Empirical Equations for the Analysis of the Time Dependence of the Luminance Properties of LCD Panels and Backlights for TV Applications

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Abstract

The time dependences of the luminance properties of 55-inch CCFL and LED backlights and 32-inch FFL backlights with LCD panels were investigated during the warm-up time from the cold start. The long-term luminance maintenance curve of a standard CCFL was examined in a time window up to 5000 hours. These two time dependences are important characteristics from the viewpoint of initial picture quality and lifetime reliability, respectively. Empirical equations were suggested for the analysis of the time dependence of these luminance data. These approaches are expected to be helpful in predicting the luminance properties of backlights based on the luminance data obtained in a limited time window.

Keywords: backlight unit (BLU), LCD, luminance curve, LED BLU, CCFL BLU, FFL BLU (Categories: [1] display materials and components; [2] liquid crystal and other non-emissive displays)

1. Introduction

The traditional CRT-(cathode ray tube)-based TVs were rapidly replaced by FPDs (flat panel displays) such as LCDs (liquid crystal displays) and PDPs (plasma display panels) in the past decade. Continuous technological innovation has been bringing about larger, thinner, and lower-power displays, which is accelerating such replacement more drastically. Recently, the so-called "LED TV" attracted much attention in the TV market due to its super-slim form factor as well as its low power consumption [1]. LED denotes the light-emitting diode, a typical solid-state lighting. LED TV falls under the category of LCD TVs, in which the LED backlight technology has been adopted. LED is considered a better light source than the conventional fluorescent lamps from the viewpoints of color gamut, power consumption, environment-friendliness, local dimming, etc. [2]. In addition, the temperature and time dependences of the characteristics of the LED backlight are expected to be superior to those of the conventional CCFL (cold cathode fluorescent lamp) backlight because the electro-optic properties of mercury-based fluorescent lamps are very sensitive to ambient temperature and to the operation time from the cold start [3].

The characteristics of FPD should satisfy many specifications, such as the luminance, color coordinates, lifetime, and reliability to various conditions, such as shock, vibration, humidity, and temperature cycle [4]. These are mainly related to the picture quality, mechanical stability, and long-time reliability. Among these, the time dependence of several properties should also meet specific requirements. For example, the long-term lifetime, which is the specific time when the luminance becomes half the original one, should be above a certain value. In addition, the increase rate of the luminance at the early stage, from the cold start, is an important factor for the initial picture quality of LCDs. There has been no published systematic investigation, however, of these characteristics of the new LED backlights as well as of the conventional CCFL backlights. As such, it would be worth carrying out a detailed investigation of the time dependence of the luminance and color properties of various kinds of backlights and light sources [5].

The present study was conducted to investigate the short- and long-term time dependences of the luminance properties of several backlights and light sources, particularly (1) the time dependence of the optical properties of a 55-inch edge-lit LED backlight and a direct-lit CCFL backlight of the same size at the initial stage, starting from the

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cold start; (2) the dependence of the initial luminance property of 32-inch LCD panels on the lamp conditions of FFL (flat fluorescent lamp) backlights; and (3) the long-term luminance maintenance curve of CCFL. The time dependence of the luminance (and the color coordinates, in some cases) of these backlight technologies will be compared. In particular, empirical equations that can well explain the time dependence of the luminance will be suggested. Although the present study is based on preliminary results and on phenomenological approaches and does not have a solid theoretical background, the results of the study may serve as basic, useful data for further studies and may also help in predicting the luminance properties of backlights based on the luminance data obtained in a limited time window.

