DEVELOPMENT OF OPTIMAL OPERATION OF THERMAL STORAGE TANK AND THE VALIDATION BY SIMULATION TOOL

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ABSTRACT

Optimization of thermal storage tank operation is one of the major areas for energy conservation in HVAC systems. In the present paper, an algorithm is developed for optimum operation of thermal storage tank, by minimizing non-linear cost function. Results are validated under stationary and random load conditions. It is concluded that the present algorithm is quite robust and provides an optimal scheme of operation.

INTRODUCTION

To meet the national requirement of 6% reduction in CO2 emission made at the COP3 Kyoto in 1997, thermal storage used for air-conditioning systems was designated one of the major CO_2 reduction means in building sectors by the Japanese government. Thermal storage tank are widely used in Japan and elsewhere to store energy at off-peak hours, thereby flattening the electricity demand and increasing the chiller COP when outside wet bulb temperature is lower than day time. However, the statistics show buildings with such systems consume more energy as compared to these without it. One of the main reasons of this problem is that air-conditioning system operators try to store maximum thermal energy at the lowest temperature level to avoid shortage on the following day. Therefore, computerized optimal operation using predicted future thermal load profile of a following day might be a powerful tool because optimal operation of the system is very complicated and beyond human experience[3],[4],[8].

The three most important factors influencing electric power consumption by an HVAC system with thermal storage tank are,

1) The operating time of the chiller: Ordinarily the operating time of the chiller is not controlled and the thermal storage tank is filled with heat without any limit. Therefore, water temperature in the tank remains low and consequently the chiller COP goes down and higher heat transfer loss from the thermal storage tank takes place.

2) The operating schedule of chiller: When the chiller operates at midnight, the water temperature in the thermal storage tank remains low after completing the heat storage operation till its use. So the heat transfer loss from the thermal storage tank becomes larger than that when the chiller operating schedule shifts to early morning. In this shifted operation, the chiller can be operated at high COP taking advantage of the morning outside low wet bulb temperature .

3) The chilled water temperature: Energy consumption in the chiller can be saved by setting the evaporator outlet water temperature as high as possible because of the improvement of the chiller COP. When the following day thermal load is not so large, too low chilled water is needless. On the other hand, if the chilled water temperature is above a fixed temperature, it cannot handle the load satisfactorily.

In the present paper, authors propose an optimal operation scheme which was developed as computerized software on MATLAB/SIMULINK environment and results are obtained using operational data of a real building. Optimization is achieved by determining optimal chiller outlet water temperature taking account the performance of storage tanks, chiller, cooling tower, pumps and AHU coil. The optimum operation is determined by minimizing non-linear cost function together with simulation of the models. Four cases of operation are considered (Table 1).

OPTIMAL OPERATION ALGORITHM

The optimal operation algorithms for HVAC systems with a thermal storage tank are made up of four blocks (Fig. 1), prediction of cooling load, determination of required heat storage, system simulation, and optimal system operation control. The first block predicts cooling load for the following day. The second block determines heat storage requirement on the basis of cooling load prediction. The third block comprises quasi-stationary model in which components are expressed as numerical expressions. By using this model power consumption of the following day at the

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Table1.Types of thermal storage system operation

Operating ways	Chiller operation time control	Operating schedule	Set point temp.	Diff. in inlet and outlet cold water temp.
N-operation	Chiller operation at full capacity until power consumption falls to 20%	Midnight operation	7°C	5°C
P1-operation	control using cooling load prediction	Midnight operation	7°C	5°C
P2-operation	control using cooling load prediction	Early morning operation	7°C	5°C
O-operation	control using cooling load prediction	Early morning operation	not fixed	5°C

systems are simulated. The last block determines how to control the systems optimally. Variable here considered is set point temperature of the chiller outlet water and constraint is mass flow rate of the pump, which supplies water to the cooling coil, and operating time of the chiller. The flow chart of the algorithms is shown in Fig. 2.

Prediction of cooling load: The following day cooling load prediction algorithm has been reported in our previous work[1],[2].

