RATIONAL OPERATION OF A THERMAL STORAGE TANK WITH LOAD PREDICTION SCHEME BY ARX MODEL APPROACH

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ABSTRACT

Thermal storage tanks are widely used in Japan mainly to shift electrical energy usage to night time for the purpose of peak demand reduction. However, the operation of the system has not often been accepted with satisfaction in a real field. Authors developed a method ensuring rational operation by utilizing predicted air-conditioning load based on an ARX model derived from building load simulation. The rational operation is achieved considering the predicted load and performance of HVAC components. The proposed method was tested in a real building equipped with a personal computer in which the algorithm was embedded. The results showed that the method has enough feasibility.

INTRODUCTION

For constructing sustainable society and avoiding global warming all the efforts not to increase CO2 emission from the present level are required. One of the ways is to maximize the total performance of power plants by leveling off the consumption of electrical energy. This can in turn reduce the number of power plants to be constructed in future and contribute to preserve nature.

In Japan thermal storage tanks have been widely used for this purpose for many years. The system is normally operated based on the experience of maintenance personnel, however, it has not often been accepted as a satisfactory one. The common way of the operation is to store maximum thermal energy by attaining the lowest temperature level for the period of cooling and the highest temperature level in heating. Most of the time, however, heat load is not large enough to consume all the stored energy, thus, it is obvious that this causes much energy loss through the surrounding constructions and less COP heat-pump operation.

To avoid this energy loss authors developed a method ensuring rational operation. The method utilizes the information of the predicted air-conditioning heating and cooling load of the following day of each day. A model which is built based on building thermal load simulation is used for load prediction, where the parameters are identified by taking the model as a mathematical time series model called an ARX model. The rational operation is performed utilizing the predicted load.

To evaluate the feasibility of the proposed method a test was carried out by equipping real building with a personal computer in which the algorithm was embedded. In this paper the methodology and the results obtained from the field operation are presented and discussed.

METHODOLOGY

The reason why air-conditioning load prediction is indispensable for rational operation of a thermal storage system is that it stores thermal energy used in future. In recent studies Neural Network and other black box type approaches have been widely used as a load prediction scheme. However a physical model approach can also be applied, where the basic algorithm is based on simulation methodology used in load calculation. The method proposed by authors falls in this category and very little works have been done in this field especially with feasibility analysis to a real building.

In a system design stage, a mathematical model which is derived from physical considerations of building thermal properties is used for air-conditioning load calculation. This is called a thermal load simulation. For the prediction of future air-conditioning load, the same method can be applied if weather data and building properties are known. When we try to apply this method to a real building, however, the main problem is that weather data and the building properties are unknown. In the present study we propose a method to estimate them, then to predict or "simulate" future air-conditioning load. The approach is divided into two stages; weather data prediction and thermal load prediction, as follows.

1. Weather Data Prediction

In most buildings the degree of air-conditioning load depends largely on outside weather conditions, especially air temperature, humidity and solar radiation. Predicting future weather data, therefore, is the important step for the load prediction. Weather forecast issued by meteorological stations can be utilized as source information.

In Japan a local meteorological station provides the forecast of general weather, maximum and minimum temperatures, lowest relative humidity, etc. Utilizing the fuzzy information, a method to generate hourly future weather data required for the load prediction was developed.

The prediction is automatically carried out every hour by a personal computer except inputting the forecast information. However, the most significant role is given to the prediction just after 21:00 because electricity price is set as the lowest from 22:00 to 8:00 by night time usage policy.

A. Temperature Prediction

Firstly, average and diurnal air temperature for the building site is estimated using the past 30 days record by the following equations.

$$\bar{\theta}_N = \frac{1}{(K \times 24)} \sum_{n=1}^{K} \sum_{J=1}^{24} \theta_{N-n,\,j} \,,\; \tilde{\theta}_{N,j} = \frac{1}{K} \sum_{n=1}^{K} \theta_{N-n,\,j} - \bar{\theta} \qquad (1)$$

Secondly, assuming linear relationship between maximum and minimum air temperatures at the site and those of the meteorological station, they are estimated by the following equations.

$$\begin{aligned} \theta_{N-n,\,\max} &\cong a_{\max}\theta_{(R)N-n,\,\max} + b_{\max} \\ \theta_{N-n,\,\min} &\cong a_{\min}\theta_{(R)N-n,\,\min} + b_{\min} \end{aligned} \qquad (2)$$

The parameters a and b should be evaluated for each specific site. The example of them are shown in Table-1 for the test site “Hadano” near Yokohama.

