in the tank.

In most cases, heat losses from tank in the daily cyclic operation are usually small, so it would be unnecessary to judge a nighttime excessive operation as improper. However, the ratio of the heat losses against small cooling load in off peak season is

S_0	0.53	0.54	0.53	0.44	1.00	0.00	0.76
S_1	-0.01	-0.04	-0.08	0.21	1.00	-0.05	0.18
S_2	0.25	0.24	0.26	0.71	0.88	0.33	-

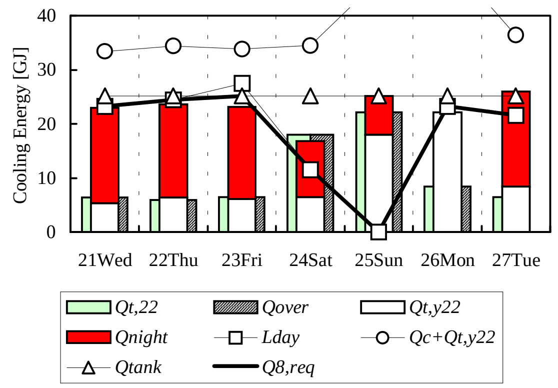

Figure 1. Example of Evaluating Result

significant. In this paper, for simplicity, all the cases of excessive operation are evaluated as improper.

Example of Evaluation

An example of evaluation of an actual office building is shown in *Figure 1*. On the day of '23 Friday', S_0 = 0.53, and this means that about a half of total chiller operation was operated in the nighttime, but it was not clear whether the operation utilized the nighttime electric rates to the maximum. As to the case of S_1 = -0.08, it is recognized that *Qtank* is selected as *Q8,req*, and *Q8* (= *Qnight* + *Qt,y22*) is nearly equal to it. From S_1, it seemed that chiller was operated properly in the nighttime. However, S_2 is a little larger than zero (S_2 = 0.26) due to daytime chiller operation, and it reduced the utilization of next nighttime electric rates.

Figure 2 shows the temperature profiles in the tank on that day. *Qover* is estimated roughly as the area between '4 p.m.' line and '10 p.m.' bold line. However, this cooling energy must have been unnecessary because next *Lday* was small as shown in *Figure 1*. So the whole cooling energy in the tank at 10 p.m. (*Qt,22*) becomes *Qover*. This excessive cooling energy was mainly generated by chiller operation from 8 p.m. (20:00) as shown in *Figure 3*.

Evaluation results on the other days are also the same as this day. Furthermore, chiller operation time on weekends is too long as described by large S_1. According to these evaluation indices and *Figure 1*, it is able to propose that chiller operating schedule from 8 p.m. and on weekends should be improved in order to increase the utilization of nighttime electric rates.

SIMULATION

For the purpose of confirming the effectiveness of indices, chiller operations for various combinations of chiller and tank capacities are simulated, and evaluation indices are applied.

The thermal storage HVAC system for simulation study is assumed to be composed of a thermal storage water tank of the multi-connected complete mixing type, a chiller, a cooling tower and air handling units (AHU). The storage tank is divided into 25 sub-tanks connected in series. The thermal storage system is shown in *Figure 4* schematically.

Tank model of multi-connected complete mixing type is based on assumption in modeling that all parts of each divided tank are useful to thermal storage, i.e.,

