Analysis of spectral power distributions of fluorescent lamps for the maximum luminous efficacy under given color and color rendering properties

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Numerical calculations were performed with an iterative linear programming method for the purposes of predicting the optimum spectral power distributions and the lighting characteristics of fluorescent lamps. Linear programming was used in order to minimize the range containing local solutions and insure convergence to the optimum solution. The optimum spectral power distributions of fluorescent lamps making all of special color rendering indices of R_1 to R_8 95 or more must be composed of four narrow spectral bands having a radiation peak at 470, 530, 580 and 620 nm.

1. Introduction

The luminous efficacy, chromaticity and color rendering properties of fluorescent lamps depend on the SPD's (spectral power distributions) of the lamps. It is the purpose for the developments of the lamps and the fluorescent lamps especially to make luminous efficacy maximum under a given color and CRI (color rendering index). Luminous efficacy of lamps is the product of these radiant efficiency by luminous efficacy of the radiation. The radiant efficacy can be improved by developments in physical and chemical properties of various materials. The luminous efficacy can be enhanced by actualizing the ideal SPD's through selection of adequate luminous materials as regards fluorescent lamps. Analysis of the optimum SPD's which give the maximum luminous efficacy under the prescribed constraints of chromaticity and color rendering properties can be made in the following two ways with the aid of digital computers:

(1) A method of analysis with constraints put on the peak wavelength, wavelength band width and the like of the luminous components to be combined in consideration of the characteristics of luminous materials.

(2) A method of analysis with constraints put on the radiant flux, chromaticity and color rendering properties, but not at all on the shape of SPD.

(Until now, the method (1) has been used to predict the optimum SPD of narrow-band type fluorescent lamps, and the three-band type lamp has been developed based on it.^{1) 2)}).

Problems to which the method (2) is applicable are, mathematically conditional extremum problems and can be dealt with effectively by mathematical programming.

In cases where the optimum SPD's are sought which maximize the objective function or the total luminous flux under the constraints of the radiant flux, chromaticity and CRI (color rendering index)

of fluorescent lamps, the constraint equations pertaining to the chromaticity and CRI are nonlinear and nonlinear programming (NLP) is generally applicable here. Walter³⁾ and Fuchida et al.⁴⁾ reported on NLP analysis of the optimum SPD's of fluorescent lamps.

Walter set up the objective function and constraint equations for 4 kinds of fluorescent lamps specified by ANSI C78.376-1969, WW, W, CW and D,⁵⁾ and analyzed the optimum SPD's. He regarded four monochromatic components at 460, 530, 580 and 620 nm of wavelength, as fundamental to the SPD's which maximize the total luminous flux under the constraints $R_a \geq 90$ or $R_a \geq 95$. However, spectral powers other than those four monochromatic components appear in the SPD's he obtained and it has not been confirmed whether or not these four monochromatic components alone can actually satisfy $R_a \geq 90$ or $R_a \geq 95$. Walter pointed out that the supersurface containing the optimum solution is fairly flat and it is possible to make small changes in the SPD's without greatly affecting the luminous efficacy or the CRI.

Fuchida et al. predicted the complications that the optimum solution may vary with the algorithm applied in the problems such as above which may yield a large number of local solutions. Therefore, they obtained the optimum solution by applying five kinds of NLP algorithms to the objective function and constraints approximately equal to those set up by Walter. They reported that analysis by each algorithm converged into almost the same optimum solution and a spectral power appeared at 490 nm where none had been reported by Walter.

We have studied the differences between the two works cited above and analyzed the optimum SPD's in the whole range of chromaticity specified in JIS Z9112-1976⁶⁾ in order to clarify in more detail the characteristics of the optimum SPD's such as monochromatic components, luminous flux, chromaticity and CRI.

In carrying out the analysis, we consider it is better to constrain the chromaticity not by chromaticity range but by chromaticity coordinates

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in order to minimize the range containing local solutions and insure convergence to the optimum solution. If this is done, the constraints on the chromaticity become linear. On the other hand, the number of sample points increases markedly. It is therefore necessary to shorten the time required for calculation of the optimum SPD's for each sample point (chromaticity coordinates). To this end, the nonlinear constraint equations relating to the color rendering index were modified to forms to which LP (linear programming) is applicable and LP was applied repeatedly to realize convergence to the optimum solution. LP does not require calculation of gradient vectors which is essential for NLP and it is expected that LP will complete the calculation in a shorter time than NLP where LP needs to be repeated only a limited number of times.

