International Journal of Air-Conditioning and Refrigeration Vol. 12, No. 3 (2004)/pp. 123-130

# The Optimal Control of an Absorption Air Conditioning System by Using the Steepest Descent Method

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**Key words**: Absorption air conditioning system, Energy conservation, Dynamic models, Steepest descent method, Optimal control algorithm

ABSTRACT: Control algorithms for an absorption air conditioning system may be developed by using dynamic models of the system. The simplified effective dynamic models, which can predict the dynamic behaviors of the system, may help to develop effective control algorithms for the system. In this study, control algorithms for an absorption air conditioning system were developed by using a dynamic simulation program. A cooling water inlet temperature control algorithm, a chilled water outlet temperature control algorithm, and a supply air temperature control algorithm, were developed and analyzed. The steepest descent method was used as an optimal algorithm. Simulation results showed energy savings and the effective controls of an absorption air conditioning system.

## Nomenclature

$C$ : control signal
$E$ : error
$G$ : constraint function
$J_k$ : cost function
$K$ : gain
$Q_{cld}$ : hourly cooling load [kW]
$Q_{ep}$ : hourly cooling capacity [kW]
$S_k$ : search direction
$T$ : temperature [℃]
$X_k$ : design variable

### Greek symbols

$\zeta_k$ : scalar distant

### Subscripts

$a$ : air
$chw$ : chiller cooling water
$ct$ : cooling tower
$ctrl$ : controller
$cw$ : cooling tower chilled water
$fan$ : fan
$i$ : inlet
$I$ : integral
$o$ : outlet
$P$ : proportional
$r$ : return
$wb$ : web-bulb temperature

## 1. Introduction

In recent years, electrical demands for the summer have increased considerably due to the use of air-conditioners. To reduce electrical demands, the Korean government has encouraged

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the use of an absorption air conditioning system for the building cooling. The use of absorption air conditioning systems may help in leveling the electric peak demand.(1)

A considerable amount of researches has been performed in the field of the absorption air conditioning system. Among them, control technologies applied for the absorption air conditioning system have brought energy saving features and performance enhancements.

Various simulation programs for the absorption air conditioning system have been developed for performance predictions. Goodheart et al.(2) developed the steady state model for a single and a half effect absorption chiller, and used it for chiller performance analysis. Han and Lee(3) developed a dynamic simulation program for an absorption air conditioning system and predicted dynamic behaviors of the system.

To develop control algorithms for an air conditioning system, the past researches were limited to develop control algorithms for fixed setpoints. But the current researches are more focused on the development of optimal control algorithms by considering physical characteristics and operation efficiencies of the whole system. Braun et al.(4) developed a dynamic simulation program by using actual measured data for a chiller system, and developed control algorithms. He showed that the developed control algorithms were more effective than the fixed setpoint control algorithm in respect of energy conservations. Cascia(5) studied a sub-optimal setpoint algorithm through the simulation, and applied this algorithm to a actual building to show its efficiencies. Han and Lee(6) performed research works for a full storage ice storage system, and proposed optimal algorithms for the system. However, the most of research works was performed by using steady-state models or dynamic models of the partial system instead of the total system. The simulation of the partial system have failed to provide the optimal solution for the total system.

In this study, optimal control algorithms for an absorption air conditioning system were developed by using a dynamic simulation program. A cooling water inlet temperature control algorithm, a chilled water outlet temperature control algorithm, and a supply air temperature control algorithm, were developed and analyzed. The steepest descent method was used as a basis of optimal algorithms.