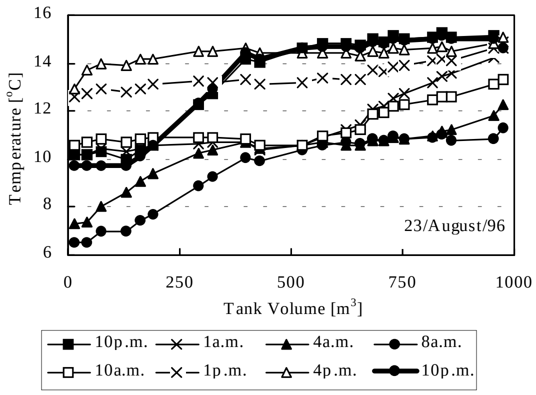

Figure 2. Temperature Profiles in Tank

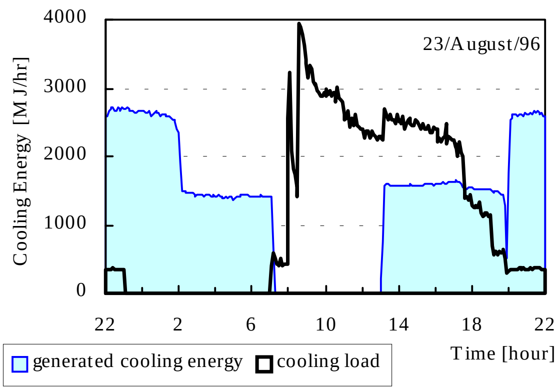

Figure 3. Load and Generated Cooling Energy

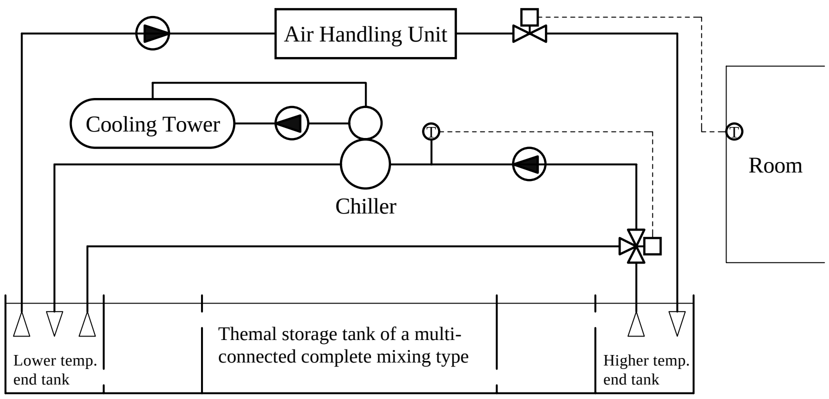

Figure 4. Thermal Storage System for Simulation Study

there are no useless (dead zone) parts, and water is mixed completely in the tank before enters the next divided tank.

Under this assumption, water temperature in the *i* th tank of divided tanks is calculated by the following equation (See *Figure 5*).

$$\rho \cdot c_p \cdot V_i \cdot \frac{dt_i}{dT} = \rho \cdot c_p \cdot F \cdot (t_{i-1} - t_i) \qquad (6)$$

where,

$$t_0 = t_{in}, \qquad V = \sum_{i=1}^{N} V_i, \qquad i = 1, \cdots, N \qquad (7)$$

The chiller modeling is based on the strategy proposed by M.Udagawa *et al.*[1] This calculated model was developed for compression type of chillers, and based on cooling and heat rejection rates and power input in compressors. This model solves a chiller (evaporator) outlet water temperature using the given inlet water temperature, water flow rate, cooling water temperature and so on.

The cooling tower model is taken from the HASP/ACSS software[2] that is commonly utilized to estimate annual energy consumption of HVAC systems. This model solves the outlet cooling water temperature from the tower using the given cooling water flow rate, ambient wet bulb temperature, specific values of the cooling tower and so on.

The air handling unit modeling is based on static analysis of each coil's row proposed by K.Yamagishi *et al.*[3] This model solves outlet water and air temperatures from coil using the given chilled water flow rate, inlet water temperature and so on.

CASE STUDY

In case study, the combinations of factors on chiller operating schedule, chiller capacity, tank capacity and chiller on/off set point temperatures in the tanks are classified into 8 cases. All cases are simulated for a week in summer under the conditions of components as follows.

Building (Room)
The supposed office building for simulation consists of four same floors. A floor area for cooling is 960 m^2, and total area is 3,840 m^2.

Cooling Load
The cooling loads for simulated period are shown in *Figure 6*. They are calculated hourly with the HASP/ACLD software that is popular program in Japan for annual load calculation under standardized weather data. The daily load of the peak day is approximately 10,500MJ at 'DAY7' in *Figure 6*.