2. Experiment

The 55-inch LED backlight that was used in this study was the edge-lit-type backlight that was developed for adoption in LED TVs. 372 white LEDs are located at the four sides of the light guide plate (LGP), on which a diffuser sheet (PTR873, Shinwha Intertek), a prism sheet (UTE32D, MNTECH), and a reflective polarizer (DBEF, 3M) have been sequentially placed to enhance the luminance of the backlight. The 55-inch CCFL backlight includes 24 CCFLs with a diameter of 3.4 mm. Over the light sources, a diffuser plate, a diffuser sheet (UTE12, MNTECH), a prism sheet (UTE32D, MNTECH), and the DBEF have been placed. This CCFL backlight is a narrow-bezel type suitable for public information display. The two different diffuser sheets are monolithic microlens types and exhibit almost the same optical performances. For the exact measurement of the spectrum, luminance, and color coordinates, a spectroradiometer (PR670, Photo Research) was used. The time dependences of the spectrum, color coordinates, and luminance were investigated in a wide time window up to 150 min. To discard any extrinsic effect on the measurement, the experiment was carried out at the same room temperature of 25±1°C.

32-inch FFL backlights with 28 semi-elliptically shaped channels covered by external electrodes at both ends were placed below LCD panels, and the time dependence of the luminance at the center of each panel was investigated at the initial stage, from the cold start. The detailed structure of the FFL backlight can be found in references 6 and 7. The ratio of Ne and Ar gas in the mixture was either 80:20 or 90:10. The pressure of the inert gas was also changed from 20 to 40 torr at the specific Ne:Ar ratio of 80:20.

The luminance maintenance curve of CCFL was investigated as a function of the operation time up to 5000 hr. The CCFL was for the 32-inch backlight with an outer diameter of 4 mm. As the main concern of this paper is the analysis of the typical lifetime data, the detailed lamp condition will not be discussed herein.

3. Results and Discussion

3.1 Initial Luminance Properties of the LED, CCFL, and FFL Backlights

Fig. 1 shows the time dependence of the luminance properties of the 55-inch CCFL and LED backlights. In the case of the CCFL backlight, the luminance is low at the cold start and then increases remarkably within a few minutes. The electrical and optical properties of mercury(Hg)-based fluorescent lamps are very much dependent on the vapor pressure of Hg (denoted as P_{Hg}) in the discharge space [3]. When the lamp is turned on, P_{Hg} is low; thus, the generation of ultraviolet (UV) light via Hg excitation is not enough to obtain high brightness. The UV photon is the main source of the excitation of the phosphor particles coated on the inner surface of fluorescent lamps. With the passage of time, P_{Hg} increases rapidly as the body temperature (i.e., cold-spot temperature) of the lamp rises. This contributes to the rapid increase in the luminance of the CCFL backlight at the initial stage as well as to the establishment of a steady state in the lamps and backlight during the op-

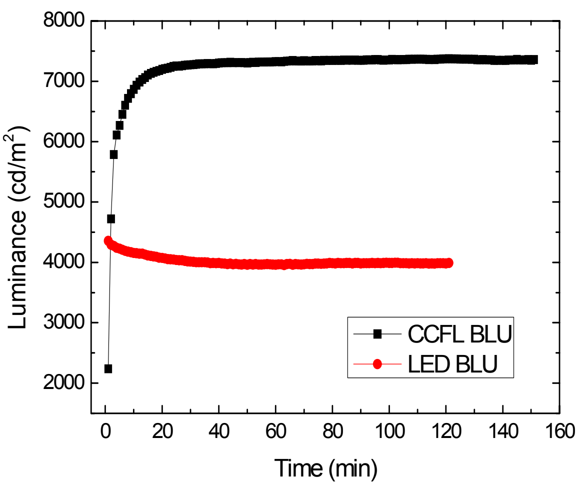

Fig. 1. Time dependence of the luminance of the 55-inch CCFL and LED backlights.

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On the other hand, the luminance of the edge-lit LED backlight changes mildly in the measured time window. The relative change in the luminance of this backlight is approximately 9%, which is in contrast to ~70% of the CCFL backlight [1]. The slight decrease in luminance may be attributed to the increase in the junction temperature of the white LEDs, and thus, to the decrease in efficiency.

Fig. 2(a) and (b) show the time dependence of the color coordinates (x,y). The relative changes in the color coordinates of both backlights will be comparable to each other if the first data point of the CCFL backlight will be excluded. The color coordinates of the LED backlight, however, are blue-shifted with time while those of the CCFL backlight behave oppositely. The changes in (x,y) are mainly due to the temperature effect on the electro-optic properties of both light sources.

