Precise control of CCT with two different CCT LED lamps  
for development of CCT tunable luminaire

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Abstract — CCT(Correlated Color Temperature), which is an important element affecting emotional feelings of workers in a space should be adequately adjusted according to the change of work atmosphere. The development of the adjustable CCT luminaries is necessary for appropriate CCT, which may detect the change of various work atmospheres and the time of day. To control CCT, an adjustable CCT luminaries use a specific method, which combines higher CCT of the lamps and lower ones. However, when two different CCT lamps are combined, the realization of target CCT using a simple proportional equation is not appropriate. Therefore, this study assessed three different methods to calculate appropriate combination ratio for two different CCT LED lamps, and then measurements were conducted with calculated values from such methods in order to find the method of precise control of CCT with two different CCT LED lamps. The appropriate method for realization of the target CCT with different CCT LED lamps has been identified by comparison between target CCT and measured CCT values. As a result, the third calculation method is the most appropriate to realize the target CCT with two different CCT LED lamps.

Keywords: CCT (correlated color temperature), the McCamy equation, CCT control, white LED luminaires.

1. Introduction
1.1 Background and objectives
To suitably design a lighting plan in the architectural space, appropriate illuminance distribution, CCT (Correlated Color Temperature) and CRI (Color Rendering Index) as well as target illuminance level must be considered. Particularly, CCT which is an important element affecting emotional feelings of
workers in a space needs to be adequately changed according to the change of work atmosphere [J. H. Chang and others 2007]. Thus, the development of the adjustable CCT luminaire is necessary for appropriate CCT performance in the architectural space.

To control CCT, an adjustable CCT LED luminaire uses specific methods which combine higher CCT of the white LEDs and lower ones [Y. J. Park and others 2009]. However, when two different CCT lamps are combined, the realization of a target CCT using a simple proportional equation is not appropriate. This is because the CCT of each lamp is changed according to the dimming control, and the maximum luminous flux of each LED lamp with various CCT is different. In addition, as you can see the CCT lines on a CIE chromaticity diagram, the spacing between 3000k, 4000k and 5000k are not equivalently sized steps. Namely, 4000K of CCT cannot be achieved with two combined lamps at the dimming level of 50% with a 3000K and 5000K lamp. Such an inappropriate lighting according to the dimming control may affect the luminous environment in a space in which workers’ alertness and performance, and color appearance of merchandise are important [H. S. Kim and others 2011].

Observing the recent studies related to changes of the characteristics of light according to the dimming level, a study analyzing the change of luminous flux and efficiency in accordance with digital dimming control of the LEDs was performed [C. L. Kuo and others 2010]. For the change in CCT in accordance with increase of luminous flux, there was a study related to the tendency of CCT decreasing in accordance with the increase of F32T8 lamp luminous flux [V. Jamjureeruk and others 2008]. Furthermore, another study analyzed the relation between voltage and CCT of HID lamps; it showed the tendency that as voltage increased, CCT of metal halide lamps and high pressure mercury lamps decreased, and CCT of high pressure sodium lamps increased [E. Enriquez and others 2005]. The tendency to decrease after the increase in CCT when increasing luminous flux of 26W Quad Tube CFL was studied [J. W. Lapointe and others 1994].

With regard to the previous studies on changes of the characteristics of lamp according to the material, Yi Yang et al. conducted a comparative study on the optical characteristics of InGaN-based multiple quantum well (MQWs) LEDs with peak emission ranging from green to ultraviolet over a wide injection range [Yi Yang and others 2008]. H. S. Kim et al. investigated the effects of current spreading on the performance of MQWs GaN/InGaN LEDs [H. S Kim and others 2001]. S. Z. Deng et al. examined the frequency characteristics of a lighting element using carbon nanotube-based composite as cold-cathode material [S. Z. Deng and others 2005]. Christian Sommer et al. presented a study by optical ray-tracing in order to determine the impact of an inhomogeneous phosphor distribution in the
color conversion elements (CCE) of phosphor-conversion based white LED light sources [Christian Sommer and others 2010]. P. C. Tsai et al. demonstrated nitride-based blue light emitting diodes with an InGaN/GaN (460 nm) multiple quantum well structure on the patterned sapphire substrates (PSSs) compared with conventional sapphire substrates (CSSs) using metal-organic chemical vapor deposition [P. C. Tsai and others 2007].