The thermal storage HVAC system is simulated every three minutes, so the cooling load data of same time interval are generated by means of interpolating the hourly data linearly.

Air Handling Unit (Coil)
The air handling unit is CAV type, and one unit is installed in each floor. The chilled water flow rate is controlled to meet cooling load by two-way-valve, and the temperature of inlet chilled water is put equal to that of lower temperature end tank.

Thermal Storage Tank
The number of divided tanks of multi-connected complete mixing type (*N*) is twenty-five and the volumes of divided tank (V_i) are equivalent to each other. In following case study, when the *V* varies, *N* is constant but each V_i varies proportionally.

The parameter *Rv* is introduced for various tank capacities in this case study.

$$Rv = \frac{V}{V_s} \qquad (8)$$

where,

$$V_s = \frac{L\,max}{\rho \cdot c_p \cdot \Delta t} \qquad (9)$$

Lmax is the daily load of the peak day, and Δt represents the maximum difference of average temperatures in the tank (7°C constant in this paper). Therefore *Rv* also shows the ratio of *Qtank* to *Lmax*.

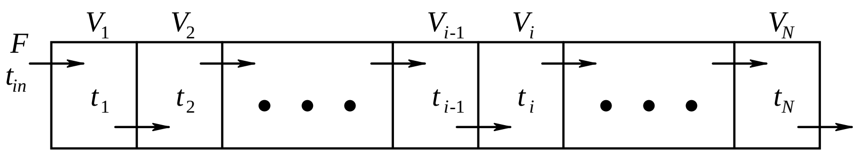

Figure 5. Thermal Storage Tank Consisting of Divided Tanks Connected in Series

Table 1. Time Set for Chiller Operation by Timer

	Timer1	Timer2	Timer3
Nighttime	10:00 p.m. - 8:00 a.m. (DAY1: 0:00 a.m. - 8:00 a.m.)	10:00 p.m. - 8:00 a.m. (DAY1: 0:00 a.m. - 8:00 a.m.) (DAY4: no operation)	10:00 p.m. - 5:00 a.m. (DAY1: 0:00 a.m. - 8:00 a.m.) (DAY4: no operation)
Daytime	8:00 a.m. - 6:00 p.m.	8:00 a.m. - 6:00 p.m. (DAY3: 8:00 a.m. - 3:00 p.m.) (DAY4: no operation)	8:00 a.m. - 6:00 p.m. (DAY3: 8:00 a.m. - 3:00 p.m.) (DAY4: no operation)

DAY3 is Saturday, DAY4 is Sunday

Table 2. Simulation Cases for Thermal Storage HVAC System

Case	Operation Mode	*Rg*	$t_{l,limit}$ [°C]	$t_{h,limit}$ [°C]	Three-way-valve
CASE1	Prediction	0.40	10.0	10.0	Normal
CASE2	Prediction	0.50	10.0	10.0	Normal
CASE3	Prediction	0.75	10.0	10.0	Normal
CASE4	Prediction	1.00	10.0	10.0	Normal
CASE5	Timer1	0.50	6.0	10.0	Normal
CASE6	Timer2	0.75	8.0	12.0	Normal
CASE7	Timer3	1.00	10.0	10.0	Normal
CASE8	Timer2	0.75	8.0	10.0	Abnormal

Chiller

The chiller inlet water temperature is controlled at 12°C by three-way-valve in case of normal condition (non-faulty condition), and the flow rate is set constant so that the outlet temperature is kept about 7°C.

In case study, the parameter *Rg* is used for comparison of different chiller capacities.

$$Rg = \frac{G}{G_s} \qquad (10)$$

where,

$$G_s = \frac{L\,max}{10} \qquad (11)$$

G_s is a chiller capacity standardized the time-averaged *Lmax* for 10 hours, while *Rg* shows the ratio of simulated chiller capacity *G* to G_s.