Determination of required heat storage: Thermal load of an HVAC system comprises cooling load (q_p), heat losses from thermal storage tank and pipes (q_l), and heat generation at the pumps (q_h). However, available thermal storage heat depends on the cooling coil performance, and cannot be determined by one temperature level. When the water temperature level in the thermal storage tank is too high, it cannot handle heat load well and room temperature becomes higher than the set point temperature. Hence, the larger is heat load, the lower is this limit required. Storing just the following day HVAC heat load is not enough when the storage operation starts from high water temperature level in the thermal storage tank due to over-consumption of the heat storage the day before.

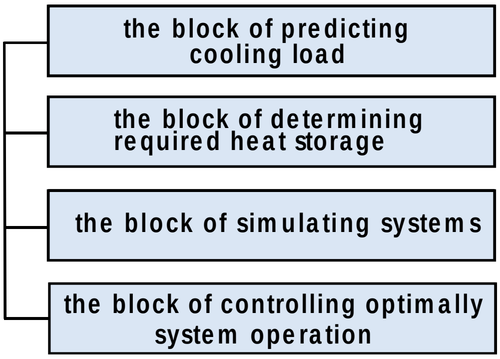

Fig. 1 Block diagram of optimum control system operation

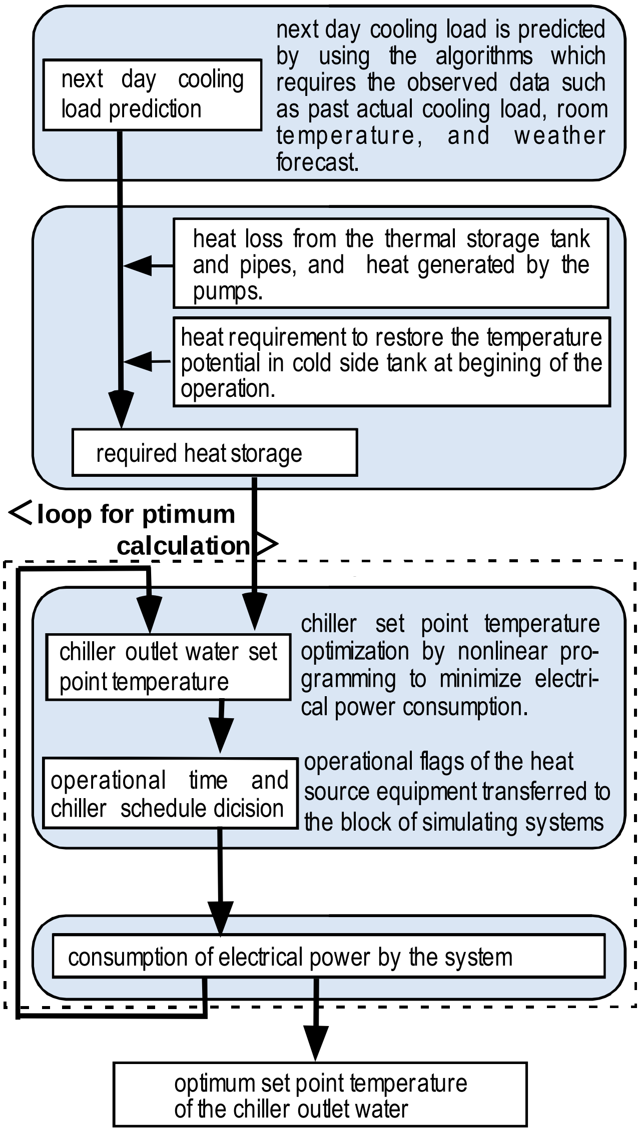

Fig. 2 : optimal system operation algorithms and composition of the blocks in thermal storage system

Table 2 : Design outline of the thermal storage system

1) thermal resource	thermal storage systems	water storage tank	
		number of rows	10
		total volume	760m^3
		thermal transmittance	3.37kJ/m^{2}h°C
		temperature outside tank	20°C
	main resources	hermetic turbo refrigerator	
		chilled water set point temp.	7°C
		refrigerating capacity	580kW
		electric power input	139kW
		cooling water mass flow rate	124m^3/h
		chilled water mass flow rate	99.8m^3/h
	cooling tower	electric power input	5.5kW
2) air conditioning systems	CAV systems	temperature and humidity set point	26°C, 50%
		mass flow rate of supply air	5.25x10^{4}m^3/h
	intake of outside air	fixed at 25%	1.75x10^{4}m^3/h