## 2. Absorption air conditioning system

Figure 1 represents the schematic diagram of an absorption air conditioning system selected

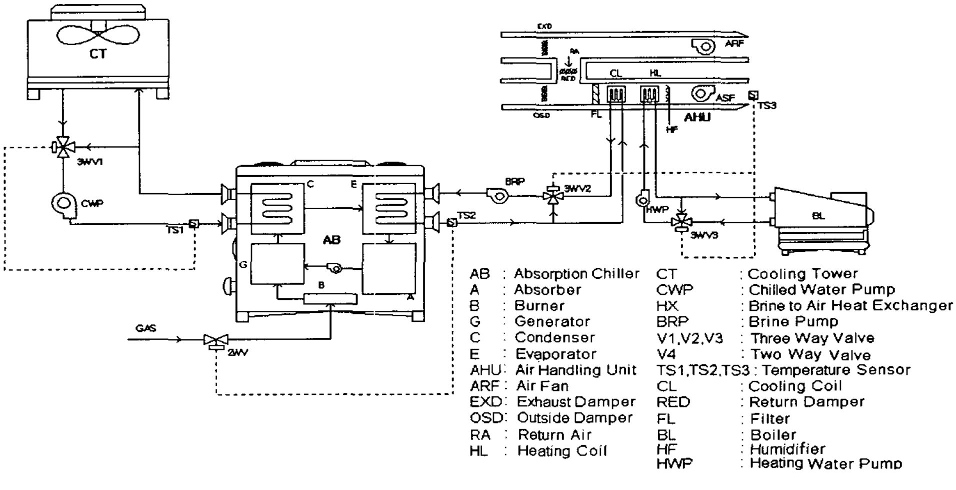

Fig. 1 Absorption air conditioning system.

for this study. As shown in this figure, the air conditioning system was composed of an absorption chiller, a cooling tower, a variable air volume air handling unit, and a boiler. To simulate dynamic behaviors of an absorption air conditioning system, dynamic models for a double effect absorption chiller, a counterflow type cooling tower, a variable air volume air handling unit (which consists of a cooling coil, a heating coil, ducts, dampers), and additional components (such as three way valves, pipes, pumps, temperature sensors, and controllers) were developed and programmed.(3,7)

## 3. Control algorithms

Control algorithms for the air conditioning system were composed of a cooling water inlet temperature control algorithm, a chilled water outlet temperature control algorithm, and a supply air temperature control algorithm.

To develop setpoint reset algorithms for each control algorithm, cost functions $J_k(X_k)$, constraint functions $G_{k,j}(X_k)$, and boundary conditions were selected. Linearizing these functions by Tayor series may lead to Eqs. (1) and (2).

$$
\begin{aligned}
&J_k(X_k) \fallingdotseq J_k(X_k^0) + \nabla J_k(X_k^0)\,\delta X_k \\
&G_{k,j}(X_k) \fallingdotseq G_{k,j}(X_k^0) + \nabla G_{k,j}(X_k^0)\,\delta X_k \le 0 \quad (1) \\
&\qquad j = 1, m
\end{aligned}
$$

$$X_{k,min} \le X_k^0 + \delta X_k \le X_{k,max} \quad (2)$$

In these equations, design variables $X_k$ represent hourly cooling water inlet temperatures $T_{cwi,k}$ for the cooling water inlet temperature control algorithm, hourly chilled water outlet temperatures $T_{chwo,k}$ for the chiller water outlet temperature control algorithm, and hourly supply air temperatures $T_{ar,k}$ for the supply air temperature control algorithm. $X_k^0$ denotes initial values for design variables, $X_{k,min}$ and $X_{k,max}$ represents the minimum and the maximum values for design variables, and $\delta X_k$ denotes $X_k - X_k^0$.

Figure 2 showed the flow diagram of the steepest descent method. $X_k$ was obtained by minimizing the linealized cost function. Initially, $\| \nabla J_k(X_k^n) \|$ was calculated. If $\| \nabla J_k(X_k^n) \|$ was replaced by $X_k$. If not, the search direction $S_k^n$ was determined by the following equation.

$$S_k^n = -\nabla J_k(X_k^n) / \| \nabla J_k(X_k^n) \| \quad (3)$$

For the given $X_k^n$ and $S_k^n$, the scalar distant $\zeta_k^n$ was obtained from the polynomial approximation method by minimizing $J_k(X_k^n + \zeta_k S_k^n)$. $X_k^{n+1}$ was obtained by the following equation,(8,9) and calculations were repeated if needed.

