ABSTRACT
For the efficient energy use, the study analyzed the outdoor wet bulb temperature in a large office building, which is operated by several chillers and cooling towers in a hot and humid weather condition. This simulation study modeled and calibrated the target building through the measured energy consumption data. Condensing water supply temperature of the cooling tower was controlled as an energy efficient measure.

The result showed that by controlling the condensing water supply temperature based on the monthly wet bulb temperature change, the energy consumption in the cooling season could be saved by 1.4%. If the control of hourly condensing water supply temperature is possible, up to 6.6% of energy can be saved.

INTRODUCTION
Plant equipment that cover the basic cooling/heating load consumes a lot of energy. Particularly, the energy consumed by chillers, cooling towers, and circulation pumps that cover cooling/heating load take large part of the total energy consumption. Thus, any efficient energy use requires an energy control of plant equipment.

This study plans to reduce energy consumption by controlling the reset temperature of condensing water based on the outdoor temperature (wet bulb temperature) among the elements of the plant equipment.

The previous study has shown that the COP of a chiller may increase by 12.1 to 110.4% by dynamically operating the cooling tower fan, and controlling the condensing water temperature according to outdoor temperature and the partial load of the chiller (Yu and Chan, 2006). Also, another study showed that the COP of the chiller can be increased by 2.3 to 110.4% by coding a model, which was verified by TRNSYS, with FORTRAN subroutines and by resetting the condensing water temperature based on outdoor temperature (Chan and Yu, 2006). Under a subtropical climate, another study could also reduce the compressor power by 8.6 to 40.2% by controlling the condensing temperature (Yu and Chan, 2005). Furthermore, they calculated the potential electricity reduction in hotel A by 18.2%, and the potential energy reduction in hotel B by 29% by controlling head pressure and condensing temperature (Chan and Yu, 2002). These studies analyzed the increase in the COP of chillers and corresponding energy reduction by controlling condensing temperature. But these studies mostly focused on air-cooled chillers and analyzed the energy reduction by a simulation under a subtropic climate based on TRNSYS. In a building, like the target building for this study, the absorption chiller and the centrifugal water chiller are dynamically operated together. The study determined that a new energy saving method could be proposed by controlling condensing water temperature using the climate data that change in a real time.

Meanwhile, controlling the condensing water temperature is normally performed by bypass and automatic control. Generally, the temperature for the condensing water is set during the installation, and is rarely reset or adjusted. But this study assumed that the condensing water temperature would be easily adjustable. The study analyzed the outdoor wet bulb temperature in a large office building that is operated by several chillers and cooling towers in a hot and humid weather condition, and also analyzed the potential energy saved by modeling the target building using the energy simulation, adjusting its energy consumption based on the measured energy usage, and controlling the condensing water supply temperature of the cooling towers.

BACKGROUND

Cooling Tower
A cooling tower cools down the condensing water used in the condenser of the chiller. The condensing water that completed its mission at the condenser of the chiller and returned to the cooling tower at a higher temperature falls down from the top of the cooling tower gradually, and as it contacts the uprising outdoor air, some of it is vaporized and the temperature of the rest is reduced (Lee et al., 2002). Such a principle can be easily explained as the heat exchange between the condensing water and outdoor air, and the temperature of the condensing water affects the performance of the chiller considerably. The temperature of the condensing water is determined by how much heat it emits. The amount
of the chiller heat emitted (Q\text{ed}) can be calculated, as in Eq. (1), by the log mean temperature difference (LMTD\text{ed}) between the total heat transfer coefficient (AU\text{ed}) of the cooling tower and the ambient outdoor wet bulb temperature (Chan and Yu, 2002; Chan and Yu, 2006; Yu and Chan, 2005; Yu and Chan, 2006).

\[
Q_{ed} = AU_{ed}LMTD_{ed} \tag{1}
\]

Meanwhile, Figure 1 shows the temperature distribution between the condensing water and outdoor air. A -(minus) B value is called “Range”, and D -(minus) C value is called “Approach”. Here, air temperature refers to the outdoor wet bulb temperature. “Range” and “Approach” become key factors in determining the capacity of the cooling tower (ASHRAE, 2008; KENCA, 2008; Jayamaha, 2006; Lee et al., 2002; McQuiston et al., 2000).