In order to avoid this problem, this block keeps water temperature level in the thermal storage tank at starting point of time to the level (θ_d) on which storage heat can be taken out. Therefore, required heat storage (q_r) is considered as the sum of the HVAC thermal load and the heat which need to restore the temperature level in the cold side tank.

$$q_r = q_p + \{q_l + q_h\} + \sum_{k=1}^{n} c_p m(\theta_k - \theta_d)$$

where,
c_p : specific heat of water [kJ/kg °C]
m : mass flow rate of the chilled water [kg]
θ_k : water temp. at the k th tank from the cold side [°C]
n : rows of the cold side tank
θ_d : temp. at which storage heat can be taken out [°C]

SYSTEM SIMULATION

Composition of the thermal storage systems that are examined in this study is shown in Fig. 3, and the outline of this systems are shown in Table 2. This systems are designed to operate chiller in the night and to store the whole heat neccesary for the following day air conditioning . Therefore, chiller is not operated in the daytime.

This block is made up of several components on MATLAB SIMULINK(Fig. 4). In this study, each of the components except a thermal storage tank is made without considering its dynamic characteristics. These components are considered as momentary stationary units and are expressed by introducing modifications in standard system simulation models [6].

Optimal system operation control: In this block, the set point temperature of the outlet chilled water and its operating schedule are decided. Depending upon the combination of constraints and purposes, many ways of operation can be planed. However, as mentioned earlier, four basic cases of operation are examined in this study. N-operation is normal operation. P1-operation and P2-operation are the operation using predicted load. Only O is an optimum operation.