Cooling Tower

The capacity of cooling tower is selected as to match the chiller standardized capacity (G_s), so it varies in proportion to *Rg*.

Chiller Operation

Several chiller operations are compared in the simulation, and it fundamentally controlled by the timer as be set in *Table 1*. A chiller is allowed to operate during these time set by timer if operation conditions are satisfied.

During the allowed period in the nighttime, chiller starts if the temperature of higher temperature end tank (t_h) is higher than set point ($t_{h,limit}$), and stops if t_h becomes lower than $t_{h,limit}$.

During the allowed period in the daytime, chiller starts if temperature of the lower temperature end tank (t_l) becomes higher than set point ($t_{l,limit}$) in order to maintain low inlet water temperature into cooling coils. Then the chiller stops when t_h becomes lower than $t_{h,limit}$.

In case study for estimating the optimal chiller operation, the operation mode 'Prediction' is introduced. This mode is assumed that the cooling loads are perfectly known before the nighttime operation by any way to predict the loads. However, in order to simplify the simulation, only the hours of chiller operation are given from known loads and chiller capacity.

Several cases of thermal storage HVAC systems are simulated under these conditions. The simulation cases conducted in this paper are shown in *Table 2*. The 'abnormal' state of three-way-valve is the case that the chiller inlet water temperature is not controlled normally and all the water flow is supplied from higher temperature end tank of the storage tank.

Each case in *Table 2* is simulated with different tank capacities from *Rv* = 0.3 to 1.2.

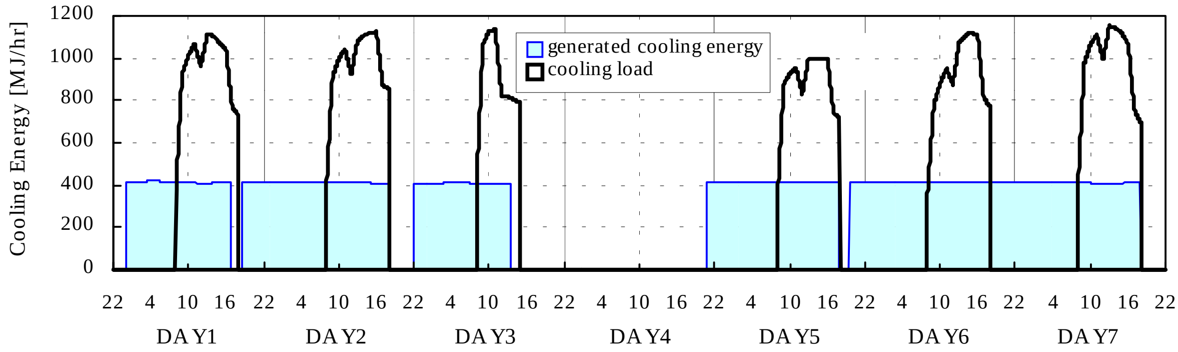

Figure 6. Generated Cooling Energy and Cooling Loads (CASE1: *Rv*=0.7)

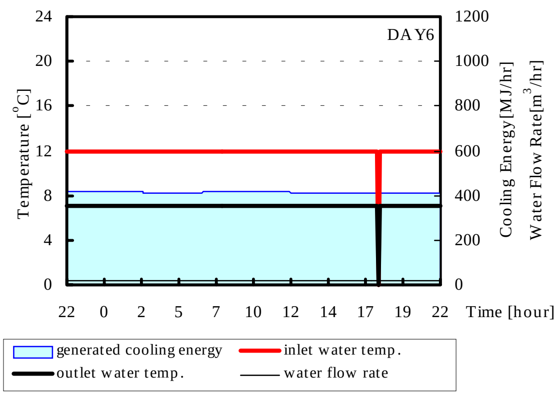

Figure 7. Trend of Chiller Operation (CASE1: *Rv*=0.7, DAY6)