Upon the reviews of the above previous research, we reached a conclusion that a detailed method for creating the target CCT with appropriate illuminance levels needs to be developed. To precisely define the method for realization of the target CCT and illuminance, three equations were assessed, and then measurements were conducted with calculated values from such equations. More specifically, the three different methods to calculate the combination ratio for two different CCT LED lamps were hypothesized. As a part of a larger study that aims to develop the practical adjustable CCT LED lighting system, this study is a preliminary study for indentifying the appropriate method for realization of the target CCT with different CCT LED lamps, which embeds IT and eventually helps to create a healthy and multi-function luminous environment.

1.2 Research method and procedure

To determine the proper dimming levels of each lamp for a specific CCT value when two lamps are mixed, a change of the characteristics of light sources according to the dimming level should first be analyzed. To do so, we measured illuminance and CCT values in various CCT lamps in accordance with changing the dimming level. Then, we also measured tristimulus values for calculating CCT. Based on such data, this study hypothesized that following three different calculation methods can be a candidate to calculate a proper dimming level, which can be called ‘the combination ratios’.

The first method is to calculate the combination ratio by using a simple proportional equation. This is just based on the meaning of the arithmetic average of each light source. This method is appropriate only if all illuminance levels are the same according to the dimming level of each lamp, and the CCT remains the same value regardless of dimming lamps. Unfortunately, this cannot be true in reality.

The second method is to calculate the combination ratio by considering a change of the characteristics of light according to dimming. This is based on the hypothesis that the CCT varies according to dimming lamps and its variations are dependent on the designated CCT. In addition, the maximum output across a wide range of various CCT lamps are different even in the same wattage lamp. This
method utilizes the simple proportional equation above, which considers a change of illuminance and CCT according to dimming lamps.

Although the second method above seems to be adequate, another method based on an appreciation that the CCT is basically calculated with tristimulus values of X, Y, Z is considered. Specifically, this method is to calculate the combination ratio by using the McCamy's Equation along with a change of tristimulus values of X, Y, Z values according to dimming lamps [O. Noboru 2003]. The McCamy's Equation is now widely used to compute the CCT of light sources.

To identify the proper method for determining the combination ratio, the white LED Bar type lamps were dimmed according to the calculated combination ratio. Then, the CCT and illumination values of the combined lamps were measured. The most appropriate method which calculates a combination ratio was chosen by comparative analysis of the measured CCT and illuminance verse the target CCT and illuminance.

2. Methods of measurement

2.1 Summary of measurement

CCT, illuminance, and tristimulus values were measured according to the dimming levels of the various LED lamps using a semi-enclosed black lighting box where there were no windows, and all ambient lights were blocked. Also, CCT and illumination values of combined light were measured in the same condition for the calculation of the combination ratio by three different methods. Table 1 shows the outline of the LED lamps and measuring instruments and Figure 1 shows images of the LED lamps and measuring instruments.

<table>
<thead>
<tr>
<th>Type</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamps 1 (for measurement)</td>
<td>LED (6W): 2800K, 4000K, 4800K, 6000K, 6300K</td>
</tr>
<tr>
<td>Lamps 2 (for combination)</td>
<td>LED (6W): 2800K, 6300K</td>
</tr>
<tr>
<td>Instruments</td>
<td>Chroma-meter: CL-200</td>
</tr>
<tr>
<td></td>
<td>Lighting box: 600×350×440(mm)</td>
</tr>
<tr>
<td></td>
<td>Dimming control software &amp; Dimming controller</td>
</tr>
</tbody>
</table>
The dimming control software and the dimming controller were utilized for the dimming control of the lamps. The software and controller are a constant voltage type (controlling current) and can control a total of 256 levels digitally. Figure 2 shows an example of combination measurement by using the lighting box.

2.2 Measured CCT and illuminance values of the white LED lamps according to the dimming levels

Figure 3 shows graphs of relative variations of measured data of CCT and illuminance values in accordance with dimming. The CCT values of white LED lamps decreased in accordance with the decrease of the relative output of light sources and vice versa. The maximum CCT values of each white LED lamp are a little different from designated CCT values from the manufacturers. This error may come from the instrument absolute errors or the tolerance of manufacturing errors. In this study, the relative variation of CCT is more important so that such errors can be ignored. A difference between the maximum absolute CCT value and minimum absolute CCT value of the lamps was respectively different according to each CCT lamp. The higher the CCT was the bigger change of absolute CCT value. The illuminance values constantly increased in accordance with an increase of...
dimming level. On the other hand, the CCT values sharply increased in accordance with a lower dimming level (around under 20%) and gradually increased in accordance with a higher dimming level.