In this paper, we report on the algorithm we used for optimization and the characteristics of the optimum SPD's we found on 40-watt fluorescent lamps.

2. Objective function and constraint equations

(1) Objective function maximizing the total luminous flux

The visible wavelength range 400~700 nm, was divided into 31 monochromatic components, each 10 nm in wavelength band width.

$$\phi = K_m \Delta \lambda \sum_{j=1}^{31} V_j P_j + \phi_{Hg} \quad \dots\dots\dots(1)$$

$$\phi_{Hg} = K_m \sum_{i=1}^4 V_i c_i (r_1 + r_2)$$

(The proportion of the mercury line spectrum was assumed constant and this equation was adopted for convenience' sake.)

where: ϕ =total luminous flux in lm; K_m =maximum luminous efficacy in lm/W; $\Delta \lambda$ =wavelength band width or 10 nm; V_j , V_i =standard spectral luminous efficiency; P_j =spectral power of fluorescent material in W; ϕ_{Hg} =total luminous flux caused by the mercury line spectrum in lm; r_1 , r_2 =the ultraviolet exciting power in 185 and 254 nm in W; c_i =relative powers of visible spectral line at 405, 436, 546 and 578 nm in the ratio to the sum of r_1 and r_2 .

Here, values of 0.0090, 0.0212, 0.0112 and 0.0032 were adopted for c_1 , c_2 , c_3 and c_4 respectively, while values of 3.49 and 21.3 W⁴) for r_1 and r_2 respectively.

(2) Constraint equation for radiant flux

The constraint on radiant flux from the excited fluorescent materials is expressed as

$$\Delta \lambda \sum_{j=1}^{31} \lambda_j P_j = \sum_{k=1}^2 \lambda_k r_k q_k \quad \dots\dots\dots(2)$$

where: λ_j =wavelength of fluorescence in nm; λ_k =wavelength of ultraviolet excitation in nm; q_k =

quantum efficiency of fluorescent material.

Here, $q_1(185 \text{ nm}) = q_2(254 \text{ nm}) = 0.77$ was adopted for q_k ⁴⁾.

(3) Constraint equation for chromaticity

The constraints on the chromaticity (x_k , y_k) are expressed as

$$\left. \begin{aligned} x_k &= \frac{\Delta \lambda \sum_{j=1}^{31} P_j \bar{x}_j + \sum_{i=1}^4 c_i (r_1 + r_2) \bar{x}_i}{\Delta \lambda \sum_{j=1}^{31} P_j \bar{s}_j + \sum_{i=1}^4 c_i (r_1 + r_2) \bar{s}_i} \\ y_k &= \frac{\Delta \lambda \sum_{j=1}^{31} P_j \bar{y}_j + \sum_{i=1}^4 c_i (r_1 + r_2) \bar{y}_i}{\Delta \lambda \sum_{j=1}^{31} P_j \bar{s}_j + \sum_{i=1}^4 c_i (r_1 + r_2) \bar{s}_i} \end{aligned} \right\} \quad \dots\dots\dots(3)$$

$$\bar{s}_j = \bar{x}_j + \bar{y}_j + \bar{z}_j, \quad \bar{s}_i = \bar{x}_i + \bar{y}_i + \bar{z}_i$$

where: $\bar{x}_j$, $\bar{y}_j$, $\bar{z}_j$, $\bar{x}_i$, $\bar{y}_i$ and $\bar{z}_i$ are tristimulus values.

(4) Constraint equation for CRI

The constraints on the special CRI's are expressed as

$$R_i \geq R_c \quad (i=1-8) \quad \dots\dots\dots(4)$$

where: R_i =special CRI of a test color (i) for calculation of the general CRI; R_c =constant.

The constraint on the general CRI R_a , as given in equation (5) below, was fundamentally not adopted here in order to keep a given value of R_i from becoming extraordinary small relative to value of R_a assumes large values and to minimize fluctuations in R_i .

$$R_a = \frac{1}{8} \sum_{i=1}^8 R_i \geq R_c \quad (i=1-8) \quad \dots\dots\dots(5)$$

However, calculations were carried out for several examples by equation (5) and the results were compared with those obtained from equation (4). No constraint was put on the special CRI's R_i ($i=9-15$). In the discussions which follow, the subscript i in R_i is 1-8 unless otherwise stated.