To explain the time dependence of the luminance of both backlights, the appropriate empirical equations that can explain the luminance data were identified. One of the most simple equations for this purpose may be a single-exponential decay or rise function. Fig. 3(a) and (b) display the fitted results denoted as solid lines, which were obtained using the following single-exponential equations:

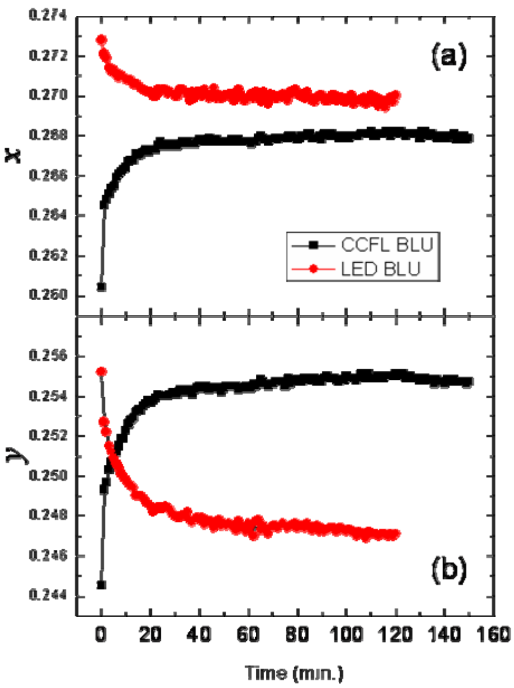

Fig. 2. Time dependence of the color coordinates (x, y) of the 55-inch CCFL and LED backlights

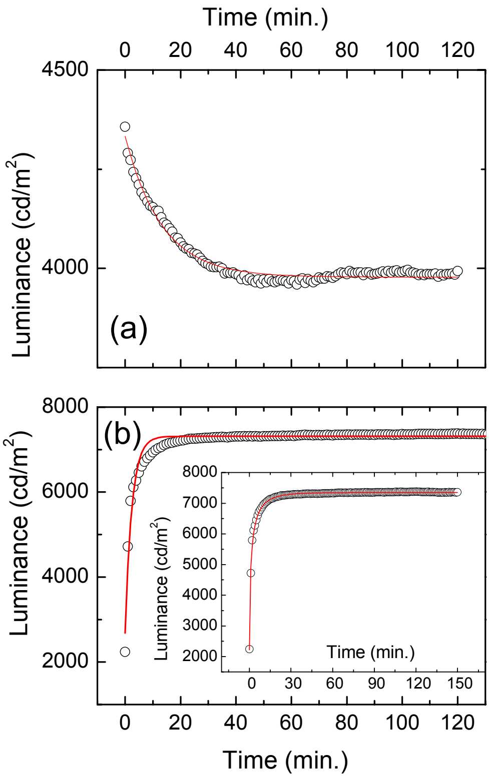

Fig. 3. Time dependence of the luminance (open symbols) and the best-fitted results (solid lines) obtained using equations (1)-(3).

$$L(t) = A\exp(-t/\tau) + L_0 \tag{1}$$

$$L(t) = B\left[1 - \exp(-t/\tau)\right] + L_0 \tag{2}$$

In these equations, L and t indicate the measured luminance and time in the unit of cd/m^2 and minute, respectively. Equations (1) and (2) were used to obtain the luminance data of the LED and CCFL backlights, respectively. A, B, τ and L_0 are the fitting parameters. τ determines the increase or decrease rate of the luminance at the initial stage of the turn-on period. As can be seen in Fig. 3(a) and (b), equation (1) can well explain the luminance data of the LED backlight, but the fitted result obtained using equation (2) for the data of the CCFL backlight exhibits some deviation from the measured data. Table 1 shows the parameters obtained from this fitting procedure.