$$X_k^{n+1} = X_k^n + \zeta_k^n S_k^n \quad (4)$$

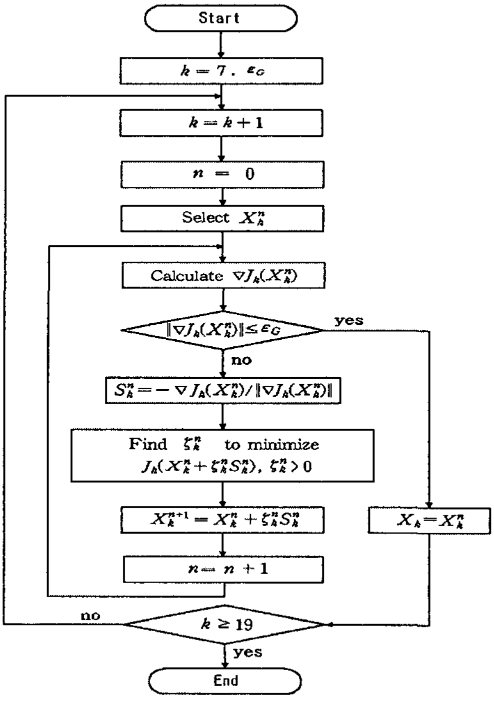

Fig. 2 Steepest descent method.

### 3.1 Cooling water inlet temperature control algorithm

The cooling water inlet temperature control system consists of a cooling tower, a three way valve, a pump, a controller, and sensors. Control algorithms were composed of the cooling water inlet temperature setpoint reset algorithm and the cooling tower three way valve control algorithm. The former was used for adjusting setpoints of the cooling water inlet temperature, the latter was used for controlling the cooling water inlet temperature to setpoints. For the setpoint reset algorithm, the steepest descent method was used.

The cost function for the cooling tower control was selected as follows;

$$\begin{aligned} J_{ctfan,k} &= (\alpha_1 + \alpha_2 T_{wb,k} + \alpha_4 T_{wb,k}^2) \\ &\quad + (\alpha_3 + \alpha_6 T_{wb,k}) T_{cwi,k} + \alpha_5 T_{cwi,k}^2 \end{aligned} \tag{5}$$

Constraint conditions, which were selected by considering design and operating conditions of the selected cooling tower, are expressed as follows;

$$J_{ctfan,k} \leq 22, \quad 25 \leq T_{cwi,k} \leq 40 \tag{6}$$

In the above equations, $\alpha_1 \sim \alpha_6$ denote constants obtained from manufacturer's data, $T_{wb,k}$ represents hourly outdoor air wet-bulb temperatures, and $T_{cwi,k}$ represents design variables which were calculated by the steepest descent method.

For three way valve controls of the cooling tower, a proportional-integral control algorithm was used. Controller output signal $C_{ctrl}$ was calculated as follows;(10)

$$C_{ctrl} = K_P\left(E + \frac{1}{T_I} \int E dt\right) \tag{7}$$

where $E$ denotes difference between the setpoint control signal and the sensor output signal, $T_I$ the integral time ($K_P/K_I$), $K_P$ the proportional gain, and $K_I$ the integral gain.

### 3.2 Chilled water outlet temperature control algorithm

The chilled water outlet temperature control system consists of a chiller, a three way valve, a pump, a controller and sensors. Control algorithms were composed of the chilled water outlet temperature setpoint reset algorithm and the chiller capacity control algorithm. The former was used for adjusting setpoints of the chilled water outlet temperature, the later was used for controlling the chilled water outlet temperature to setpoints by chiller capacity control. For the setpoint reset algorithm, the steepest descent method was used.