As to the constraints, we differ from Walter mainly in those restricting the chromaticity and CRI as follows. We fixed chromaticity to a selected point and calculated the CRI by the method described in CIE (1st edition) JIS. On the other hand, Walter limited the chromaticity to the MacAdam ellipses specified by ANSI⁵⁾ and calculated the CRI by the method in CIE (2nd edition). We used 0.77 as quantum efficiency of the fluorescent material whereas Walter used 1. Also, our total luminous flux of the mercury spectral lines is somewhat different from his.

3. Algorithm for optimization by repeated applications of LP

The values of R_i are obtained from the following equations. According to CIE (1st edition), one calculates R_i with incorporation of the lightness index. The equation (6) is used here since it gives approximately the same results as the method of CIE (2nd edition).

$$\left. \begin{aligned} \Delta U_i &= (u_{ki} - u_k) - (u_{oi} - u_i) \\ \Delta V_i &= (v_{ki} - v_k) - (v_{oi} - v_i) \\ \Delta E_i &= 800\sqrt{\Delta U_i^2 + \Delta V_i^2} \\ R_i &= 100 - 4.6\Delta E_i \end{aligned} \right\} \dots\dots\dots(6)$$

where: u_{ki}, v_{ki} = UCS chromaticity coordinates of test color (i) under sample light source,

u_{oi}, v_{oi} = UCS chromaticity coordinates of test color (i) under reference illuminant,

u_k, v_k = UCS chromaticity coordinates of sample light source, and

u_o, v_o = UCS chromaticity coordinates of reference illuminant.

The constraint equation for ΔE_i is obtained from equation (4) as follows:

$$\Delta E_i \geq \Delta E_c \frac{100 - R_c}{4.6} \dots\dots\dots(7)$$

Procedure 1

LP is used to calculate the SPD's which satisfy given chromaticity coordinates (u_k, v_k) under the following constraints and maximize the total luminous flux:

$$|\Delta U_i| \leq \Delta E_c, \quad |\Delta V_i| \leq \Delta E_c \dots\dots\dots(8)$$

In general, an increase in total luminous flux causes a decrease in CRI. Therefore, $\Delta U_i, \Delta V_i$ and ΔE_i are calculated for the SPD's obtained and designated as $\Delta U'_i, \Delta V'_i$ and $\Delta E'_i$ respectively. Then, because of the constraints of equation (8) at least one or more of $\Delta U'_i$ and $\Delta V'_i$ become equal to $\Delta E'_i$ and:

$$\Delta E_c < \Delta E'_m < \sqrt{2} \Delta E_c \dots\dots\dots(9)$$

where $\Delta E'_m$ is the maximum value of $\Delta E'_i$. Thus, the constraint equation (7) is not satisfied.

Procedure 2

LP is used to calculate the SPD's which satisfy given chromaticity coordinates (u_k, v_k) under the following constraints and maximize the total luminous flux:

$$\left. \begin{aligned} \text{If } |\Delta U'_i| \geq |\Delta V'_i|, \\ \text{then } |\Delta U_i| = |\Delta V_i| \leq |\Delta U'_i| \frac{\Delta E_c}{\Delta E'_i} \\ \text{If } |\Delta U'_i| < |\Delta V'_i|, \\ \text{then } |\Delta U_i| = |\Delta V_i| \leq |\Delta V'_i| \frac{\Delta E_c}{\Delta E'_i} \end{aligned} \right\} \dots\dots\dots(10)$$

The values of $\Delta U_i, \Delta V_i$ and ΔE_i are calculated for the SPD's obtained and designated as $\Delta U''_i, \Delta V''_i$ and $\Delta E''_i$ respectively.

Then, the following equations hold:

$$\left. \begin{aligned} \text{If } |\Delta U'_i| \geq |\Delta V'_i|, \\ \text{then } \Delta E''_i \leq 800\sqrt{\left(\Delta U'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2 + \left(\Delta U'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2} \\ \text{If } |\Delta U'_i| < |\Delta V'_i|, \\ \text{then } \Delta E''_i \leq 800\sqrt{\left(\Delta V'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2 + \left(\Delta V'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2} \end{aligned} \right\} \dots\dots\dots(11)$$