The large difference in τ indicates that the change rate of the luminance at the initial stage is larger in the CCFL backlight than in the LED backlight. To improve the fitting

Table 1. The best-fitted result of the time dependence of the luminance obtained using equations (1) and (2)

Parameters	*A* or *B* (cd/m^2)	τ (min.)	L_0 (cd/m^2)	Equation Used
LED backlight	3978±2	13.3±0.4	355±6	$L(t) = A\exp(-t/\tau) + L_0$
CCFL backlight	4630±100	2.4±0.1	2680±100	$L(t) = B[1-\exp(-t/\tau)] + L_0$

procedure for the luminance data of the CCFL backlight, the following stretched-exponential form was tried. This form has been used in various fields, such as in the analysis of the complex dielectric spectrum measured within a broadband frequency range of complex systems, such as supercooled liquids and glasses [8].

$$L(t) = B\left[1-\exp(-t/\tau)^{\beta}\right] + L_0 \qquad (3)$$

The inset of Fig. 3(b) shows the fitted result that was obtained using the above equation, which is very much consistent with the measured data. The best-fitted results are B=5130±30 cd/m^2, τ =1.7 min, L_0=2220±30 cd/m^2, and β=0.53. It should be pointed out that the above empirical equations have no physical meaning based on any solid microscopic origin but were considered only to explain the luminance data numerically from a practical point of view. These approaches may be helpful in predicting the luminance properties of the backlights based on the luminance data obtained in a limited time window.

Fig. 4 shows two normalized luminance data of the LCD panels with FFL backlights as a function of time up to 30 min. The luminance values were normalized by using the saturated value at 30 min. The luminance data could be well fitted by equation (2), i.e., by a single-exponential functional form. The best-fitted results for the data of all the six panels are presented in Table 2, and some of the results are shown as solid lines in Fig. 4. It will be noticed that the warm-up time from the cold start is much longer in the FFL backlights compared to the CCFL backlights. This is mainly due to the difference in the heat capacity between CCFL

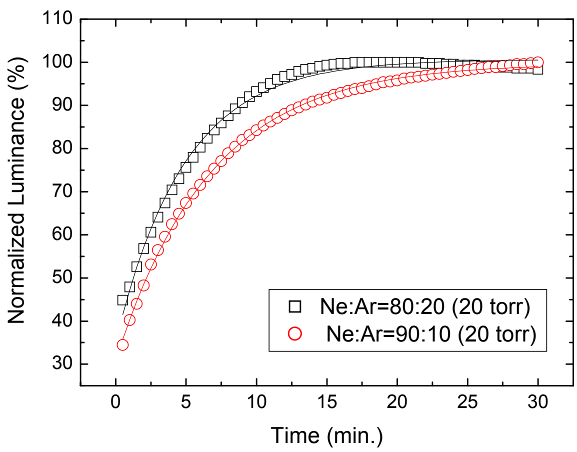

Fig. 4. Time dependence of the normalized luminance for the LCD panels with two FFL backlights (symbols), and the best-fitted results (solid lines) obtained using equation (2).

Table 2. The best-fitted results of the time dependence of the luminance of the LCD panels with FFL backlights obtained using equation (2)

Ne:Ar (%) Pressure (Torr)	*B* (%)	τ (min.)	L_0 (%)
90:10 20	67.9±0.4	6.7±0.1	33.8±0.4
	68.9±0.3	6.7±0.1	30.9±0.3
80:20 20	65.5±0.9	4.9±0.1	35.1±1.0
	69.5±0.9	5.4±0.1	31.4±1.0
80:20 30	73.8±0.8	6.2±0.1	28.2±0.9
80:20 40	50.2±0.7	4.0±0.1	49.8±0.7