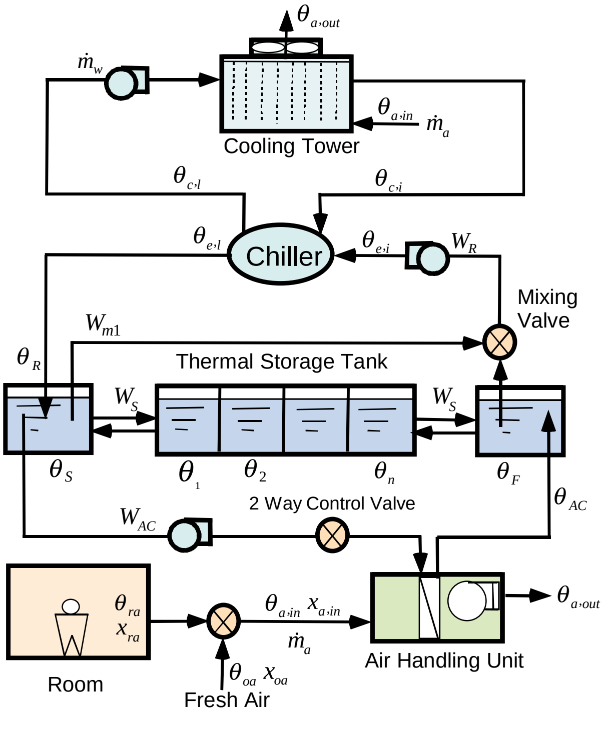

Fig. 3 : Block diagram of HVAC system with a thermal storage tank

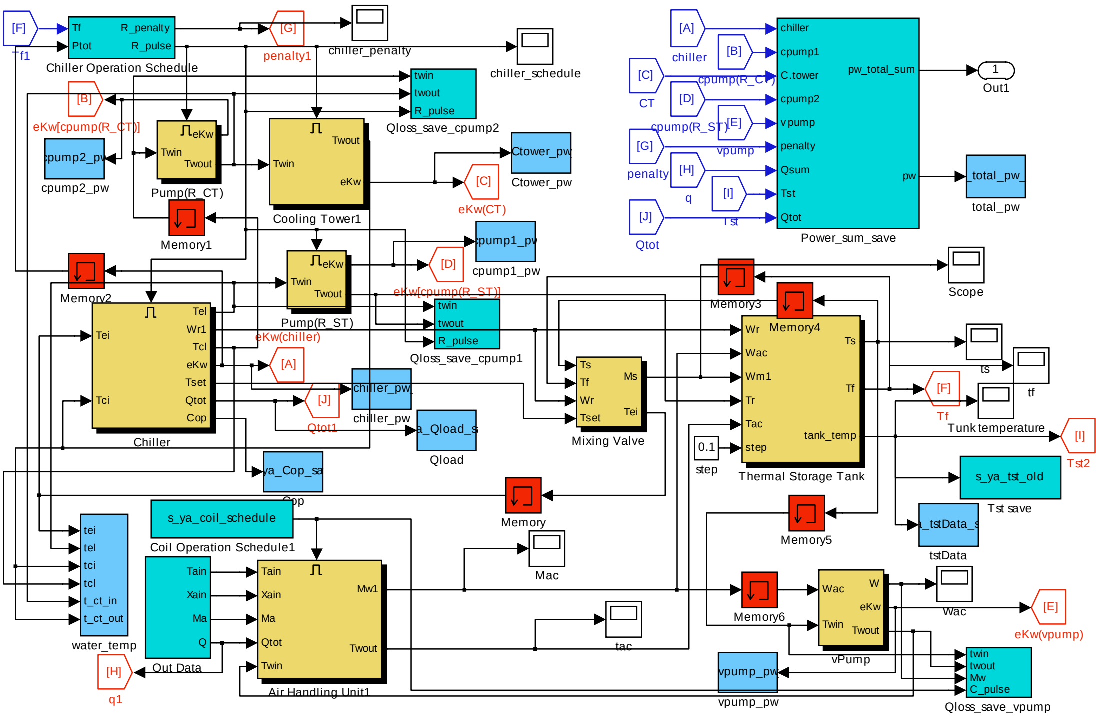

Fig. 4 : Block diagram of optimum control system operation

N-operation: This corresponds to normal operation. Chiller operates at maximum capacity untill power consumption falls down to 20% of rated performance.

P1-operation: This may be designated “midnight operation”. It’s operation commences with the beginning of the “night time tariff”, and stops when the heat storage meets the demand.

P2-operation: This operation may be designated “early morning operation”. The operating mode of the chiller is same as in previous case. However, timing is set such that its operation ends at the beginning of air conditioning operation.

O-operation: This operation is similar to the early morning operation. However, set point temperature of outlet chilled water is optimized in order to increase chiller’s COP. The problem is solved by nonlinear programming. Operating schedule of the chiller is kept same as in early morning operation. The following constraints were applied,

* Mass flow rate at the pump, which supplies water to the cooling coil, is smaller than its designed rate.

* Operating time of the Chiller is shorter than the maximum time length ($t_{\max}$) to which night time tariff is applied. (In this examination, $t_{\max}$ is setted for 10 hour).

These constraints are replaced by penalties when solved by nonlinear programming to make the problem non-restricted.

$$r_p = 1 + a\left(\frac{\dot{m} - \dot{m}_{\max}}{\dot{m}_{\max}}\right)^2 \qquad (\dot{m} \ge \dot{m}_{\max})$$

$$= 1 \qquad (\dot{m} < \dot{m}_{\max})$$

$$r_{time} = 1 + b\left(\frac{t - t_{\max}}{t_{\max}}\right)^2 \qquad (t \ge t_{\max})$$

$$= 1 \qquad (t < t_{\max})$$

Where,
r_p : coefficient of pump power supply
$\dot{m}$: mass flow rate [kg/h]
$\dot{m}_{\max}$: designed water mass flow supplied to AHU coils [kg/h]
r_t : coefficient of chiller power supply
t : operating time of the chiller [h]
$t_{\max}$: maximum operating time of the chiller [h]
a , b : weight of the constraints

Cost function including the penalties is as follows,

$$J = \sum E + r_p \cdot E_p + r_t \cdot E_{ref}$$

Where,
$\sum E$: consumption of electric power at each of the components except chiller and pump
E_p : consumption of electric power of at the pump
E_{ref} : rated power consumption at the chiller