Furthermore, if $\Delta E'_i \approx E_c$, the following equations

hold true as $\Delta U'_i$ is generally proportional to $\Delta V'_i$:

$$\left. \begin{aligned} \text{If } |\Delta U'_i| \geq |\Delta V'_i|, \\ \text{then } \Delta E''_i \leq 800\sqrt{\left(\Delta U'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2 + \left(\Delta V'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2} \\ \leq 800\sqrt{\left(\Delta U'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2 + \left(\Delta U'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2} \\ \text{If } |\Delta U'_i| < |\Delta V'_i|, \\ \text{then } \Delta E''_i \leq 800\sqrt{\left(\Delta U'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2 + \left(\Delta V'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2} \\ \leq 800\sqrt{\left(\Delta V'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2 + \left(\Delta V'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2} \end{aligned} \right\} \dots\dots\dots(12)$$

where:

$$800\sqrt{\left(\Delta U'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2 + \left(\Delta V'_i \frac{\Delta E_c}{\Delta E'_i}\right)^2} = \Delta E_c$$

If $\Delta E'_m$, the maximum values of $\Delta E'_i$, becomes so nearly equal to ΔE_c as to make equation (12) hold true after execution of Procedure 1, the following relation will be satisfied after execution of Procedure 2:

$$\Delta E''_i \leq \Delta E_c + \epsilon \dots\dots\dots(13)$$

where ϵ is a sufficiently small positive number. Since an increase in total luminous flux generally causes a decrease in CRI, at least one or more of $\Delta E''_i$ can be expressed as follows:

$$\Delta E''_i = \Delta E_c + \epsilon \dots\dots\dots(14)$$

Therefore, the SPD's then satisfy the constraint of equation (7) and maximize the total luminous flux.

If equation (13) is not satisfied by execution of Procedure 1 and 2, a convergence can be obtained by repeating further only Procedure 2. Our experiences indicate that Procedure 2 needs to be repeated from 2 to 10 times when $\epsilon \approx 10^{-4} \Delta E_c$ produced a convergence.

4. Optimization of SPD's

Optimization was first done on the SPD's of 31 monochromatic components, each 10 nm in wavelength band width, of the visible wavelength range 400~700 nm. The study was restricted to the four chromaticity range, WW, WW, W and D, specified in JIS Z9112-1976.⁶⁾

4.1 Chromaticity range and total luminous flux

Figure 1 shows the chromaticity range in which the SPD's satisfying $R_i \geq 90$ or $R_i \geq 95$ may exist. This chromaticity range extends from the Planckian locus P at center approximately symmetrically toward the green side (+) and the violet side (-) along each isotherm line. The width of this range increases as the CCT (correlated color temperature) rises. It is only natural that, as the constraints on the CRI become severe, the chromaticity range containing SPD's satisfying such severe constraints becomes narrower. The locus L in Fig. 1. represents the chromaticity locus of the SPD's which maximize the total luminous flux at each CCT in the chromaticity range satisfying

Fig. 1 The chromaticity ranges where the spectral power distributions satisfying $R_i \geq 90$ or $R_i \geq 95$ exist (enclosed by dot-and-dash lines or broken lines) and the chromaticity locus L maximizing the total luminous flux under $R_i \geq 95$ ($i=1-8$) at given correlated color temperature.

$R_i \geq 95$. The locus L runs near the green side boundary of the range.

Figure 2 shows the maximum total luminous flux under the constraint $R_i \geq 95$ as a function of CCT. The discontinuity in CCT between 5300 and 5400 K is due to the calculating procedure in which a Planckian radiator is used the reference illuminant at 5300 K and below whereas CIE daylight is used at 5400 K and above. This discontinuity will appear in some of the later figures for the same reason. The total luminous flux is large in a low CCT range, for example WW 30 and WW, and diminishes as the CCT rises from W to D. The maximum of about 3480 lm appears in the CCT range of 3300 to 3500 K and the luminous efficacy there is about 87 lm/W.

Figure 3 shows the relation between the maximum total luminous flux and the chromaticity deviation from the Planckian locus under the constraint of $R_i \geq 95$ at CCT of 3500, 4500 and 6500 K. The total luminous flux increases as the chromaticity moves on a given isotherm line from the violet side boundary to the green side boundary and reaches a maximum immediately before the green side boundary. Also, the total luminous flux decreases sharply as the chromaticity comes very close to either of the boundaries.