Table-1 coefficients of eq. (2) for Hadano

	a [-]		*b* [K]	
	max	*min*	*max*	*min*
summer	0.960	0.924	0.458	0.637
winter	0.936	1.089	-0.555	-0.979

Thirdly, the average temperature of a future day is estimated by the equation (3). This approximation is validated separately.

$$\theta_{N,\,ave} \cong (\theta_{N,\,\max} + \theta_{N,\,\min})/2 \qquad (3)$$

Finally, the objective future temperatures can be predicted by the equation (4).

$$\hat{\theta}_{N,\,j} = \theta_{(N-1),\,ave} + \frac{(j-12)(\hat{\theta}_{N,\,ave} - \theta_{(N-1),\,ave})}{24} + \tilde{\theta}_{N,\,j}\,\frac{\Delta\hat{\theta}_N}{\Delta\tilde{\theta}} \qquad (4)$$

where,

$\Delta\tilde{\theta}_N = \max(\tilde{\theta}_{N,j}) - \min(\tilde{\theta}_{N,j})$, $\Delta\hat{\theta}_N = \hat{\theta}_{N,\,\max} - \hat{\theta}_{N,\,\min}$

The right hand side terms are the average temperature of the past 24 hours, the linear trend towards the future, and the future diurnal temperature swing evaluated by amplitude modulation respectively.

B. Humidity Prediction

In weather forecast the lowest relative humidity is predicted without the indication of occurrence time. It is reasonable to make an assumption that the time coincides with the time of highest temperature, that is 14:00 normally. The following linear formula can be used for prediction because humidity ratio variation within a day is small.

$$\hat{x}_{N,\,j} = x_{(N-1),\,ave} + \frac{(j-12)(\hat{x}_{N,\,ave} - x_{(N-1),\,ave})}{24} \qquad (5)$$

where, $\hat{x}_{N,\,ave} = f_S(\hat{\theta}_{N,\,\max}, \hat{\phi}_{N,\,\min})$

The f_S is a function to obtain humidity ratio from dry bulb temperature and relative humidity.

C. Solar Radiation Prediction

Strong relationship is expected between weather and solar radiation. But weather is forecasted in words like “clear with cloudy periods” with more than 20 variations. A method to relate this fuzzy explanation with solar radiation was developed.

To eliminate seasonality measured daily total global solar radiation is normalized by dividing them by the extraterritorial value, and then the normalized value is categorized based on 6 weather categories -- Table-2 --, as shown in Figure-1.

Table-2 weather category

category	weather
1	clear, fair
2	slightly cloudy, fine - cloudy or rainy occasionally
3	fine - cloudy later, cloudy - fine occasionally or later
4	cloudy, cloudy - rain and/or sunshine occasionally
5	cloudy - rain occasionally, rain - cloudy occationally
6	rain, heavy rain

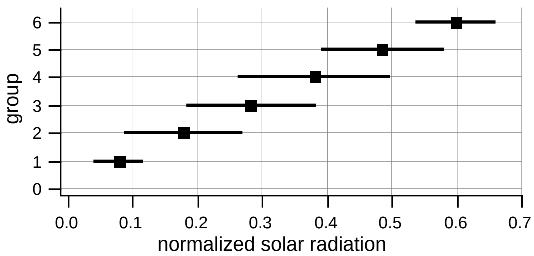

Figure-1 normalized solar radiation and weather group based on real data

For the present study 221 days record was used. The mark ■ and the bar shows the average and the standard deviation of the normalized solar radiation for each category. The optimum number of categorization was 6 for the present data because no improvement was obtained with a larger value. As weather forecast is not perfect, however, additional uncertainty will be added on the predicted solar radiation. Figure-2 shows the final accuracy when forecast information is used. The procedure of solar radiation prediction is summarized as follows.

1) When weather forecast is acquired the weather is categorized and normalized solar radiation η_N is predicted according to Figure-2.

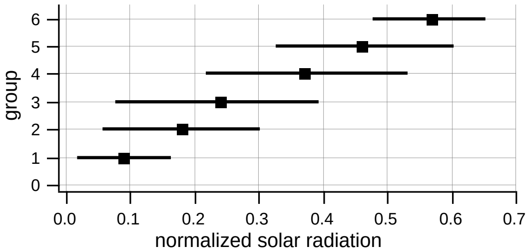

Figure-2 normalized solar radiation and weather group based on real data

2) The solar radiation is predicted using the following equation.