**Figure 1** Temperature relationships between water and air in counterflow cooling tower

### Condenser temperature and energy savings

The temperature of “Range” and “Approach” in the cooling tower affects the energy consumption made by the cooling tower and chiller. The larger the “Range,” and the smaller the “Approach,” the higher the energy reduction can become (Jayamaha, 2006; KARSE, 2004; Wulfinghoff, 1999). The typical “Approach” temperature is 5°C and for the absorption chiller, it is between 6 ~ 9°C (KENCA, 2008). As shown in Figure 2, the lower the condensing water supply temperature, the more improved the efficiency of the chiller can become. The control of the condensing water supply temperature can increase the efficiency of the chiller and save the operating cost (Jayamaha, 2006). Theoretically, the condensing water supply temperature can cool down the outdoor wet bulb temperature so as to allow the condenser water whose temperature is lower than the dry bulb temperature of the ambient air. But it requires a larger surface area and a larger air circulation rate, and therefore, it is practically impossible (KENCA, 2008).

**Figure 2** Pressure-enthalpy (P-h) diagram showing effect of reducing condenser water temperature on chiller efficiency

### MODELING AND CALIBRATION

#### Building modeling

The target building is G building located in Seoul. Table 1 shows overview of the target building and shown in Figure 3 are the overall plant equipment and the air-conditioning system diagram of the target building (Kwak, R. et al., 2011; Kwak, Y. et al., 2011).

**Table 1 Overview of the target building**

<table>
<thead>
<tr>
<th>CATEGORIES</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target building</td>
<td>G building in Seoul</td>
</tr>
<tr>
<td>Stories</td>
<td>B6 ~ 38F</td>
</tr>
<tr>
<td>Floor area</td>
<td>141,551 m²</td>
</tr>
<tr>
<td>Main facilities</td>
<td>Office, Arcade, Parking lot</td>
</tr>
</tbody>
</table>
| Plant equipment | • Absorption chiller heater: 1,200 RT x 3EA 
                   • Absorption chiller:310 RT x 2 EA 
                   • Centrifugal water chiller: 310 RT x 1 EA 
                   • Boiler: 4,000 kg/h x 1 EA, 2,000 kg/h x 1 EA |
| HVAC            | • Office: single duct CAV or VAV(Fan Power Unit) 
                   • B2F ~ B4F: CAV 
                   • Basement, Arcade: CAV or VAV |
| Generator       | • 1,400 kW x 3 EA 
                   • Type: Gas Engine, Co-generator |

**Figure 3** The overview of plant equipment and air-conditioning system
There are various types of chillers in the target building because the operation time and the usage of each chiller depends on the energy policy. The main chillers are three absorption chiller heaters, which cover the most of the weekly cooling load. Two absorption chillers use the waste heat of the cogenerator, and supplement the main chillers. The centrifugal water chiller is operated normally at night, and sometimes during daylight if necessary. Shown in Figure 4 is the operation plan for the actual chillers on a week day in August, 2009 (Kwak, R. et al., 2011).

Model Calibration
The target building was modeled by collecting related drawings, interviews with operators, and climate data. Later, the model was revised by comparing the measured energy consumption in 2009 and the simulated energy consumption. As in Eq. (2), (3) and (4), the model was revised by reviewing the error using the monthly data calibration equation (M&V Guideline, 2002). If the model does not satisfy the value of acceptance, the causes for the error are analyzed to adjust the input value. Then the input file is adjusted and the error is compared again. Shown in Figure 5 is the process explained above (Kratii, 2000). The calibrated model is determined as the baseline model, which is used to calculate the energy savings.

\[
ERR_{\text{month}} = \frac{(M - S)_{\text{month}}}{M_{\text{month}}} \times 100
\]  

(2)

\[
ERR_{\text{year}} = \sum_{\text{year}} \frac{ERR_{\text{month}}}{N_{\text{month}}}
\]  

(3)

\[
\text{CV(RMSE}_{\text{month})} = \frac{\text{RMSE}_{\text{month}}}{A_{\text{month}}} \times 100
\]  

(4)

Shown in Figure 6 is the comparison between the electricity consumption of the the measured and simulation model. Table 2 is the result of the calculated errors (ERR, CV(RMSE_{month})) based on the Eq. (2), (3), and (4). The percentage difference of ERR_{month}, ERR_{year}, CV(RMSE_{month}) between the measured and simulation energy consumption are less than ±15%, ±10%, ±10%, respectively. Since the
error value is within the acceptance value, it is determined that the model calibration was successful (M&V Guideline, 2002).