4.2 Optimum SPD's

Figure 4 shows each spectral power of the SPD's which maximize the total luminous flux under the constraint of $R_i \geq 95$ at given CCT's. This figure reveals the following features of the optimum SPD's satisfying $R_i \geq 95$ in the whole range of chromaticity specified in JIS Z9112-1978.⁶⁾

(1) None of the optimum SPD needs radiation outside the wavelength range of 460-620 nm (ex-

Fig. 2 The maximum total luminous flux under $R_i \geq 95$ ($i=1-8$) as a function of correlated color temperature.

Fig. 3 Relation between total luminous flux and deviation from the Planckian locus $R_i \geq 59$ ($i=1-8$); $\square$ designating maximum).

cluding the mercury spectral line).

(2) There are four monochromatic components of primary importance, 470, 530, 580 and 620 nm, and two of secondary importance, 460 and 520 nm.

The first feature agrees with Walter's findings. As for the second feature, Walter concluded four monochromatic components of 460, 530, 580 and 620 nm to be of primary importance from his calculations performed under the constraints $R_i \geq 90$ and $R_i \geq 95$. We also obtained the results like Walter under $R_i \geq 90$ that the spectral power at 460 nm is greater than that at 470 nm in the whole CCT range.

In spite of the above-mentioned differences in the constraints between Walter and ours, both arrived at the optimum SPD's with almost the same features.

The ultraviolet excitation power, relative spectral distribution of the mercury line spectrum and the (quantum) efficiency of fluorescent materials considerably depend on the lamp construction and the performance of the component materials. A comparative study was therefore made on the optimum

Fig. 4 The monochromatic components of spectral power distributions maximizing the total luminous flux under $R_i \geq 59$ ($i=1-8$) at given correlated color temperatures (excluding the mercury spectral line).

SPD's for different values of above-mentioned parameters. The results indicate that, although the relative special distributions are different, there was no difference in monochromatic components at which the spectral powers appeared.

Inspection of Fig. 2 and 4 shows that the number of monochromatic components is six at the most (excluding the mercury spectral lines here and same as above) in the CCT range of 3300–3500 K where

the total luminous flux assumes the maximum value or a value close to it whereas this number becomes greater in other CCT ranges. Also, Walter obtained the results that, under the constraints $R_i \geq R_c$ or $R_a \geq R_c$, the total luminous flux increases but the number of monochromatic components decreases as R_c decreases from 95 to 90 down to 50. These findings lead to the following conclusion: in conversion of ultraviolet-excited radiant powers of a fluorescent lamp into spectral powers of the visible wavelength range by means of a fluorescent material, the luminous efficacy can be enhanced and a given CRI's can be satisfied by minimizing the number of monochromatic components and concentrating the spectral powers to specific monochromatic components. An increase in the number of monochromatic components raises the CRI but lowers the luminous efficacy.

Figure 5(a) shows the SPD which maximizes the total luminous flux under $R_i \geq 95$ at 4500 K. The deviation from the Planckian locus is 0.0037 uv. Fig. 5(b) shows the SPD which maximizes the total luminous flux under $R_i \geq 95$ at 4500 K and -0.0040 uv. Comparison of Fig. 5(a) and 5(b) indicates that the total luminous flux in (a) is greater than that in (b) by 487 lm or by about 14% and that the SPD in (a) has 8 monochromatic components and is over the range of 460–620 nm whereas that in (b) has 9 monochromatic components and is over the range of 430–630 nm. Furthermore, the proportion of spectral powers in the wavelength range of high spectral luminous efficiency to the total spectral powers is greater in (a) than in (b).

Fig. 5 Spectral power distributions satisfying $R_i \geq 95$ ($i=1-8$) at 4500 K (hatched bars for the mercury spectral lines).

Thus, of the SPD's obtained at a given CCT under the same constraints of the CRI, the SPD maximizing the total luminous flux has the smallest number of monochromatic components and a higher proportion of spectral powers falling the wavelength range of high spectral luminous efficiency. The chromaticity of the SPD maximizing the total luminous flux at a given CCT is present near the green side boundary and this is due to the fact that the monochromatic component of 555 nm at which the spectral luminous efficiency is maximum is

yellowish green (see Fig. 3).

Figure 6, (a) and (b), shows typical SPD's maximizing the total luminous flux under $R_i \geq 95$ at given CCT's. Fig. 6, (c) and (d), shows SPD's maximizing the total luminous flux under $R_a \geq 95$ in the same chromaticity coordinates as those for SPD's in (a) and (b).