$$J_{N,j} = \frac{1}{r^2}\eta_N\ I_0 \sin\beta_j \qquad (6)$$

2. Air-Conditioning Load Prediction

For air-conditioning load prediction a mathematical model for thermal load calculation or simulation can be used as long as the detail of the building properties are known. However, in real buildings, the detail is unknown, therefore a simpler model must be used which model parameters are identified based on measured data. For the simplicity the following assumptions are made; 1) all the rooms are air-conditioned as a single room, 2) solar radiation passing through windows instantaneously becomes heat load, and 3) no interaction exists in moisture and heat transfer. Then a thermal balance equation is written as follows.

$$\begin{aligned} c_{pa}G_R\frac{d\theta_R}{dt} &= \sum_L\int_0^\infty \varphi_{T,L}(\tau)\theta_{Sol,L}(t-\tau)d\tau \\ &+\int_0^\infty \varphi_A(\tau)\theta_R(t-\tau)d\tau + \sum_L\int_0^\infty \varphi_{S,L}(\tau)J_L(t-\tau)d\tau \qquad (7) \\ &+c_{pa}G_o(t)\{\theta_0(t)-\theta_R(t)\} + q_{SR}(t) + q_{SA}(t) \end{aligned}$$

Latent load by humidity x is defined as $x\,(i_o + c_{pv}\theta)$. Approximating this term as $(x\,i_o)$, the humidity balance equation is obtained as follows.

$$i_oG_R\frac{dx_R}{dt} = i_oG_o(t)\{x_0(t)-x_R(t)\} + q_{LR}(t) + q_{LA}(t) \qquad (8)$$

Adding equation (7) and (8), and approximating specific enthalpy of moist air by $h \cong c_{pa}\theta + i_o x$, the following equation is obtained.

$$\begin{aligned} G_R\frac{dh_R}{dt} &= \sum_L\int_0^\infty \varphi_{T,L}(\tau)\theta_{Sol,L}(t-\tau)d\tau \\ &+\int_0^\infty \varphi_A(\tau)\theta_R(t-\tau)d\tau + \sum_L\int_0^\infty \varphi_{S,L}(\tau)J_L(t-\tau)d\tau \qquad (9) \\ &+G_o(t)\{h_0(t)-h_R(t)\} + q_R(t) + q_A(t) \end{aligned}$$

By discretizing the above equation with time, we have,

$$\begin{aligned} G_R(h_{R,j}-h_{R,j-1}) &= \{\sum_L\sum_{p=0}^{\infty}\Phi_{T,L,p}\theta_{Sol,L,j-p} \\ &+\sum_{q=0}^{\infty}\Phi_{A,q}\theta_{R,j-q} + \sum_L\sum_{r=0}^{\infty}\Phi_{S,L,r}J_{L,j-r} \qquad (10) \\ &+G_{o,j}(h_{0,j}-h_{R,j}) + q_{R,j} + q_{A,j}\}\Delta t \end{aligned}$$

The following approximations are applied to the equation (9).

1) Although specific enthalpy is a function of dry bulb temperature and humidity ratio, it can be approximated as a function of temperature only when space humidity does not change largely. That is, $G_R(h_{R,j}-h_{R,j-1}) \cong a\ (\theta_{R,j}-\theta_{R,j-1})$.
2) The enthalpy of infiltrating air is also approximated in the same manner and the flow rate is assumed constant. The errors caused by this assumption is small if the flow rate is not so large. Therefore, $G_{o,j}(h_{0,j}-h_{R,j}) \cong a_I(\theta_{o,j}-\theta_{R,j})$.
3) Since measuring the internal heat load q_R is impractical, the load is approximated by assuming that the profile ζ_R with time is given and only the unit level a_R is unknown. That is, $q_{R,j} = a_R\ \zeta_{R,j}$.
4) The goal of load prediction is the total load q_{AC} including not only the space load q_A but also the load of outside air intake q_o. It is assumed that q_o is proportional to the enthalpy difference between the space and outside, the profile ζ_o of intake air volume with time is given, and only the unit level a_o is unknown like 3). That is, $q_o \cong a_o\zeta_{o,j}(h_{0,j}-h_{R,j}) = a_o\zeta_{o,j}\Delta h_j$.
5) The terms including convolution are evaluated up to a finite number.