The total electricity consumption can be categorized by the type of use, as in Lighting/Elec. Equip.(46%) > Plant (26%) > HVAC (22%) > Power (6%) in the order of the electricity consumption (refer to Figure 7).

Since the measured energy consumption by element and the simulated energy consumption were determined to have been calibrated well, the study excludes the analysis of each element of plant equipment, and compares and analyzes the total energy consumption. However, this study analyzed only the electricity consumption and excluded the analysis of gas consumption.

Also, the study focuses on the cooling energy consumption in cooling seasons, and therefore, compares the electricity consumption of the plant from June to September.

### RESULT AND DISCUSSION

#### Control of the condensing water supply temperature related to the chillers

As has been mentioned, lowering the condensing water supply temperature can reduce energy consumption. But, once it exceeds the permissible range, lowering the condensing water supply temperature can in fact result in consuming more energy. Also, shown in Figure 8, controlling the condensing water supply temperature requires to find the optimal temperature point by considering the efficiency of the overall system that includes both the cooling towers and chillers (Jayamaha, 2006).

Therefore, comparing the energy consumption based on the control of condensing water supply temperature should not compare the each energy consumption of the facility; rather, it should consider both the plant equipment, such as the chillers and cooling towers, and the energy consumption of the circulation pump. Since this refers to the electricity consumption of the previously categorized “Plant” (refer to Figure 7), the study will compare not the total energy consumption of the building, but compare the electricity consumption of the plant.

### Cooling tower design conditions in Korea

Due to the hot and humid summer climate in Korea, the design temperature of the cooling tower is somewhat higher than that in the USA. Shown in Table 3 is the comparison between the cooling tower design temperature of Korea and USA (KENC, 2008; Jayamaha, 2006). Table 4 is the cooling tower design conditions and specifications of the target building, which are identical to the usual cooling tower design temperature in Korea. (Kwak, R. et al., 2011).
Controlling condensing water supply temperature (Total)
The study tried and controlled the condensing water supply temperature differently from the design condition by changing (increasing or decreasing) the design temperature by 1°C and analyzing the corresponding energy consumption. Shown in Figure 9 is the total energy consumption by controlling the condensing water supply temperature. Here, the total energy consumption refers to the sum of the electricity usage from June to September in the plant. The comparison of the total energy consumption shows that as opposed to the design temperature (32°C), the energy consumption was the smallest at 30°C, 2°C lower than the design temperature. This means that by lowering the condensing water supply temperature by 2°C from 32°C, 11 MWh (0.3%) of the total energy consumption can be saved from 3,924 MWh to 3,913 MWh.

![Figure 9 Total energy consumption by controlling condensing water supply temperature [MWh]](image)

Controlling condensing water supply temperature (monthly)
The comparison of the total energy from June to September shows that as in Figure 9, the energy consumption was the lowest at 3,913 MWh when the condensing water supply temperature was at 30°C. However, the comparison of the energy consumption based on the control of the monthly condensing water supply temperature is shown in Figure 10 and Table 5. As shown in Figure 10 and Table 5, while the total energy consumption was lowest when the condensing water supply temperature was at 30°C, the temperature at which the monthly energy consumption was smallest was different each month: in June, it was 29°C; in July, it was 33°C; in August, it was 34°C; and in September, it was 28°C. (refer to Table 5 shadow zone). Particularly in July and August, the smallest energy consumption was recorded while the measured condensing water supply temperature was higher than the design temperature. Since the target building mixes and uses the absorption chiller heaters, absorption chillers, and centrifugal water chiller, the energy consumption was smallest when the condensing water supply temperature was higher than the design temperature.