The cost function for the chiller control was selected as follows;

$$\begin{aligned} J_{ch,k} &= (b_1 + b_2 T_{cwi,k} + b_4 T_{cwi,k}^2) \\ &\quad + (b_3 + b_6 T_{cwi,k}) T_{chwo,k} + b_5 T_{chwo,k}^2 \end{aligned} \tag{8}$$

Constraint conditions, which were determined by considering the maximum chiller capacity and operation conditions of a selected chiller, are expressed as follows;

$$Q_{cld,k} - Q_{ep,k} \leq 0, \quad 0 \leq T_{chwo,k} \leq 12 \tag{9}$$

In the above equations, $b_1 \sim b_6$ denote constants obtained from manufacturer's data, $Q_{cld,k}$ represents hourly cooling loads determined by the cooling load estimation algorithm,(11) and $T_{chwo,k}$ represents design variables which were calculated by the steepest descent method.

The chiller capacities were controlled by the absorption chiller fuel supply valve. The proportional-integral algorithm was used.

### 3.3 Supply air temperature control algorithm

The supply air temperature control system consists of an air handling unit, a three way valve, a pump, a controller and sensors. Control algorithms were composed of the supply air temperature setpoint reset algorithm and the supply air temperature control algorithm. The former was used for adjusting setpoints of the supply air temperature, the latter was used to control the supply air temperature to setpoints by the three way valve. For the setpoint reset algorithm, the steepest descent method was used.

The cost function for the air handling unit control was selected as follows;

$$J_{afan,k} = (c_1 + c_2 T_{chwo,k} + c_4 T^2_{chwo,k}) + (c_3 + c_6 T_{chwo,k}) T_{ar,k} + c_5 T^2_{ar,k} \tag{10}$$

A constraint condition was determined by indoor air temperature control ranges. This condition may be selected as follows;

$$25 \le T_{ar,k} \le 29 \tag{11}$$

In the above equations, $c_1 \sim c_6$ denote constants obtained from manufacturer's data, and $T_{ar,k}$ represents design variables which were calculated by the steepest descent method.

The proportional-integral control algorithm was used to control the supply air temperature by the three way valve of the cooling coil.

### 4. Simulation results

Table 1 Data used for simulation

| Unit | Variable | Value |
|---|---|---|
| Cooling tower | $a_1$ | $1.493 \times 10^{3}$ |
| | $a_2$ | $4.021 \times 10^{2}$ |
| | $a_3$ | $-6.161 \times 10^{1}$ |
| | $a_4$ | $-1.886 \times 10^{1}$ |
| | $a_5$ | $5.093 \times 10^{-1}$ |
| | $a_6$ | $-2.139 \times 10^{-1}$ |
| | $K_P$ | $1.500 \times 10^{0}$ |
| | $K_I$ | $5.000 \times 10^{-2}$ |
| Absorption chiller | $a_1$ | $-3.373 \times 10^{2}$ |
| | $a_2$ | $5.329 \times 10^{2}$ |
| | $a_3$ | $-5.229 \times 10^{0}$ |
| | $a_4$ | $-2.961 \times 10^{1}$ |
| | $a_5$ | $-1.670 \times 10^{-3}$ |
| | $a_6$ | $1.803 \times 10^{-3}$ |
| | $K_P$ | $1.620 \times 10^{0}$ |
| | $K_I$ | $2.000 \times 10^{-2}$ |
| Air handling unit | $a_1$ | $1.619 \times 10^{-1}$ |
| | $a_2$ | $-4.896 \times 10^{-3}$ |
| | $a_3$ | $1.395 \times 10^{0}$ |
| | $a_4$ | $-2.000 \times 10^{-4}$ |
| | $a_5$ | $-1.000 \times 10^{-4}$ |
| | $a_6$ | $-1.250 \times 10^{-2}$ |
| | $K_P$ | $1.070 \times 10^{0}$ |
| | $K_I$ | $1.000 \times 10^{-2}$ |

To analyze the effectiveness of control algorithms, a dynamic simulation program of an absorption air conditioning system was used. In the simulation program, the whole system was devided into three subsystems such as the cooling water inlet temperature control system, the chiller water outlet temperature control system, and the supply air temperature control system. A 450 RT double-effect absorption chiller, a 700 RT counterflow cooling tower, and a 600 CMM variable air volume air handling unit, were selected for the cooling simulation. Table 1 showed selected data for the simulation of the absorption air conditioning system.