Redefining parameters a the following equation is obtained.

$$\begin{aligned} q_{A,j} &= \sum_L\sum_{p=0}^{p} a_{T,L,p}\theta_{Sol,L,j-p} + \sum_{q=0}^{q} a_{A,q}\theta_{R,j-q} \\ &+\sum_L\sum_{r=0}^{r} a_{S,L,r}J_{L,j-r} + a_R\ \zeta_{R,j} + a_o\ \zeta_{o,j}\Delta h_j + \varepsilon_j \qquad (11) \end{aligned}$$

This shows that air-conditioning load is the addition of linearly summed up terms of the past known values and error term ε. The parameters a have to be identified and order p and q should be fined separately. The identification of the parameters a are obtained applying successively the following least square estimation method.

$$\begin{cases} \hat{a}_j = \hat{a}_{j-1} + K_j(q_{AC,j} - u_j\hat{a}_{j-1}) \\ K_j = \dfrac{P_{j-1}u_j^{\,T}}{1+u_jP_{j-1}u_j^{\,T}} \\ P_j = P_{j-1} - \dfrac{P_{j-1}u_j^{\,T}u_jP_{j-1}}{1+u_jP_{j-1}u_j^{\,T}} \end{cases} \qquad (12)$$

where vectors a and u_j are defined as follows.

$$a = (a_{T,1,1},\cdots,a_{T,L,p},a_{A,0},\cdots a_{A,q},a_{S,1,0},\cdots,a_{S,L,r},a_R\ ,a_o\ )$$
$$u_j = (\theta_{0,1,j},\cdots,\theta_{0,\ L,j-p},\theta_{R,j},\cdots,\theta_{R,j-q},J_{1,j},\cdots,J_{L,j-q},$$
$$\zeta_{R,j},\zeta_{o,j},\Delta h_j)$$

The optimal order p and q are estimated by minimizing AIC values defined as follows.

$$AIC = N\log\sigma_e^2 + 2(p+q) \qquad (13)$$

Estimation of the optimal order has to be carried out with an appropriate interval on batch calculations with the consideration of changes in seasons and building internal conditions with time. Especially during the starting period just after the completion of construction careful attention has to be paid for parameter identification and order estimation.

Based on the parameters and order of the model, the future load or predicted load can be calculated applying the equation (11) assuming $\varepsilon_j = 0$, where future weather data are given. The space temperature included in the second term of the right hand side is unknown when air-conditioning is off. This can be estimated by modifying the equation (11) taking q_{AC} and the 5th term on the right being as zero.

$$\theta_{R,j} = \frac{1}{a_{A,0}}\Big(\sum_L\sum_{p=0}^{p} a_{T,L,p}\theta_{Sol,L,j-p} + \sum_{q=1}^{q} a_{A,q}\theta_{R,j-q} + \sum_L\sum_{r=0}^{r} a_{S,L,r}J_{L,j-r} + a_R\,\zeta_{R,j}\Big) \qquad (14)$$

This expression is defined as an ARX (Auto-Regressive Exogenous) model in the field of time series analysis.

As explained before the most major prediction is carried out at 21:00 every day. At this time, space air temperatures until restarting of the system and air-conditioning loads after the time are predicted based on equation (14) and (11) respectively.

3. Rational Operation

A method of rational operation of a energy plant with a storage tank was developed by the authors. The goal is to level off electricity consumption utilizing the information of the predicted load obtained by the above procedure.

The energy is consumed by cooling or heating coils in common systems. The consumed energy is proportional both to the water temperature difference through a coil and the flow rate. The inlet water temperature to the coil depends on the temperature of the tank, however, the outlet temperature depends on the coil performance, inlet water temperature and the thermal load of the coil. This means that not only the state of the tank but also system performance and load conditions are necessary to determine the consumed energy.

A) Available Stored Thermal Energy

Figure-3 shows an example of coil performance evaluated from measured data. A following quadratic equation model, which relate water flow rate with inlet water temperature and thermal load, is made to simulate the performance.

$$\dot{m}_c = c_0 + c_1 q_A + c_0 q_A{}^2 + (c_3 + c_4 q_A + c_5 q_A{}^2)T_{in} + (c_6 + c_7 q_A + c_8 q_A{}^2)T_{in}{}^2 \qquad (15)$$

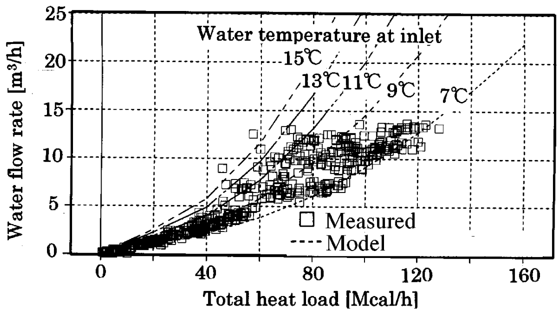

Figure-3 coil performance

The dotted lines in the Figure-3 show the model performance for typical temperatures. In application the inlet temperature is fed from the tank outlet temperature and the load is given by the load prediction, thus the outlet temperature of the coil can be calculated as follows only when $\dot{m}_c$ is less than the design value or maximum flow rate.

$$T_{out} = T_{in} + q_A/\dot{m}_c \qquad (15)$$

Here we define available stored thermal energy as the amount of thermal energy obtained by multiplying the water temperature difference and flow rate.