Fig. 3. The results of measurement of illuminance and CCT values, and comparison of change-rate (a) Illuminance vs. CCT of 2700K, (b) Change-rate of illuminance vs. CCT of 2700K, (c) Illuminance vs. CCT of 4000K, (d) Change-rate of illuminance vs. CCT of 4000K, (e) Illuminance vs. CCT of 4700K, (f) Change-rate of illuminance vs. CCT of 4700K, (g) Illuminance vs. CCT of 6000K, (h) Change-rate of illuminance vs. CCT of 6000K, (i) Illuminance vs. CCT of 6000K, (j) Change-rate of illuminance vs. CCT of 6000K

2.3 Calculation of the combination ratio
2.3.1 Using a simple proportional equation
The first method is to calculate the combination ratio by using a simple proportional equation. As mentioned introduction, this method is expected to cause errors because the CCT of lamp is changed according to the dimming control, and the spacing of the CCT lines on a CIE chromaticity diagram, between 3000k, 4000k and 5000k are not equivalently sized steps. Nonetheless, the first method was studied in order to know that the errors how much large. The specific values were applied to the target CCT ($K_{SET}$) and illuminance ($E_{SET}$) of the following (1) and (2) while the measured CCT values of two lamps ($K_H$ and $K_L$) were applied to (2). $K_H$ and $K_L$ were measured at the maximum light output of two different CCT lamps. The required illuminance values of two lamps ($E_{H,req}$ and $E_{L,req}$), which meet the specific target CCT and illuminance values can be calculated by solving these two equations.
\[ E_{SET} = E_{H,\text{req}} + E_{L,\text{req}} \]  
\[ K_{SET} = \frac{(K_H \times E_{H,\text{req}}) + (K_L \times E_{L,\text{req}})}{E_{H,\text{req}} + E_{L,\text{req}}} \]  

\( E_{SET} \) in the lighting box was set to 100lx and 200lx, respectively, and \( E_{H,\text{req}} \) and \( E_{L,\text{req}} \) were calculated under the seven different target CCT such as 3000K, 3500K, 4000K, 4500K, 5000K, 5500K, and 6000K using a 2800K and 6300K LED lamps. The calculated illuminance values using a simple proportional equation of the lamps can be found in Table 2.

2.3.2 Considering a change of CCT and illuminance values in accordance with dimming

Since the first method in the previous section does not consider the variation of CCT values in accordance with dimming, the second method applies a change of CCT and illuminance values according to the dimming level to Eqs. (1) and (2) for the calculation of the combination ratios. CCT and illuminance values according to the dimming level of the lamps were measured, and then a regression equation was obtained for each CCT lamp by conducting the regression analysis as shown in Figure 4.

![Fig. 4. CCT and illuminance values according to the dimming level of the LED lamps. (a) Illuminance vs. dimming level, (b) CCT vs. dimming level](image)

<table>
<thead>
<tr>
<th>Regression equation</th>
<th>Coefficient of determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_L(x_L) = 1.125x_L - 26.19 )</td>
<td>( R_L^2 = 0.9982 )</td>
</tr>
<tr>
<td>( E_H(x_H) = 1.352x_H - 31.70 )</td>
<td>( R_H^2 = 0.9983 )</td>
</tr>
<tr>
<td>( K_L(x_L) = 10.61\ln(x_L) + 2785.9 )</td>
<td>( R_L^2 = 0.9786 )</td>
</tr>
<tr>
<td>( K_H(x_H) = 62.02\ln(x_H) + 5988.7 )</td>
<td>( R_H^2 = 0.9920 )</td>
</tr>
</tbody>
</table>

The illuminance values according to the dimming level show a linear function shape while the CCT values show a logarithmic function shape. If Eqs. (3) and (4) are regression equations of illuminance and CCT, Eqs. (3) and (4) will be expressed as Eqs. (5) and (6) using (1), respectively and (7) is expressed by substituting Eqs. (5) and (6) into (2). \( E_{H,\text{req}} \) can be calculated by substituting target CCT
and illuminance into (7), and $E_{L,\text{req}}$ can be calculated by substituting $E_{H,\text{req}}$ into (1). The calculated $E_{H,\text{req}}$ and $E_{L,\text{req}}$ using the second method can be found in Table 2.

$$E_H(x_H) = ax_H + b, \quad K_H(x_H) = c \ln(x_H) + d$$

(3)

$$E_L(x_L) = a'x_L + b', \quad K_L(x_L) = c' \ln(x_L) + d'$$

(4)

$$E_L(x_L) = a'x_L + b'K_L(x_H) = c' \ln\left(\frac{E_{H,\text{req}} - b}{a}\right) + d'$$

(5)

$$K_L(x_L) = c' \ln\left(\frac{E_{\text{SET}} - E_{H,\text{req}} - b'}{a'}\right) + d'$$