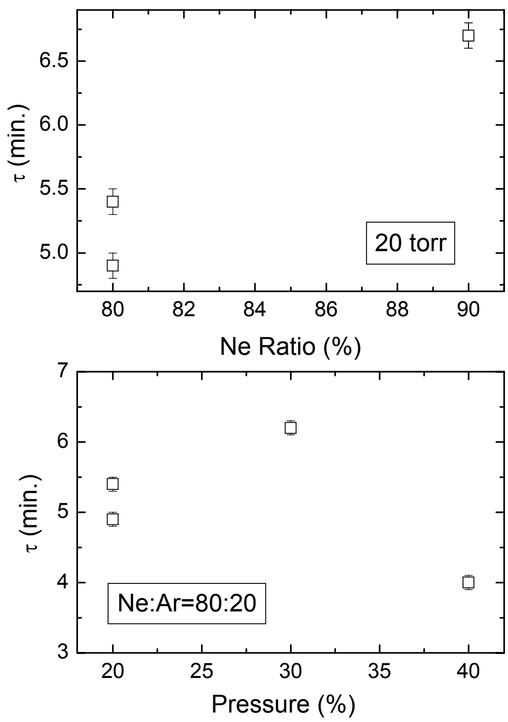

Fig. 5. Dependence of τ of the LCD panels with FFL backlights on either the Ne ratio (a) or the pressure (b) of the FFLs.

and FFL. FFL consists of two glass plates with a thickness of 0.7 mm and an area of 740×390 mm^2. Since the specific heat of the soda lime glass is 0.75 kJ/kg· K, the total heat capacity of one FFL is about 1.1 kJ/K. This means that approximately 280 W is needed to heat the lamp by 45 K within 3 min, which is much larger than the power necessary for heating CCFLs under the same conditions.

Fig. 5 exhibits the obtained τ of the LCD panels with various FFL backlights, depending on the Ne:Ar ratio and the gas pressure. It was noticed that τ increases along with the Ne ratio. In addition, τ seems to exhibit the maximum value at a gas pressure of about 30 torr when the Nr:Ar ratio is fixed at 80:20. These results indicate that the warm-up time of the FFL backlight is sensitive to the conditions of the inert gas included in the FFLs, which should be optimized to reduce the warm-up time for better initial picture quality.

3.2 Long-Term Luminance Maintenance Curves of CCFL

Fig. 6 shows the relative luminance maintenance curve of CCFL as a function of time up to 5000 hr in a semilog plot, as a function of $t^{1/2}$. The luminance value is normalized by the initial one when the lamp is freshly turned on after aging. The decrease in the luminance of the fluorescent lamps is due to several factors, such as the degradation of the phosphor powders impacted by UV photons or Hg ions, the blackening of the glass tubes due to the adsorption of Hg atoms, and the termination of the lamp life due to the shortage of liquid Hg. Several empirical equations were proposed to explain the luminance maintenance curve of the fluorescent lamps for general lighting [9-10]. One equation

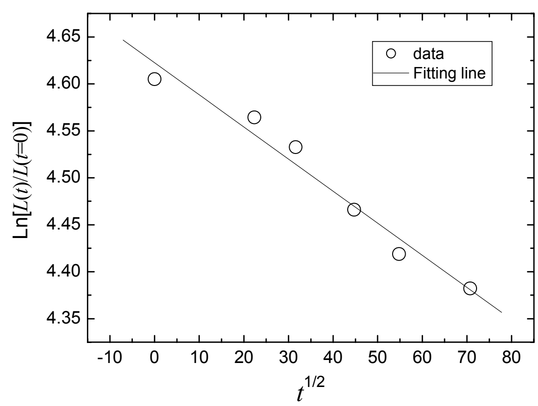

Fig. 6. Luminance maintenance curve (open circles) of the CCFL shown in a semilog plot as a function of $t^{1/2}$. The solid line denotes the best-fitted result obtained using equation (5).

was suggested based on three reactions with different rate constants, as follows:

$$L(t=0) - L(t) = A\left(1-e^{-at}\right) + B\left(1-e^{-bt}\right) + C\left(1-e^{-ct}\right) \quad (4)$$