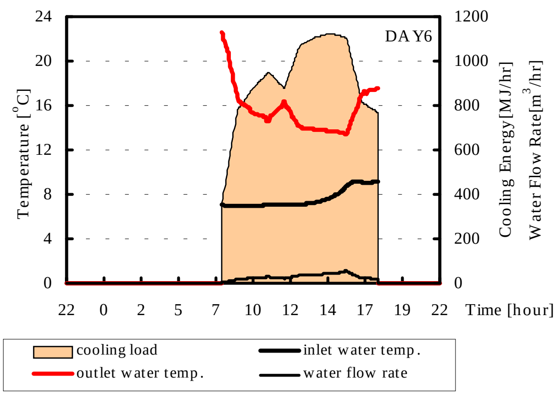

Figure 8. Trend of AHU Operation (CASE1: *Rv*=0.7, DAY6)

RESULTS AND DISCUSSIONS

Figure 6 shows the trend of generated cooling energy and cooling loads for the CASE1 (*Rv* = 0.7). As a result of the simplified load prediction, chiller starts operation before 10 p.m. in cases that the loads of next day are large. These operations accomplish to remove the loads perfectly even though the chiller capacity is small compared with the loads.

At first, the results of simulation in 'DAY6' of the same case are described in details. *Figure 7* shows the trend for chiller operation. The inlet water temperature and the water flow rate are constant from the given simulation conditions. The outlet water temperature maintains about 7°C. It is considered that the influence of cooling water temperature from cooling tower is small at the simulation case. Therefore the generated cooling energy by chiller is also nearly constant.

Figure 8 shows the trend of operation for air handling units. It is recognized that the outlet water temperature is very high when the load is small, and water flow rate increases according to the increase in cooling load. These results seem to be typical of air handling units operation with CAV systems.

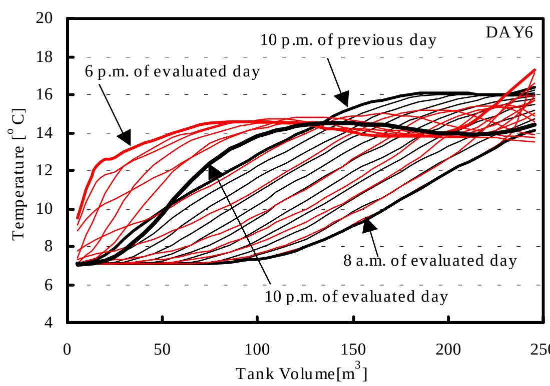

Figure 9. Temperature Profiles in Tank (CASE1: *Rv*=0.7, DAY6)

Figure 9 shows the profiles of hourly tank temperatures of each divided tank, and the axis of tank volume is increased from lower temperature end tank to higher one. The temperature of lower tank end accounts for the raise of inlet water temperature into air handling units. While, the higher zone temperature at 10 p.m. of previous day is higher than that of 10 p.m. of evaluated day. It is caused by high outlet temperature of air handling units due to smaller load of previous day.

Figure 10 shows the evaluation results with indices at the same case. Although there are a few days that *Qt,22* is large, calculated *Qover* is small and S_2 is nearly equal to zero because *Qt,22* is judged as essential energy for next day's cooling.

To confirming the differences of evaluation under several cases in *Table 2*, following average values of indices are applied because the original indices are defined for evaluating daily chiller operation, and are insufficient for the comparisons of several simulation cases simultaneously.

$$S_{0,ave} = \frac{\sum_{DAY=1}^{7} Gnight}{\sum_{DAY=1}^{7} (Gnight + Gday)} \qquad (12)$$

$$S_{1,ave} = \frac{1}{7}\sqrt{\sum_{DAY=1}^{7} (S_1)^2} \qquad (13)$$

$$S_{2,ave} = \frac{1}{7}\sqrt{\sum_{DAY=1}^{7} (S_2)^2} \qquad (14)$$

Figure 11, *12* and *13* show the results of case studies. In these figures, there are no values when cooling load could not be removed completely.