(6)

$$K_{\text{SET}} \times E_{\text{SET}} = E_{H,\text{req}}\left[c \ln\left(\frac{E_{H,\text{req}} - b}{a}\right) + d\right] + (E_{\text{SET}} - E_{H,\text{req}})\left[c' \ln\left(\frac{E_{\text{SET}} - E_{H,\text{req}} - b'}{a'}\right) + d'\right]$$

(7)

2.3.3 Considering a change of tristimulus values in accordance with dimming

The third method is to calculate a combination ratio by applying the change of tristimulus values according to the dimming level to the McCamy’s Equations for the calculation of the combination ratios. The tristimulus values of two lamps ($X_L,Y_L,Z_L$ and $X_H,Y_H,Z_H$) in accordance with the dimming level of the lamps were measured to identify the degree of changes. Figure 5 shows the regression equations based on the measured tristimulus values according to the dimming level of each lamp.

![Regression equations](image)

Fig. 5. The measured tristimulus values according to the dimming level of the LED lamps (a) 2800K, (b) 6300K
When two different CCT lamps are combined, a sum of tristimulus values for each lamp is the same as measured tristimulus values of the combined lamps, which was verified by conducting the preliminary measurement. Thus, the tristimulus values of combined light ($X_C$, $Y_C$, $Z_C$) in the combined lamps can be expressed as $X_C = X_H + X_L$, $Y_C = Y_H + Y_L$, and $Z_C = Z_H + Z_L$. Also, the $Y$ value of tristimulus values can be expressed as in (8) because the $Y$ value indicates the luminance value. After making two linear equations with two variables of the required dimming levels ($x_{H, req}$ and $x_{L, req}$), by substituting $X_C$, $Y_C$, $Z_C$ into the following Eqs. (8) to (10), $x_{H, req}$ and $x_{L, req}$ of the lamps are calculated by solving two equations. Finally, the calculated dimming levels of $x_{H, req}$ and $x_{L, req}$ are substituted into a regression equation of $Y_H(x_{H})$ and $Y_L(x_{L})$, which corresponds to each illuminance, and then required illuminance values of $E_{H, req}$ and $E_{L, req}$ are calculated. (8) is the McCamy’s Equation which is one of the most typical methods of calculating CCT.

\[ E_{SET} = Y_C = Y_H + Y_L \]  \hspace{1cm} (8)

\[ K_{SET} = -473n^3 + 3601n^2 - 6861n + 5514.31 \]  \hspace{1cm} (9)

\[
\begin{align*}
\ln n &= (x - 0.3320)/(y - 0.1858) \\
x &= X_C/(X_C + Y_C + Z_C) \\
y &= Y_C/(X_C + Y_C + Z_C)
\end{align*} \hspace{1cm} (10)

For example, if we realize a target CCT of 3000K and target illuminance of 100lx by combining the lamps, one equation is obtained to calculate a linear simultaneous equation with two variables by summarizing (8) into a linear equation with two variables, which are $x_{H}$ and $x_{L}$ as in the equation, $0 = 1.113 \times x_L + 1.317 \times x_H - 57.2 - [100lx]$. Next, after calculating the three values on $n$ by changing (9) to $0 = -473n^3 + 3601n^2 - 6861n + 5514.31 - [3000K]$ and solving a third-order cubic equation, the left term of (10) is substituted by choosing one value, which is less than 1, among the three calculated $n$ values above. By substituting a tristimulus regression function of $X_C(x_{H}, x_{L})$, $Y_C(x_{H}, x_{L})$, and $Z_C(x_{H}, x_{L})$ of the combined lamps into (10) and summarizing these equations into a function whose dependent variables are the chromaticity coordinates ($x$, $y$) and independent variables are $x_{H}$ and $x_{L}$, the other linear equation with two variables ($x_{H, req}$, $x_{L, req}$) is obtained to calculate a linear simultaneous equation with two variables ($x_{H, req}$, $x_{L, req}$). $x_{H, req}$ and $x_{L, req}$ are then calculated by solving the above two equations with two variables. The required illuminance, which was converted through the equation of trend line of $Y_H(x_{H})$ and $Y_L(x_{L})$ applied to
calculating $x_{H, req}$ and $x_{L, req}$ of the LED lamps, can be found in Table 2.