For, as has been mentioned, the “Approach” temperature of the absorption chiller is set higher than that of the typical “Approach”. If the design condensing water supply temperature (32°C) is set to 29°C, 33°C, 34°C and 28°C from June to September, respectively, the total energy consumption will become 3,868 MWh (876 MWh + 1,079 MWh + 1,106 MWh + 807 MWh), which is smaller than 3,294 MWh at 32°C of the design temperature by 56 MWh (1.4%). Therefore, energy saving can be expected by controlling the condensing water supply temperature by each month.

![Figure 10 Monthly energy consumption based on the control of condensing water supply temperature [MWh]](image)

<table>
<thead>
<tr>
<th>TEMP.</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>27°C</td>
<td>913</td>
<td>1,121</td>
<td>1,270</td>
<td>828</td>
<td>4,222</td>
</tr>
<tr>
<td>28°C</td>
<td>881</td>
<td>1,134</td>
<td>1,191</td>
<td>807</td>
<td>4,013</td>
</tr>
<tr>
<td>29°C</td>
<td>876</td>
<td>1,102</td>
<td>1,152</td>
<td>808</td>
<td>3,938</td>
</tr>
<tr>
<td>30°C</td>
<td>877</td>
<td>1,089</td>
<td>1,131</td>
<td>816</td>
<td>3,913</td>
</tr>
<tr>
<td>31°C</td>
<td>884</td>
<td>1,083</td>
<td>1,121</td>
<td>827</td>
<td>3,915</td>
</tr>
<tr>
<td>32°C</td>
<td>891</td>
<td>1,080</td>
<td>1,115</td>
<td>838</td>
<td>3,924</td>
</tr>
<tr>
<td>33°C</td>
<td>898</td>
<td>1,079</td>
<td>1,112</td>
<td>848</td>
<td>3,937</td>
</tr>
<tr>
<td>34°C</td>
<td>915</td>
<td>1,122</td>
<td>1,106</td>
<td>866</td>
<td>4,009</td>
</tr>
<tr>
<td>35°C</td>
<td>923</td>
<td>1,120</td>
<td>1,107</td>
<td>872</td>
<td>4,022</td>
</tr>
</tbody>
</table>

Controlling condensing water supply temperature (hourly)
Controlling the condensing water supply temperature is based on the amount of heat transferred between the outdoor wet bulb temperature and condensing water ($Q_{cd} = AU_{cd} LMTD_{cd}$). Thus, it can be considered that the condensing water supply...
temperature is governed by the outdoor wet bulb temperature. Shown in Figure 11 is the measured climate data from June to September, 2009, which signifies that the amount of heat transfer of condensing water can differ by the hourly-changing outdoor wet bulb temperature. Also, because the monthly outdoor temperature distribution is different, the study categorized the outdoor wet bulb temperature.

As in Figure 11, most of the measured outdoor wet bulb temperature in 2009 was lower than the design outdoor wet bulb temperature. Since the heat transfer with air in fact occurs not at the design outdoor wet bulb temperature, but at the measured outdoor wet bulb temperature, energy saving can be possible by lowering the condensing water supply temperature.

The analysis of the frequency of the hourly wet bulb temperature shows that in June, the frequency of wet bulb temperature between 17 and 20°C occupied 54% (392) of the total frequency, and in July, the frequency of wet bulb temperature between 20 and 23°C occupied 82% (613) of the total frequency. Also, the frequency of wet bulb temperature at 21 to 24°C in August occupied 69% (515) of the total frequency in August, and in September, the frequency at 16–19°C occupied 71% (511) of the total frequency, all of which show that the wet bulb temperature was highest in August, followed by July, June and September. Dramatically, the energy consumption was in the same order as the wet bulb temperature, from August to July, June and September.

As shown in Table 5, controlling the condensing water supply temperature at 29°C in June and 28°C in September reduced energy consumption. But, lowering the temperature increased the energy consumption in July and August because the outdoor wet bulb temperature in July and August is higher than that in June and September, which results in less heat transfer between condensing water and ambient air. It is typically known that when the outdoor wet bulb temperature is high, the air volume is small, the condensing water temperature is high, and the amount of condensing water is small, the cooling tower’s heat transfer performance degrades (KENCA, 2008).