In *Figure 11*, the operations with load prediction (CASE1 to CASE4) which is estimated to be ideal cases show the larger $S_{0,ave}$ than the other cases of

S_0	0.40	0.50	0.64	0.00	0.45	0.42	0.50
S_1	0.00	0.00	-0.02	0.03	-0.01	-0.01	-0.01
S_2	0.00	0.00	0.03	0.00	0.00	0.00	-

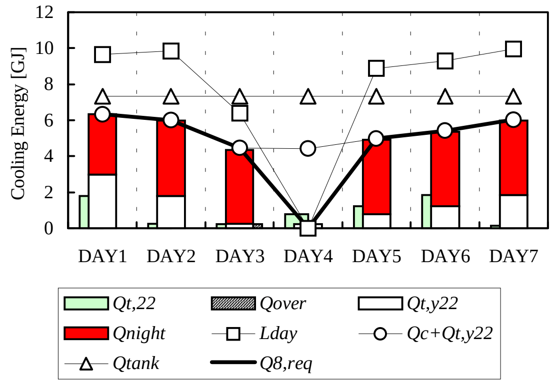

Figure 10. Result of Evaluation (CASE1: *Rv*=0.7)

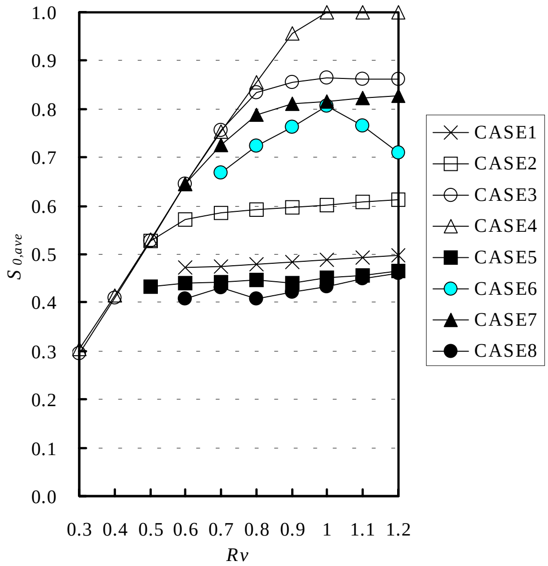

Figure 11. Comparison of $S_{0,ave}$ for Case Study

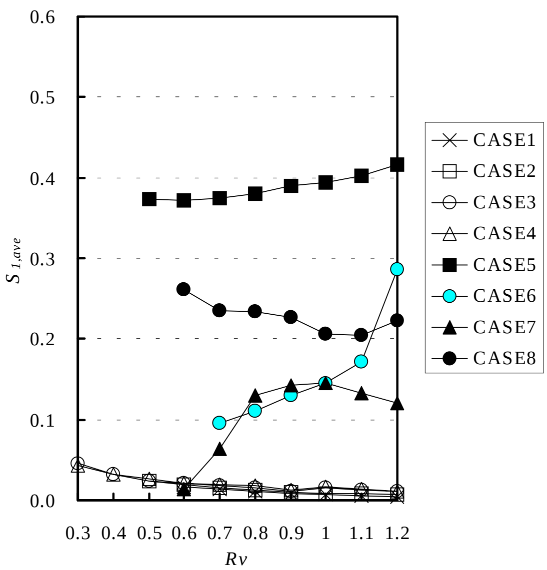

Figure 12. Comparison of $S_{1,ave}$ for Case Study

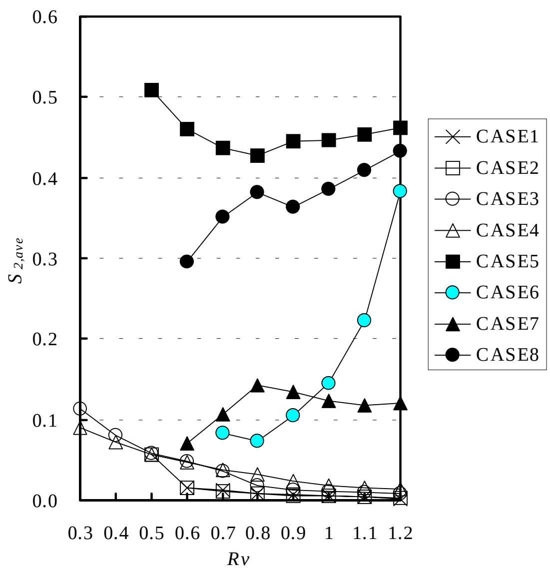

Figure 13. Comparison of $S_{2,ave}$ for Case Study

same *Rg*. From this, it is concluded that operating costs of the other cases are uneconomical. However, in actual operation, there are no values to compare their operation, so $S_{1,ave}$ and $S_{2,ave}$ values become important for evaluation.

$S_{1,ave}$ values shown in *Figure 12* are not able to reflect the large or small against *Q8,req*. Judging from the simulation conditions, the simulation results such as in *Figures 6* to *9* of each case and $S_{2,ave}$ values shown in *Figure 13*, the results of operation and evaluation except 'Prediction' mode are follows.

1. The main reason why $S_{1,ave}$ and $S_{2,ave}$ are large in CASE5 is that the chiller operates too long on weekends (DAY3 and DAY4) due to 'Timer1'.
2. The raises of $S_{1,ave}$ and $S_{2,ave}$ with *Rv* in CASE6 are caused by excessive nighttime chiller operation against cooling load.
3. In CASE7, the setting of 'Timer3' restricts excessive nighttime chiller operation. Therefore when *Rv* are large, $S_{1,ave}$ and $S_{2,ave}$ are smaller than those of CASE6.
4. In CASE8, three-way-valve could not be controlled normally. Both $S_{1,ave}$ and $S_{2,ave}$ show the improperly large values.

CONCLUSIONS

The evaluation indices represent the improper values when some faults exist in the thermal storage systems. Their effectiveness of evaluating the chiller cost saving operation is confirmed using actual measured data and simulating the system operation.