### Table 2. The combination ratios using three methods

<table>
<thead>
<tr>
<th>Target CCT</th>
<th>Calculated combination ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st method ($E_{L, req}$: $E_{H, req}$) 100lx&amp;200lx</td>
</tr>
<tr>
<td>3000K</td>
<td>4.4:95.6</td>
</tr>
<tr>
<td>3500K</td>
<td>18.8:81.2</td>
</tr>
<tr>
<td>4000K</td>
<td>33.1:66.9</td>
</tr>
<tr>
<td>4500K</td>
<td>47.5:52.5</td>
</tr>
<tr>
<td>5000K</td>
<td>61.8:38.2</td>
</tr>
<tr>
<td>5500K</td>
<td>76.2:23.8</td>
</tr>
<tr>
<td>6000K</td>
<td>90.5:9.5</td>
</tr>
</tbody>
</table>

3. Results of measurement

Table 3 shows the error ratios using three methods. According to Table 3, the first method shows an average error ratio of 9.68% and an error ratio range of 2.8 to 14.8% in all target CCT and two target illuminance values. In general, error ratios increase to around the target CCT of 4000K and then decrease. Additionally, error ratios of the target illuminance of 200lx were a little lower than those of the target illuminance of 100lx. Also, the second method shows an error ratio range of 2.3 to 12.9% in all target CCT and two target illuminance values. Error ratios increase to around the target CCT of 4000K and then decrease. The second method shows an average error ratio of 8.52%, which is about 1.16% lower than that of the first method. But, the absolute value of 8.52% is still larger to accomplish the target CCT. The third method shows an error ratio range of 0.12 to 0.83% in all target CCT and two target illuminance values, and an average error ratio of 0.42%. There is no trend of the variation in the error ratios.

### Table 3. The error-ratios using three methods

<table>
<thead>
<tr>
<th>Target CCT</th>
<th>Error-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st method</td>
</tr>
<tr>
<td></td>
<td>100lx</td>
</tr>
<tr>
<td></td>
<td>$E_{error}$</td>
</tr>
<tr>
<td>3000K</td>
<td>2.7%</td>
</tr>
<tr>
<td>3500K</td>
<td>0.5%</td>
</tr>
<tr>
<td>4000K</td>
<td>1.7%</td>
</tr>
<tr>
<td>4500K</td>
<td>1.1%</td>
</tr>
</tbody>
</table>
Figure 6 shows a comparison of the average error ratios from the three combination methods. Both the first method and the second method show higher error ratios. On the other hand, the last method can be the most appropriate method because its average error ratio is much lower than other methods.

![Comparison of average error ratios of the combined LED lamps according to combination methods](image)

**Fig. 6. Comparison of average error ratios of the combined LED lamps according to combination methods**

### 4. Conclusions

In this study, a change of CCT and illuminance according to the dimming level of the white LED Bar type lamp was analyzed first. Then, using the results, the combination ratios for two different CCT lamps were calculated. The three different methods, using a simple proportional equation to more sophisticated tristimulus values, were used to calculate such ratios. To find out the appropriate calculated method, CCT and illuminance values are measured with calculated ratios from three different methods, and then a comparison analysis is conducted between the target and measured CCT.

The main findings can be summarized as follows:

1) The differences between the maximum absolute and minimum absolute CCT values of white LED lamps according to the maximum and minimum dimming levels were different respectively for each designated CCT. The bigger differences of absolute CCT values from the higher CCT lamps were found. A change tendency of CCT values is a little different according to the dimming level for each of the CCT lamps but the overall tendency for each CCT lamp is similar. Illuminance values constantly increased in accordance with an increase of dimming level. On the other hand, the CCT values sharply increased at the lower dimming level and gradually increased at the higher dimming level.
2) The results of the first calculation method show a higher average error ratio of 9.68% in all target
CCT and two target illuminance values.
3) The second method shows a reduction of 1.16% in error ratio compared to that of the first
calculation method. However, it still shows a higher mean error ratio of 8.52% for the lamps. It is
speculated that other considerations should be added to find an appropriate combination ratio.
4) The results of the last method show a very small average error ratio of 0.42% in all target CCT
and two target illuminance levels. Therefore, the third calculation method is the most appropriate
method to calculate the combination ratio of the white LED Bar type lamp.

To expand applications of dimmable LED lamps, the precise control of CCT using the variation of
tristimulus values should be implemented especially for CCT changeable LED lighting systems. Of
course, the measurement of tristimulus values for all LED lamps is not a simple task. However,
significance of this study is to propose the appropriate calculation method for making a particular CCT
luminous.

Acknowledgments
This work was supported by Mid-career Researcher Program through NRF grant (No. 2011-0013621)
funded by the Korea Ministry of Education, Science and Technology. This research was also supported
by the MKE(The Ministry of Knowledge Economy), Korea, under the Convergence-ITRC(Convergence
Information Technology Research Center) support program (NIPA-2011-C6150-1101-0002) supervised by
the NIPA(National IT Industry Promotion Agency)

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