Fig. 6 Spectral power distributions under $R_i \geq 95$ ($i=1-8$) in (a) and (b) and those under $R_a \geq 95$ in (c) and (d) (hatched bars for mercury spectral lines).

The wavelength range for the SPD's under $R_a \geq 95$ is 460~620 nm just as under $R_i \geq 95$ and the number of monochromatic components is the same at 3500 and 6500 K respectively. There is a difference, however, that the spectral powers at 580 and 620 nm under $R_a \geq 95$ are weaker than the corresponding ones under $R_i \geq 95$ and strong spectral powers appear at 570 and 610 nm under $R_a \geq 95$. On the other hand, comparison of the CRI shows that the special CRI's R_i ($i=9-15$) fluctuate less under $R_i \geq 95$ than under $R_a \geq 95$. As a consequence, a comprehensive assessment based on the SPD, total luminous flux and CRI is that the optimum SPD under $R_i \geq 95$ is superior to that under $R_a \geq 95$.

The spectral power of 490 nm pointed out by Fuchida et al. appeared weakly in the SPD at 2700 K of the SPD's maximizing the total luminous flux under $R_i \geq 95$ at given CCT's, but not at any other CCT. However, a spectral power of 480 nm appeared in the SPD's having the chromaticity coordinates on the violet side of the Planckian locus in the chromaticity range satisfying $R_i \geq 95$. This spectral power became stronger as the deviation from the Planckian locus to the violet side increased (see Fig. 5).

4.3 Special CRI's

The special CRI's R_i ($i=9-15$) fluctuated widely from one index to another because of no imposition of constraints.

Figure 7 shows the relationship between R_i ($i=9-15$) and CCT for the SPD's maximizing the total luminous flux under $R_i \geq 95$ ($i=1-8$) at each CCT (see Fig. 4).

Fig. 7 Special color rendering indices R_i ($i=9-15$) of spectral power distributions maximizing the total luminous flux under $R_i \geq 95$ ($i=1-8$) at given correlated color temperatures.

In the whole CCT range of 2700~8000 K, R_{13} (complexion) is greater than 95 and R_{14} (foliage) and R_{10} (Y) are relatively constant at 92~95 and 82~83 respectively. The CRI's R_{11} (G) R_{15} (actual complexion) are the highest at 2700 K, both 94, and decrease as the CCT rises. The index R_{12} (B) is 85, the highest, near 3200 K and decreases markedly at higher CCT's. The index R_9 (R) is the lowest at 68 in the WW range and, outside this range, it increases as the CCT rises.

Inspection of Fig. 2 and 7 indicates that SPD's maximizing the total luminous flux under $R_i \geq 95$ at each CCT shows a high luminous efficacy in the low CCT range corresponding to WW 30 and WW

at the same time high values of special CRI's there as a whole.

5. Optimization of SPD's of specific monochromatic components

Optimization of SPD's of 31 monochromatic components obtained by dividing the visible wavelength range 400~700 nm by a wavelength band width of 10 nm showed that fundamental monochromatic components maximizing the total luminous flux under $R_i \geq 95$ at each CCT are 470, 530, 580 and 620 nm. Optimization was performed over again on these four monochromatic components.

5.1 Chromaticity range and total luminous flux

Figure 8 shows the chromaticity range satisfying $R_i \geq 90$. This range covers CCT's 2700~4600 K, contains the Planckian locus P and is slightly drawn toward the green side. The chromaticity locus L of the SPD's maximizing the total luminous flux at each CCT is the green side boundary of this range.

Fig. 8 The chromaticity range (shaded area) where four monochromatic components of 470, 530, 580 and 620 nm alone satisfy $R_i \geq 90$ ($i=1-8$) and the chromaticity locus L giving the optimum spectral power distributions.

Here, there existed no chromaticity range where the above-mentioned four monochromatic components alone satisfy $R_i \geq 95$. Addition of the monochromatic component of 460 nm to these four, namely existence of at least five monochromatic components, is necessary to satisfy $R_i \geq 95$. In order to anticipate a still wider chromaticity range, six monochromatic components by further addition of the monochromatic component of 520 nm are necessary. On the other hand, a minimum of four monochromatic components is required to satisfy $R_i \geq 90$ and a combination of the first mentioned four monochromatic components alone can satisfy this constraint.

It was impossible to find a combination of other four monochromatic components to satisfy $R_i \geq 90$ than the foregoing.