The “Approach” temperature shows the relation between the condensing water supply temperature and the outdoor wet bulb temperature. Considering the result of the previous studies, the monthly outdoor wet bulb temperature in June, July, August and September is 18°C, 22°C, 23°C, and 17°C, respectively. Meanwhile, the condensing water supply temperature at which the energy consumption was smallest was 29°C in June, 33°C in July, 34°C in August, and 28°C in September. Of particular interest is that the “Approach” temperature of both the condensing water supply temperature and the monthly representative wet bulb temperature in from June to September is 11°C. While it was previously suggested that when the “Approach” temperature is low, energy can be saved. However, the target building mixes and uses various types of chillers and the outdoor dry bulb temperature is high, and thus, the “Approach” temperature is calculated high. If the correlation between the outdoor wet bulb temperature and energy consumption between June and September is to be analyzed, the calculation of the smallest energy consumption can be calculated by Eq. (5).

\[
T_{cd} = \begin{cases} 
28°C & \text{(for } T_{WB} < 17°C) \\
T_{WB} + 11°C & \text{(for } 17°C \leq T_{WB} \leq 23°C) \\
34°C & \text{(otherwise)} 
\end{cases}
\]  

(5)

But, as in Table 5, setting the condensing water supply temperature in June to 28°C does not result in the smallest energy consumption. The temperature was actually at 29°C. On the other hand, if the condensing water supply temperature in September is set from 28°C to 29°C, the difference in energy consumption is negligible. Thus, Eq. (5) is corrected by the energy consumption in June and September, which results in the following Eq. (6).

\[
T_{cd} = \begin{cases} 
29°C & \text{(for } T_{WB} < 18°C) \\
T_{WB} + 11°C & \text{(for } 18°C \leq T_{WB} \leq 23°C) \\
34°C & \text{(otherwise)} 
\end{cases}
\]  

(6)

Using Eq. (6), the study applied the EMS class by EnergyPlus to control the hourly condensing water supply temperature. The EMS class by EnergyPlus, as shown in Figure 12, consists of the H/W objects, such as Sensors and Actuators, and S/W objects, such as ProgramCallingManager, Program, Subroutine, and Variables(Ellis et al., 2007).
Controlling the condensing water temperature is normally performed by bypass and automatic control. Generally, the temperature for the condensing water is set during the installation, and is rarely reset or adjusted. But this study assumed that the condensing water temperature would be easily adjustable. Due to the hot and humid summer climate in Korea, the study analyzed the outdoor wet bulb temperature in a large office building that is operated by several chillers and cooling towers, and also analyzed the potential energy saved by modeling the target building using the EMS class by EnergyPlus, adjusting its energy consumption based on the measured energy usage, and controlling the condensing water supply temperature of the cooling towers.

Based on the design condensing water supply temperature as the basis, the study analyzed the total energy consumption between June and September, the cooling season by controlling either the total condensing water supply temperature, or the monthly and hourly temperature. The analysis resulted in the following energy savings:

- Under the design condensing water supply temperature: 3,924 MWh
- By controlling the total condensing water supply temperature: 3,913 MWh (0.3% savings to the design condensing water supply temperature)
- By controlling the monthly condensing water supply temperature: 3,868 MWh (1.4% savings to the design condensing water supply temperature)
- By controlling the hourly condensing water supply temperature: 3,665 MWh (6.6% savings to the design condensing water supply temperature)

The result showed that by controlling the condensing water supply temperature based on the monthly wet bulb temperature change, the energy consumption in the cooling season (June to September) could be saved by 1.4%. If the control of the hourly condensing water supply temperature is possible, up to 6.6% of energy can be saved.

**NOMENCLATURE**

- $Q_{cd}$: heat rejection
- $\Delta U_{cd}$: overall heat transfer coefficient of the condenser
LMTD_{cd} : log mean temperature difference of condenser water and outdoor wet bulb temperature

M: measured[kWh]
S: simulated[kWh]
N_{month}: number of utility bills in the year
ERR_{month}: monthly error
ERR_{year}: yearly error
RMSE_{month}: root mean square monthly error
A_{month}: mean of the monthly utility bills
CV(RMSE_{month}): coefficient of variation of RMSE
T_{cd}: condenser water supply temperature
T_{WB}: outdoor wet bulb temperature

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