RESULT AND DISCUSSION

In the present study, for the purpose of validating optimum operation algorithm, four basic cases of operation are compared on the basis of power consumption under similar stationary and random load

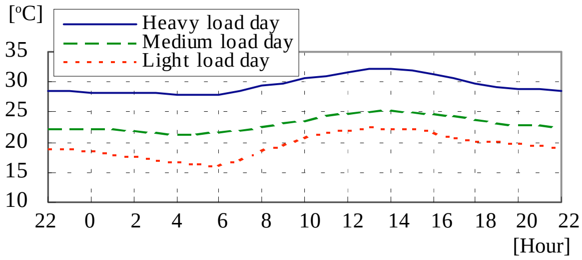

Fig. 5 : variation of dry bulb temperature with time

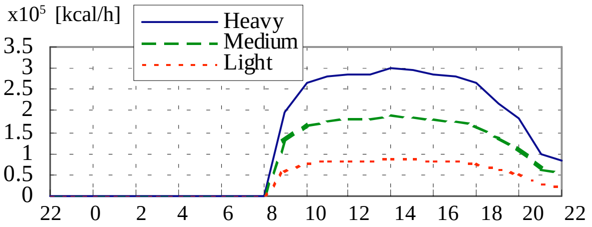

Fig. 7 : variation of cooling load with time under stationary load condition

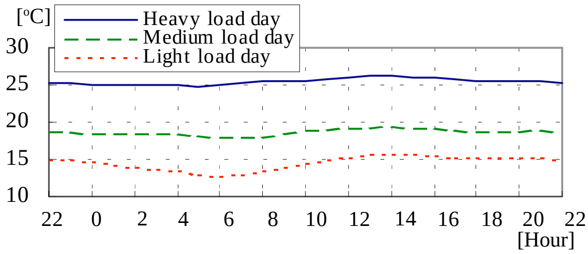

Fig. 6 : variation of wet bulb temperature with time

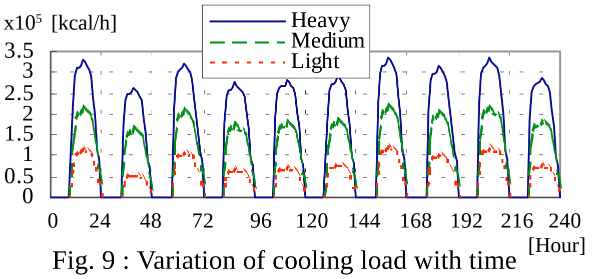

Fig. 9 : Variation of cooling load with time under random load condition

conditions. In an actual system operation, predicted load has the probabilistic error in a certain range. However, in this study, it is assumed that the predicted load has no probabilistic error. The study considering this probability may be considered in future developments.

Periodically Stationary Load Condition: Three types of load profile for examining several cases of operation under periodically stationary load condition are prepared on the basis of load level (Fig. 7). Weather data that correspond to three types of load, heavy, midium, and light load, are shown in Fig. 5 & 6. Time