It is important for evaluation to estimate correct tank capacity. Especially, the temperature in completely discharged tanks has significant influence on not only tank capacity but also actual charged cooling energy in the tank.

When cooling load is small against tank and chiller capacity and charging is excessive for nighttime only, evaluation indices show improper value. If the heat loss from tank is not so significant, evaluation index S_0 must be emphasized as needed.

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NOMENCLATURE

F	:flow rate	[m^3/hr]
G	:chiller capacity	[J/hr]
Gnight	:generated cooling energy in the nighttime	[J]
Gday	:generated cooling energy in the daytime	[J]
Lday	:cooling load in the daytime	[J]
Lmax	:daily load of peak day	[J]
Lnight	:cooling load in the nighttime	[J]
N	:number of divided tanks	[-]
Q8	:charged cooling energy at 8:00 a.m.	[J]
Q8,req	:required cooling energy at 8:00 a.m.	[J]
Qc	:storable cooling energy by 10 hours chiller operation in the nighttime	[J]
Qnight	:charged cooling energy in the nighttime	[J]
Qover	:excessively charged cooling energy at 10 p.m.	[J]
Qtank	:storable cooling energy in tank	[J]
Qt,y22	:stored cooling energy in tank at 10 p.m. of previous day	[J]
T	:time	[hr]
V	:volume of the whole tank system	[m^3]
V_i	:volume of *i* th divided tank	[m^3]
c_p	:water specific heat	[J/m^3]
i	:tank number	[-]
t_h	:temperature of higher temperature end tank	[°C]
$t_{h,limit}$	:the lowest allowable inlet temperature to generator	[°C]
t_i	:water temperature in *i* th divided tank	[°C]
t_{in}	:water temperature entering the end divided tank	[°C]
t_l	:temperature of lower temperature end tank	[°C]
$t_{l,limit}$	:the lowest allowable inlet temperature to cooling coils	[°C]
Δt	:the maximum temperature difference of average temperature in the tank	[°C]
ρ	:water density	[kg/m^3]