Graphical example of the available stored thermal energy is shown in Figure-4 by the shaded areas, where the future values are shown imaginary in series to the rightward because the temperature profile in the tank proceeds toward left with time. The state of the graph is at 12:30 and the numbers show future time.

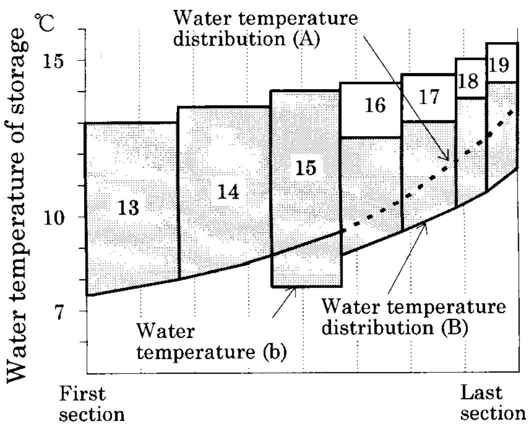

Figure-4 concept of available stored thermal energy

The outlet temperature increases with the progress of tank energy consumption. As a result the amount of the available energy decreases with time and finally the stored energy becomes not be able to satisfy the load demand. In Figure-4 this happens at 16:00 and the white box indicated by 16 shows the amount of shortage. This has to be avoided in real operation. The safest way is to keep the tank water as cold as possible (high when heating), however, this causes energy loss mainly due to low COP operation of a heat pump and partly due to not enough insulation of water tank surroundings, which is usually designed allowing 5 to 10 % thermal loss. Therefore a following strategic rational approach was developed.

B) Rational Operation

Based on the predicted load and the measured state values both of storage tanks and building space, future shortage occurrence can be predicted or simulated in advance. Thus if plant operation is required, allocation of operation time is carried out with time zone priority, namely, the highest 22:00 -- 8:00, middle 8:00 -- 13:00 or 16:00 -- 22:00, and the lowest 13:00 -- 16:00. This priority is based on leveling off electricity usage. As a summary rational operation of an energy plant is obtained as follows.

1) Obtaining hourly flow rate of a coil by equation (14) up to the next evening and checking whether they are all less than the design value. If this is satisfied future operation of energy plant is not required.
2) If not at any time, allocating operation time zone based on; a) the time before the shortage occurrence, b) the highest priority time zone which is available, and c) time when other electric energy use will be minimum.
3) Estimating the temperature distribution in the tank based on the simple assumption that it is formed as the result of mixed water temperature of the tank and the energy plant.
4) Going back to step 1) and check through until no shortage time remains before the next evening.

An example which shows how the tank temperature distribution changes and how the plant operation time is allocated are given in Figure-4 and 5 respectively. However they are not coincidental examples to each other in time.