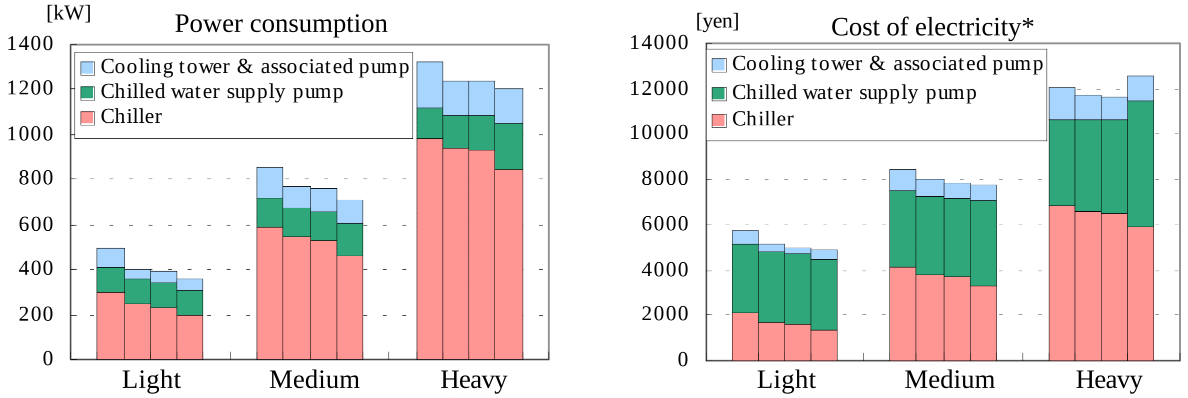

Fig. 8 : Comparison of power consumption and cost of electricity in periodically stationary load condition

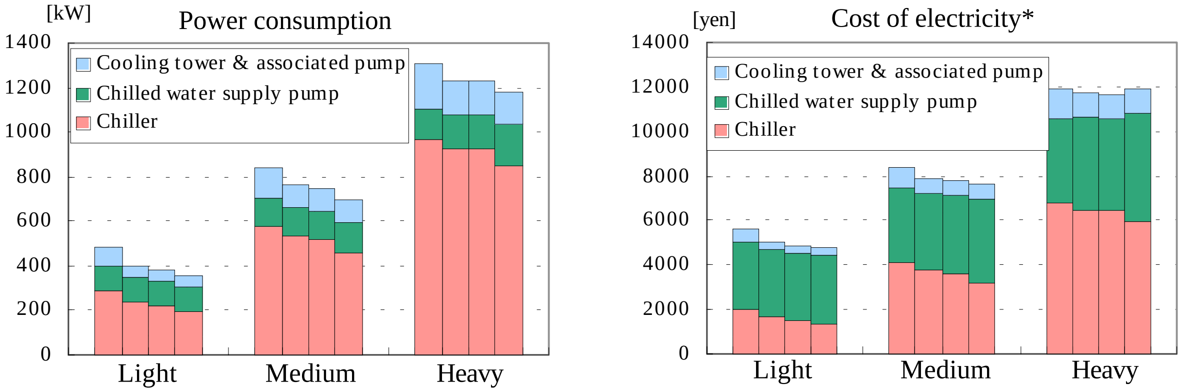

Fig. 10 : Comparison of power consumption and cost of electricity in random load condition

From the left, Maximum operation,Midnight operation,Early morning operation,Early morning-Optimum operation

caution*optimization about the cost of electricity is not examined step for the simulation is kept 90 seconds. (At O-operation, time step is 360 seconds to save computational time.)

At O-operation, optimum set point temperature of the chiller outlet water remains at 10.9°C, 13.7°C and 16.9°C under heavy, medium, and light load conditions respectively. Energy consumption reduces by 8.6%, 17.0% and 26.8% in heavy, medium, and light load conditions respectively as compared to that in N-operation. However, this turns out to be the most costly mode of operation (Fig. 8). It is because power consumption at the pump in the daytime is quite large, as chilled water temperature is higher.

Random load condition: To examine several cases of operation under random load condition three load level were also prepared. 10 days examples are shown in Fig. 9. (These are made by processing the load data measured at a real building [5].) Time step for the simulation is fixed at 90 seconds as in the previous case.

Under these conditions, energy consumption reduces almost in the same manner as observed under periodically stationary load condition. However, in heavy load condition, cost disadvantage at O-operation is not found (Fig. 10). It also demonstrates that it is possible to operate optimally with stability even under random load condition. In this case, water temperature in the tank is stirred like actual operation.

CONCLUSIONS

It may be concluded that the proposed algorithm controls the set point temperature, operating time, and operating schedule of the chiller optimally with stability. Algorithm presented can be applied to real systems. Therefore, among the four cases of operations, the O-operation attains the largest energy conservation about 18%. However, investigations into the following issues at optimum operation conditions are further solicited, 1) probabilistic reliability of the cooling load prediction, 2) addition of the restrictions in order to deal with the several problems that occur in adopting to the real systems, 3) purpose of the optimum operation. Nevertheless the basic concept of the present work can be applied with small modifications. For example, CO_2 reduction can be achieved by replacing cost function.

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