In this equation, $L(t=0)$ and $L(t)$ are the luminance values at operation times 0 and t, respectively. A, B, C are fitting parameters, and a, b, c are rate constants. When this equation, however, was applied to the data of CCFL in Fig. 6, meaningful parameters could not be obtained due to the superfluous number of fitting parameters. In addition, the physical origins of the three assumed reactions and their effect on the luminance maintenance curve are questionable. In the present study, another model based on the degradation of phosphor powders is considered as the main factor that determines the luminance maintenance curve of the lamps. The phosphor powders are continuously attacked by UV photons and Hg ions during the lamp operation, and their surface layers gradually become amorphous and non-luminescent. Shown in Fig. 7 is a schematic figure exhibiting the creation of an amorphous surface layer of phosphor crystals. It shows that the periodicity of atoms is disordered by continuous ion (Hg^+) and UV bombardments. Since the atoms in the amorphous layer near the surface may diffuse into the bulk of crystalline powders with the passage of time, the depth of the amorphous layer may increase according to the theory of particle diffusion, and is proportional to the square root of the time ($t^{1/2}$). Therefore, the luminance maintenance curve may be explained by the so-called Lehmann equation [10], as follows:

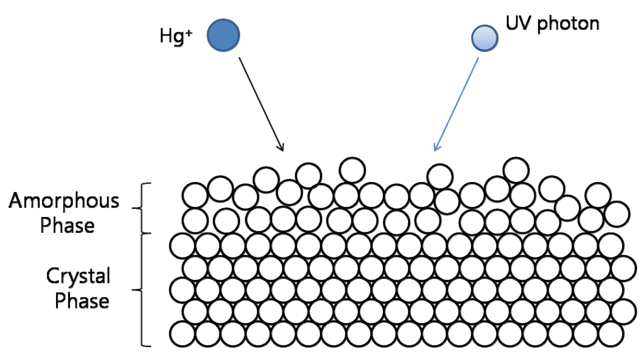

Fig. 7. A schematic figure showing an amorphous surface layer of phosphor crystals due to ion and UV bombardments.

$$L(t) = L\left(t = 0\right)\exp\left(-\sqrt{t/\tau}\right) \tag{5}$$

In this equation, the time constant τ indicates the time when the luminance decreases to exp(-1)~37% of the original value. The luminance data of CCFL was fitted using equation (5), resulting in $\tau=8.55\times10^4$ hr. The best-fitted result is shown as a solid line in Fig. 6 and seems to be in reasonable agreement with the experiment data. From these data, the lifetime of the present CCFL (i.e., the time when the luminance becomes half its original value) can be estimated to be about 4.10×10^4 hr. The lamp lifetime, however, is also affected by the amount of available liquid Hg in the lamp. The luminance will decrease suddenly when the liquid Hg is used up after gradual decrease due to phosphor degradation.

4. Summary

The present study was conducted to investigate the short- and long-term time dependences of the luminance properties of several backlights and light sources, and to suggest empirical equations for the analysis of the luminance data monitored in a limited time window. The following conclusions can be derived from this study:

(1) The time dependence of the optical properties of the 55-inch LED and CCFL backlights were investigated. The change in the luminance at the early stage was found to be much more substantial in the CCFL backlight than in the LED backlight. This may be attributed to the more sensitive dependence of the optical characteristics of CCFLs on the ambient temperature and mercury vapor pressure in the discharge lamps. Empirical equations were developed based on the single- and stretched-exponential decays and were shown to explain the luminance data quite well. These results indicate that the LED backlight is more favorable than the CCFL backlight from the viewpoint of the initial picture quality of LCD TV.

(2) The single-exponential function adequately explained the luminance data of the LCD panels with FFL backlights at the initial stage of the turn-on period. The rise time was sensitive to the gas condition in the FFLs (i.e., the gas composition and the pressure), which should be optimized to reduce the warm-up time from the cold start, and to obtain better initial picture quality. The rise times of the FFL backlights were much longer than those of the CCFL backlights, which can be attributed to the much larger heat capacity of the FFLs.

(3) The long-term luminance maintenance curve of CCFL was measured up to 5000 hr and was fitted using the Lehmann equation, based on the simple model for phosphor degradation. The experiment data were in reasonable agreement with the fitted result, which suggests that the phosphor degradation process due to the creation of an amorphous surface layer of phosphor crystals is the main cause of the luminance decrease of CCFL in the long-term time window.

In spite of the purely phenomenological approaches that were employed in this study to identify the time dependence of the luminance data of several backlights and light sources, the results of this study may serve as basic, useful data for further studies and may also help in predicting the luminance properties of backlights based on the data obtained in a limited time window.

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