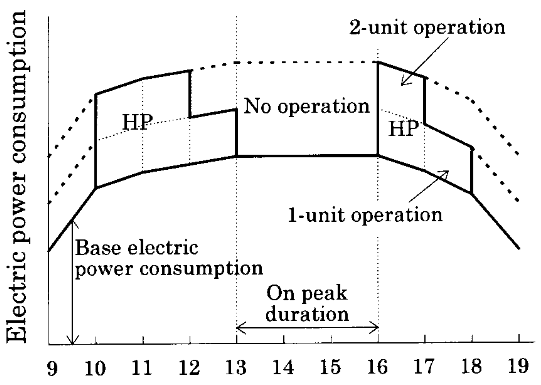

Figure-5 allocation of energy plant operation

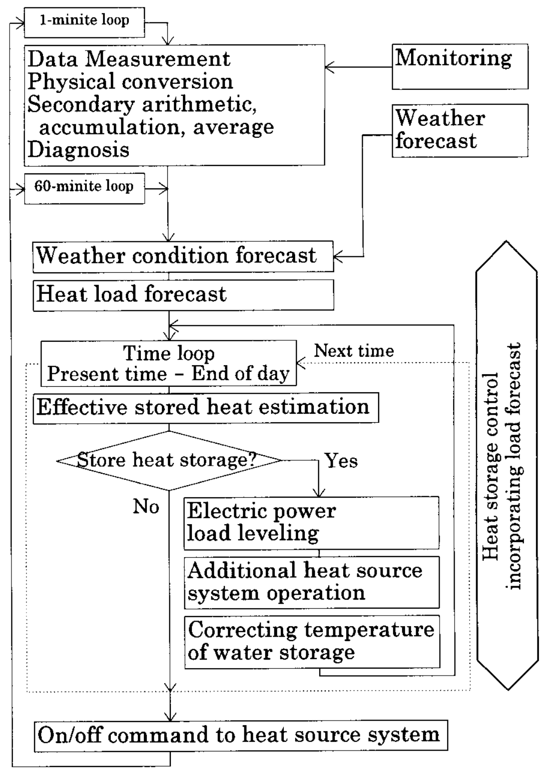

Figure-6 rational control algorithm

In Figure-6 the algorithm is summarized as a flow chart.

APPLICATION

The verification test of the method explained above was performed at an office building located in Kanto District in Japan; four storied building with the total floor area of 3,149 m^2. The energy plan system consists of two air-source heat pumps and a heat storage water tank. The secondary side of the air-conditioning system is a single duct air conditioning system plus fan-coil unit system. The rational control of the heat storage tank was verified under actual operation.

Figure-7 shows the measuring and control system. Data from 46 points were transmitted to a general-purpose data acquisition system and the control was performed by a personal computer without human assistance. Weather forecast data used for the load prediction were manually fed through a public telephone line from a remote site.

1. Off-Line Verification Test

Prior to the on-site verification test the method for weather data prediction and load prediction was tested using the past and recent data sets in off-line mode. Data sets used were taken from the winter and the summer of 1984, 85 and 1993, 94. In Figure-8 the real and predicted (dotted line) weather data; air dry bulb temperature, moisture ratio and global solar radiation, for the winter of 1985 are shown as an example. Similar but more detailed results for the winter of 1994 are shown in Figure-9 together with predicted loads. We can see good accuracy is obtained in them.

Standard deviations of errors in three weather elements are shown in Table-3 for comparison for four periods. Since there is a much time difference between the past and recent data sets, accuracy increase of weather forecast was expected due to improvement of weather forecast but significant improvement was not found.

duration	temperature	humidity ratio	solar radiation
1985.2.1 -- 3.2	2.29	0.90	79.60
1994.1.26 -- 2.24	2.29	1.36	64.40
1984.6.26 -- 7.27	2.27	2.71	110.70
1993.8.1 -- 8.28	2.49	2.77	99.20

Table-3 errors in weather data prediction (standard deviation)