Table 2 Outside wet-bulb temperature

| Time | 8~9 | 9~10 | 10~11 | 11~12 | 12~13 | 13~14 | 14~15 | 15~16 | 16~17 | 17~18 | 18~19 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{wb,k}$(℃) | 24.3 | 23.5 | 23.5 | 22.8 | 24.6 | 24.2 | 24.8 | 23.7 | 23.5 | 23.5 | 24.7 |

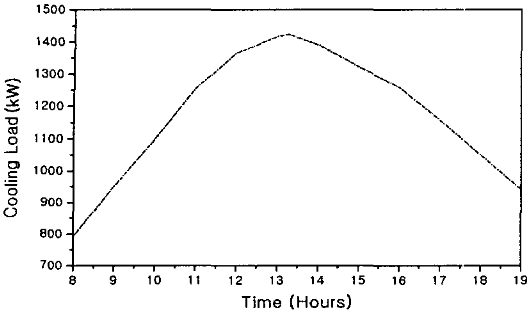

Fig. 3 Cooling load.

In the simulation, the air conditioning unit were assumed to operate from 8 : 00 am to 7 : 00 pm. Figure 3 and Table 2 showed the zone cooling load and the outside wet-bulb temperature used for the simulation.

Figure 4 showed room temperature control results when the room temperature was set to 27℃. Simulation results from the setpoint reset control algorithm were compared with those from the fixed setpoint control algorithm. For the fixed setpoint control algorithm, setpoints for cooling water inlet temperature, chiller water outlet temperature, and supply air temperature, were assumed to be 7℃, 32℃, and 17℃, respectively. As shown in this figure, control results from these algorithms were satisfactory where control accuracies were within the 4% error near the setpoint.

Figure 5 showed results from the cooling water temperature control, and Fig. 6 showed the cooling tower power consumption from this control. Simulation results from the setpoint reset control algorithm were compared with those from the fixed setpoint control algorithm. For the fixed setpoint control algorithm, the cooling water temperature was assumed to be 32℃. As shown in these figures, temperature controls from these algorithms were good within acceptable error ranges. But the power consumption in the case of using the setpoint reset control algorithm was 448.3 kWh, whereas that

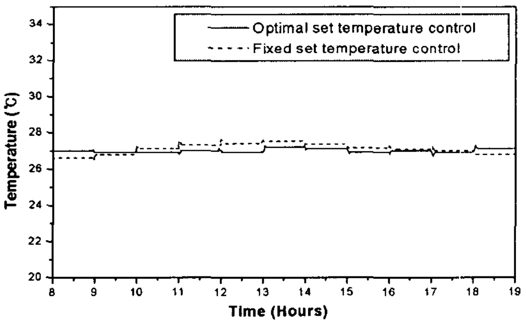

Fig. 4 Room temperature control.

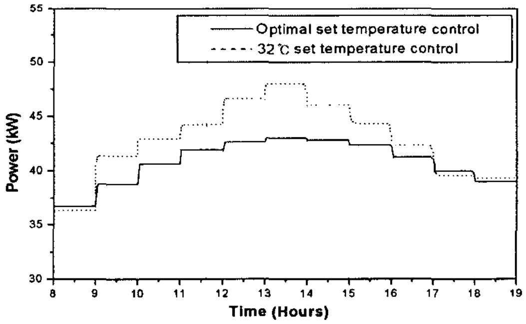

Fig. 6 Cooling tower power consumption.