Figure 9 shows the maximum total luminous flux as a function of CCT. The total luminous flux is roughly constant at 3565 ± 15 lm in the low temperature ranges of WW 30 and WW and diminishes sharply as the CCT rises in the W range.

5.2 SPD and CRI

Figure 10 shows each spectral power of the SPD's which maximizing the total luminous flux under $R_i \geq 90$ at given CCT.

Fig. 9 The maximum total luminous flux of spectral power distributions of 470, 530, 580 and 620 nm alone satisfying $R_i \geq 90$ ($i=1-8$) as a function of correlated color temperature.

Fig. 10 Each spectral power of the spectral power distributions of 470, 530, 580 and 620 nm alone maximizing the total luminous flux under $R_i \geq 90$ at given correlated color temperatures.

The spectral power of 470 nm, the shortest of the four wavelengths shown, increases with increasing CCT, but that of 620 nm, the longest, decreases contrarily. The spectral powers of 530 and 580 nm remain nearly unchanged as CCT rises.

Figure 11 shows typical examples of SPD's. Figure 12 shows the characteristics of R_a and R_i ($i=9-15$) against CCT.

Fig. 11 Spectral power distributions of 470, 530, 580 and 620 nm alone maximizing the total luminous flux at given chromaticity (hatched bars for the mercury spectral line).

Fig. 12 Spectral power distributions of 470, 530, 580 and 620 nm alone maximizing the total luminous flux under $R_i \geq 90$ ($i=1-8$) at given correlated color temperatures.

The indices R_9 , R_{10} and R_{15} markedly increase in the W range where the total luminous flux decreases sharply. Figure 10 suggests that these marked increases are due to a slight decreases in the spectral power of 580 nm in the W range.

The SPD in Fig. 6(a) has weak spectral powers at 480 and 520 nm in comparison with the one in Fig. 11(a). This difference alone causes such dif-

ferences in total luminous flux, R_a and R_i as shown in the figures. Also, the SPD in Fig. 11(b) composes of half as eight monochromatic components as the SPD in Fig. 5(a) and the former is lower than the latter in total luminous flux and R_a by 1% and 2% respectively, but the former shows improvements over the latter in R_9-R_{15} by 12, -2, 12, 2, -2, -3 and 1 respectively.

The SPD's thus chosen by the process of optimization represent distributions of spectral powers of monochromatic components which are most effective in improving the total luminous flux and slight changes in each spectral power cause large change in the total luminous flux and CRI.

6. Conclusion

The visible wavelength range 400~700 nm of a 40 W fluorescent lamp was divided into 31 monochromatic components, each 10 nm in wavelength band width, and the optimum SPD was analyzed by applying LP to simultaneous equations consisting of the objective function maximizing the total luminous flux and the constraint equations on the radiant flux, chromaticity coordinates and special CRI's R_i ($i=1-8$). The following conclusions were obtained.

(1) In conversion of ultraviolet excitation into spectral powers of the visible wavelength range by means of fluorescent materials, the highest luminous efficacy with satisfaction of given chromaticity and CRI can be produced by minimizing the number of monochromatic components and concentrating spectral powers to the chosen specific monochromatic components.

(2) Four monochromatic components, 470, 530, 580 and 620 nm, are of primary importance and two, 460 and 520 nm, are of secondary importance for the SPD's of fluorescent lamps of high color rendering properties which give the highest luminous efficacy and make all of the special CRI's of R_i to R_8 90 or 95 or more.

Further improvements in the luminous efficacy and color rendering properties of fluorescent lamps can be expected in the future if fluorescent materials which show high quantum efficiency in a sufficiently narrow spectral band having a radiation peak at the above-mentioned specific monochromatic components are made available.

References

- (1) Ivey, H. F.: J. Opt. Soc., 53 (1963) 1185.
- (2) Koedam, M., Opstelten, J. J.: Lighting Res. Tech., 3 (1971) 205.
- (3) Walter, W.: Illum. Engng., 7 (1978) 66.
- (4) Fuchida, T., Akiyama, J. and Sugiyama, H.: J. Illum. Engng. Inst. Jpn., 63 (1979) 247.
- (5) American National Standards Institute: "Specifications of the chromaticity of fluorescent lamps".
- (6) Japanese Industrial Standards: "Chromaticity Classification of Fluorescent Lamps" JIS Z9112-1976, Jpn. Std. Assoc.

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