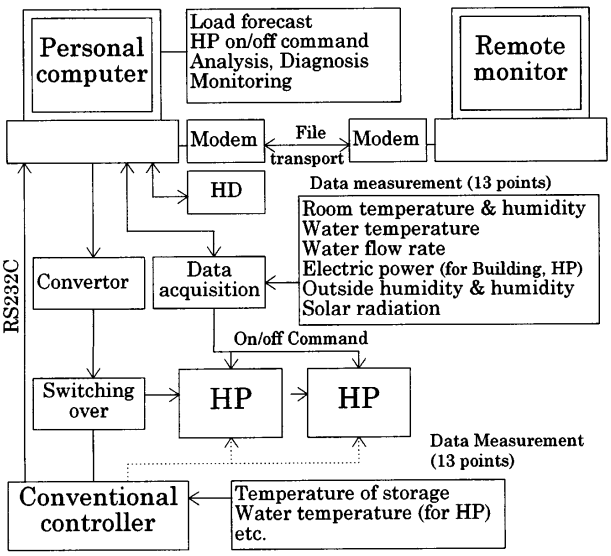

Figure-7 measuring and control system

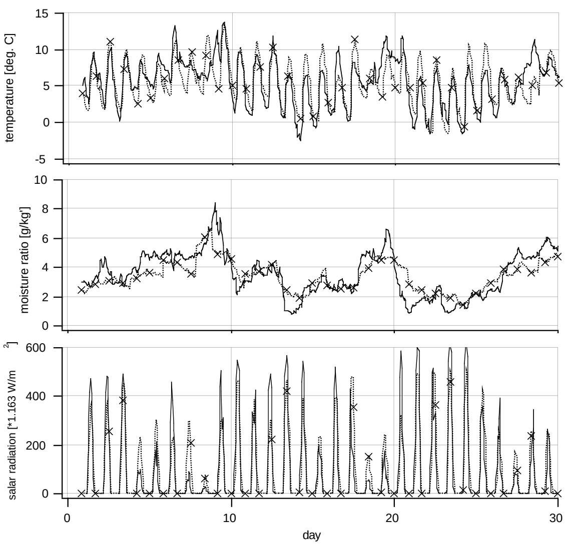

Figure-8 weather data prediction
Feb. 1 -- Mar. 2, 1985

In Figure-10 and 11 the results of the predicted loads of the summer and the winter of 1983, 84 are shown, where total daily loads obtained by summing up predicted hourly loads are given instead of hourly loads. The relative accuracy is 12.2 % for the winter and 29% for the summer. The accuracy of the summer is lower than that of the winter. One reason of this is that this summer was unusual weather, therefore accurate prediction was quite difficult. Nevertheless we can see the trend is quite similar to the real one. The optimal model order was (2,2,2,1,1) for the winter and (4,4,4,1,1) for the summer corresponding to the terms of the equation (10).

The errors originate in both weather forecast issued by a meteorological bureau and the load prediction

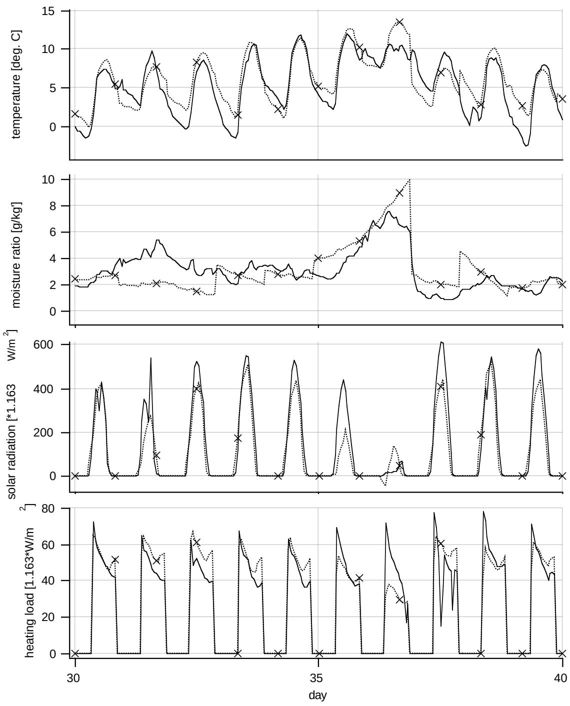

Figure-9 weather data and thermal load prediction Feb. 15 -- 24, 1994

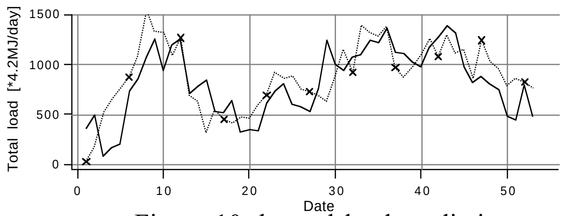

Figure-10 thermal load prediction
July 20 -- Sept. 10, 1993

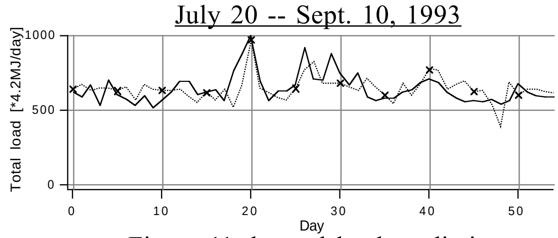

Figure-11 thermal load prediction
Jan. 3 -- Feb. 27, 1994

model. By predicting loads using real weather record not forecasted, it was found that the contribution to the inaccuracy are 1/3 from the forecast and 2/3 from the prediction model.

2. On-Site Vilification Test

An automated verification test was conducted on-site without human assistance except weather forecast data feeding from a remote site. Figure 12 and 13 show the results of the test in the summer of 1993, and in the winter of 1994. Both results showed that the proposed method is feasible.

A. Thermal Storage Water Temperature

The temperature of the water in the first tank section was kept between 8 °C and 12 °C in summer operation, and between 27 °C and 30 °C in winter operation. Compared with the conventional thermal storage systems, these cold water temperatures were slightly high and the hot water temperatures were very low down to 15 °C. This temperature control results would not be achieved even utilizing the knowledge of an experienced operator. Even with these temperature levels no adverse effect on the secondary side of the air-conditioning system was detected. On the contrary heat loss through tank boundaries is avoided by keeping temperatures properly.

B. Low Temperature Limit Control

In winter Japan islands receive an attack of low temperature high pressure system originating in main island China. Of course weather forecast aims to predict this, however, sometimes quite low unexpected temperature is experienced. Therefore lowest temperature limit control was added on the rational plant operation as one of the fail-safe counter measures. This measure should be used carefully because it tends to keep tank temperature high. This was avoided by providing two set temperatures for night and day time, and also by activating only when room temperature falls below a specified temperature. It was shown that higher temperatures more than demand of the rational operation were observed due to activation of this control in 1994 winter.