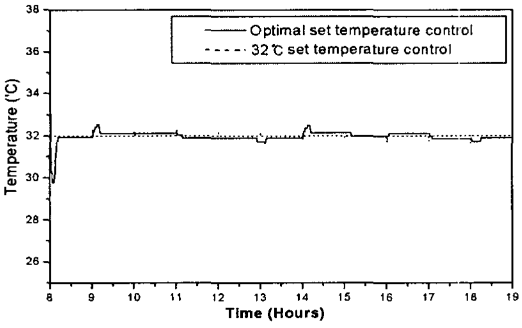

Fig. 5 Cooling water temperature control.

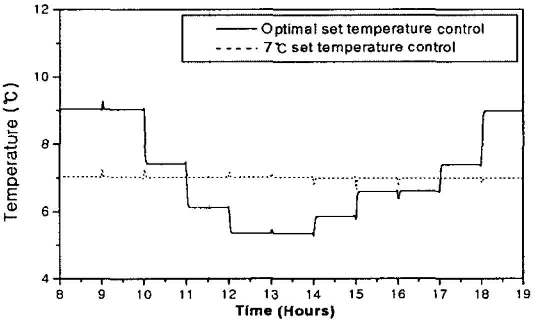

Fig. 7 Chilled water temperature control.

of the fixed setpoint control algorithm was 471.1 kWh. The power consumption saved by the setpoint reset control algorithm was 4.8%.

Figure 7 showed results from the chilled water temperature control, and Fig. 8 showed absorption chiller power consumption from this control. Control results from the setpoint reset control algorithm were compared with those from the fixed setpoint control algorithm. For the fixed setpoint control algorithm, the chilled water temperature was assumed to be 7℃. As shown in these figures, temperature control results from these algorithms were good within acceptable error ranges. But the power consumption from the setpoint reset control algorithm was 9824.8 kWh, whereas that from the fixed setpoint control algorithm was 10635.1 kWh. The power consumption saved by the setpoint reset control algorithm was 7.6%.

Figure 9 showed the supply air temperature control, and Fig. 10 showed the air handling unit power consumption from this control. Control results from the setpoint reset control algorithm were compared with those from the fixed setpoint control algorithm. For the fixed setpoint control algorithm, the supply air temperature was assumed to be 17℃. As shown in these figures, temperature control results from these algorithms were good within acceptable error ranges. But the power consumption from the setpoint reset control algorithm was 297.17 kWh, whereas that from the fixed setpoint control algorithm was 323.2 kWh. The power consumption saved by the setpoint reset control algorithm was 9.7%.

Figure 11 showed the total power consumption of the absorption air conditioning system. When the setpoint reset control algorithm was applied, the power consumption was 10564.8 kWh, whereas that from the fixed setpoint control algorithm was 11429.4 kWh. The total power consumption saved by the setpoint reset

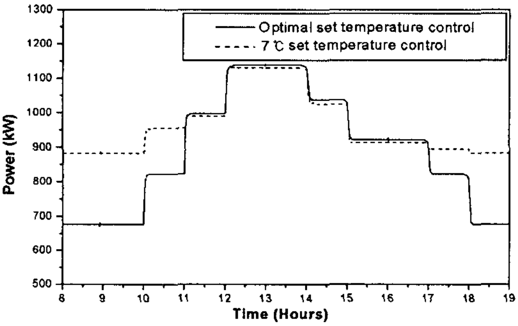

Fig. 8 Absorption chiller power consumption.

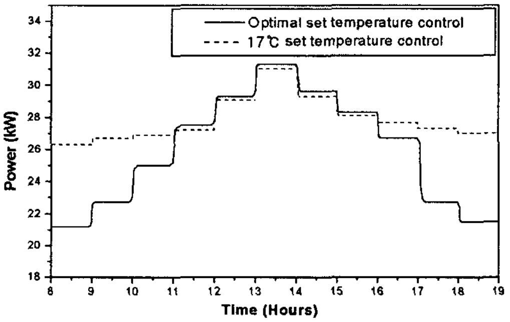

Fig. 10 Air handling unit power consumption.

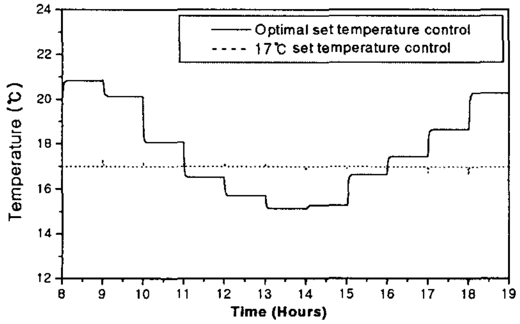

Fig. 9 Supply air temperature control.

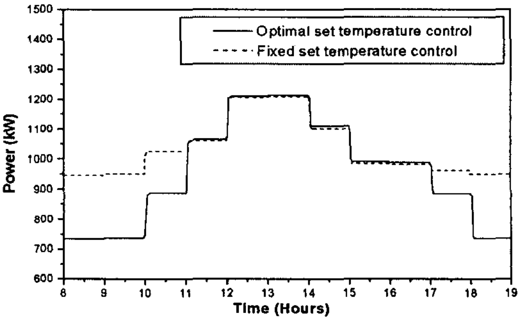

Fig. 11 Total power consumption.

control algorithm was 7.6%.

## 5. Conclusions

In this study, control algorithms for an absorption air conditioning system were developed. Algorithms consisted of the cooling water inlet temperature control algorithm, the chilled water outlet temperature control algorithm, and the supply air temperature control algorithm. To analyze the performance of control algorithms, dynamic simulation models were developed and used. Simulation results showed the 7.6% total energy saving and the stable controls of an absorption air conditioning system. Therefore, it may be concluded that control algorithms developed for this study may be effectively used for the energy savings and the effective controls of the absorption air conditioning system.

## References

1. Dorgan, C. B., Dorgan, C. E. and Leight, S. P., 1995, ASHRAE's new application guide for absorption cooling/refrigeration using recovered heat, ASHRAE Transactions, Vol. 101, Pt. 2, pp. 392-397.
2. Goodheart, K. A., Klein, S. A. and Schults, K., 2002, Economic assessment of low firing temperature absorption chiller systems, ASHRAE Transactions, Vol. 108, Pt. 1, Paper # AC-02-10-1.
3. Han, D. and Lee, S., 1999, Dynamic simulation of the absorption air conditioning system, Proceedings of Winter Annual Conference, SAREK, pp. 457-462.
4. Braun, J. E., Klein, S. A. and Beckman, W. A., 1989, Methodologies for optimal control of chilled water system without storage, ASHRAE Transactions, Vol. 95, pp. 652-662.
5. Cascia, M. A., 2000, Implementation of a near optimal global setpoint control method in a DDC controller, ASHRAE Transactions, Vol. 106, Pt. 1, Paper # 4340.
6. Han, D. and Lee, J., 2002, Optimal control algorithms for the full storage ice cooling system, Korean Journal of Air-Conditioning and Refrigeration Engineering, Vol. 14, No. 4, SAREK, pp. 350-358.
7. Clark, D. R., 1984, HVACSIM+ Building System and Equipment Simulation Program; Reference manual, NBSIR 84-2996, NIST.
8. Vanderplaats, G. N., 1984, Numerical Optimization Techniques for Engineering Design, McGraw-Hill.
9. Belegundu, A. D. and Chandrupatla, T. R., 1999, Optimization Concepts and Applications in Engineering, Prentice Hall.
10. Franklin, G. F., Powell, J. D. and Emami-Naeini, A., 2001, Feedback Control of Dynamic Systems, Addison Wesley.
11. Han, D. and Lee, J., 2000, Real-time building load prediction by the on-line weighted recursive least square method, Korean Journal of Air-Conditioning and Refrigeration Engineering, Vol. 12, No. 6, SAREK, pp. 609-615.