C. Night Time Shifting Ratio

The energy plan should be operated during night time, however, if the stored energy is not enough to satisfy load requirement, day time operation has to be activated. The night time shifting ratio is defined as the ratio of night electricity usage to the daily total. The average ratio for the summer of 1993 was 55%, which is not high enough being expected. This is because one heat pump became accidentally out of order and the tank capacity is not designed to store whole energy to suffice peak load demand. However, in the winter, the ratio reached up to 100% due to enough tank capacity for heating requirement. To

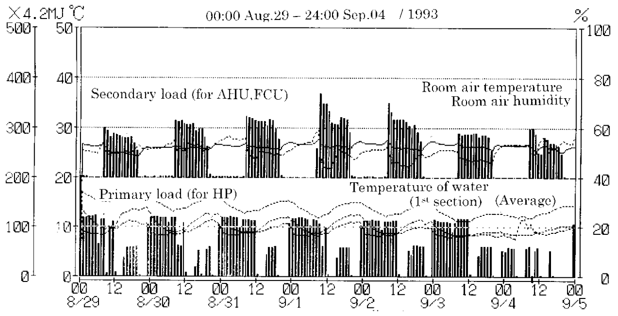

Figure-12 on-site test result, summer of 1993

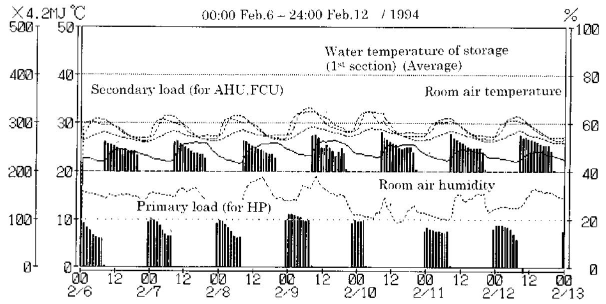

Figure-13 on-site test result, winter of 1993

attain this high value the rational operation played a major role.

CONCLUSIONS

In the present study a rational operation method is proposed and the results of the feasibility test in a real building are reported. The followings are the conclusions obtained in our study.

1) The proposed prediction and operation method is based on physical expressions or models, therefore it can be called simulation to estimate future state.
2) The relative accuracy of load prediction is 12 % for winter and 29% for summer. The accuracy for winter can be accepted with satisfaction, but the accuracy for summer should be improved more in future. One of the causes of the inaccuracy is unknown internal load which has more influences on total load of cooling.
3) Inaccuracy driven from weather forecast or load prediction can be assessed independently because both processes are modeled separately. In the present study the former contribution was 1/3 and the latter was 2/3.
4) The present method can be applied to arbitrary type of buildings and operation schedule. Most methods does not have this feature.
5) By applying the optimal control method successful results were obtained without particular human manipulation; that is, automated rational control was achieved.
6) This control strategy can be generic to any buildings and systems because it does not require specific experience of operator personnel and

characteristics of a building.

7) This method can automate adjustment of thermal storage tank operation, which usually require experience of operators, and is adaptive to the future changes of building usage and system characteristics.

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NOMENCLATURE

$\theta(\hat{\theta})$: air temperature (estimated)
$\bar{\theta}$: average air temperature
$\tilde{\theta}$: diurnal air temperature
θ_{Sol} : sol-air temperature
$x(\hat{x})$: humidity ratio (estimated)
J : solar radiation on horizontal surface
η : normalized solar radiation
I_0 : solar constant
β : solar height
i_o : heat of water evaporation at 0 °C
r : ratio of the distance between the earth and the sun to the average distance
c_{pa}, c_{pv} : specific thermal capacity of dry air and water vapor
$c_{pa}G_R$: room thermal capacity
G_o : mass flow rate of infiltration air
φ : impulse response
q_R, q_{SR}, q_{LR} : total, sensible and latent heat generated in a room
q_A, q_{SA}, q_{LA} : total, sensible and latent heat provided by an AC system
ζ_R, ζ_o : profile of internal heat load and OA intake with time
a : model parameter
u : input variable
$\dot{m}_c$: water flow rate through a cooling coil
c : model parameter of a cooling coil
T_{in}, T_{out} : coil inlet and outlet water temperature

subscript

$N(n)$: day (day shifted)
j : hour
(R) : reference site
T, A : transmissive and absorptive response
S : transmitting solar response
L : orientation
R, O : room and outdoor