

THEORETICAL LIMITS OF NATURAL LIGHT EMULATION

Josep Carreras¹, Jesús Quintero¹ and Charles E. Hunt^{1,2}

¹IREC, Institute for Energy Research of Catalunya

²CLTC, California Lighting Technology Center, University of California

ABSTRACT

We present in this work a theoretical prospection on the limits of efficacy and color rendering for artificial sources trying to emulate natural light conditions.

Both luminous efficacy and any color rendering metric such as color rendering index[1] (CRI) can be simultaneously optimized through spectral narrowing the spectrum of a source emulating a blackbody radiator. Blackbody spectra are a reasonable starting point since they represent the most basic form of natural illumination.

A set of reduced spectra for every CCT that fulfill a set of user-defined criteria over luminous efficacy of radiation, general CRI and Δ_{uv} , are found. It is shown that, over all, the best rated spectra for 3000K, 5500K and 8000K correspond to the following [Efficacy, CRI (Ra)] pairs: [363 lm/W,90.5], [313 lm/W,95.4] and [288 lm/W, 96.6] respectively, all of them satisfying $\Delta_{uv} < 5.4 \times 10^{-3}$.

Keywords: Efficacy, color rendering index, blackbody

1. INTRODUCTION

Natural sunlight (color temperature = 5500K) and Soft-White incandescent light bulbs (color temperature = 3000K) are both black body radiation sources[2]. Their light is typically what consumers call “natural light” and they render all colors (CRI=100) in the visible spectrum. The 5500K natural light is favored for best acuity and minimal eye strain and 3000K is popular because its warm color is relaxing.

The incandescent light bulb, being a blackbody radiator, has been a near ideal artificial light source, because it renders color well. As seen in Figure 1, the luminous efficacy of radiation of a full spectrum (FS) blackbody at 3000K is very

poor (21 lm/W), which is the reason that incandescent lighting is an obvious target for elimination in the international energy conservation effort.

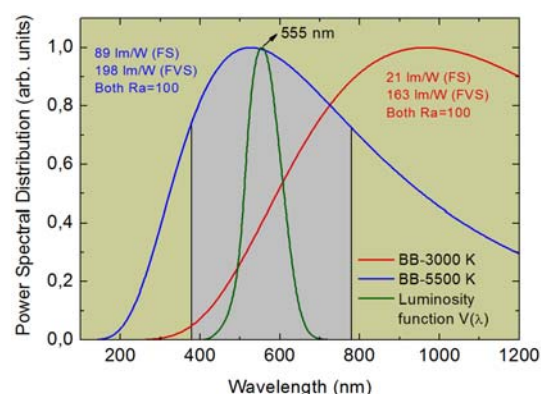


Fig. 1: Normalized spectra of two blackbody sources with CCTs of 3000K (red) and 5000K (blue). The green line is the luminosity function for photopic vision, V_{λ} .

However, the efficacy of a lamp designed to emulate a blackbody radiator can be highly improved if one is able to restrict the spectral content over the visible region (full visible spectrum, FVS), increasing the efficacy by a factor of 8 for a CCT of 3000K, up to a value of 163 lm/W. This FVS blackbody spectrum still maintains the same CRI score as the FS blackbody, so there is no degradation of light quality in the FVS by eliminating output in the UV and IR zones. We explore here how far the spectrum can be narrowed around 555 nm without substantially deteriorating color quality.

2. SPECTRAL NARROWING OF BLACKBODY RADIATORS

To explore reducing spectra for each projected CCT, the efficacy, special CRI (15 numbers), Δ_{uv} , and final CCT have been carried out for a set of ~40.000 reduced visible spectra (RVS).

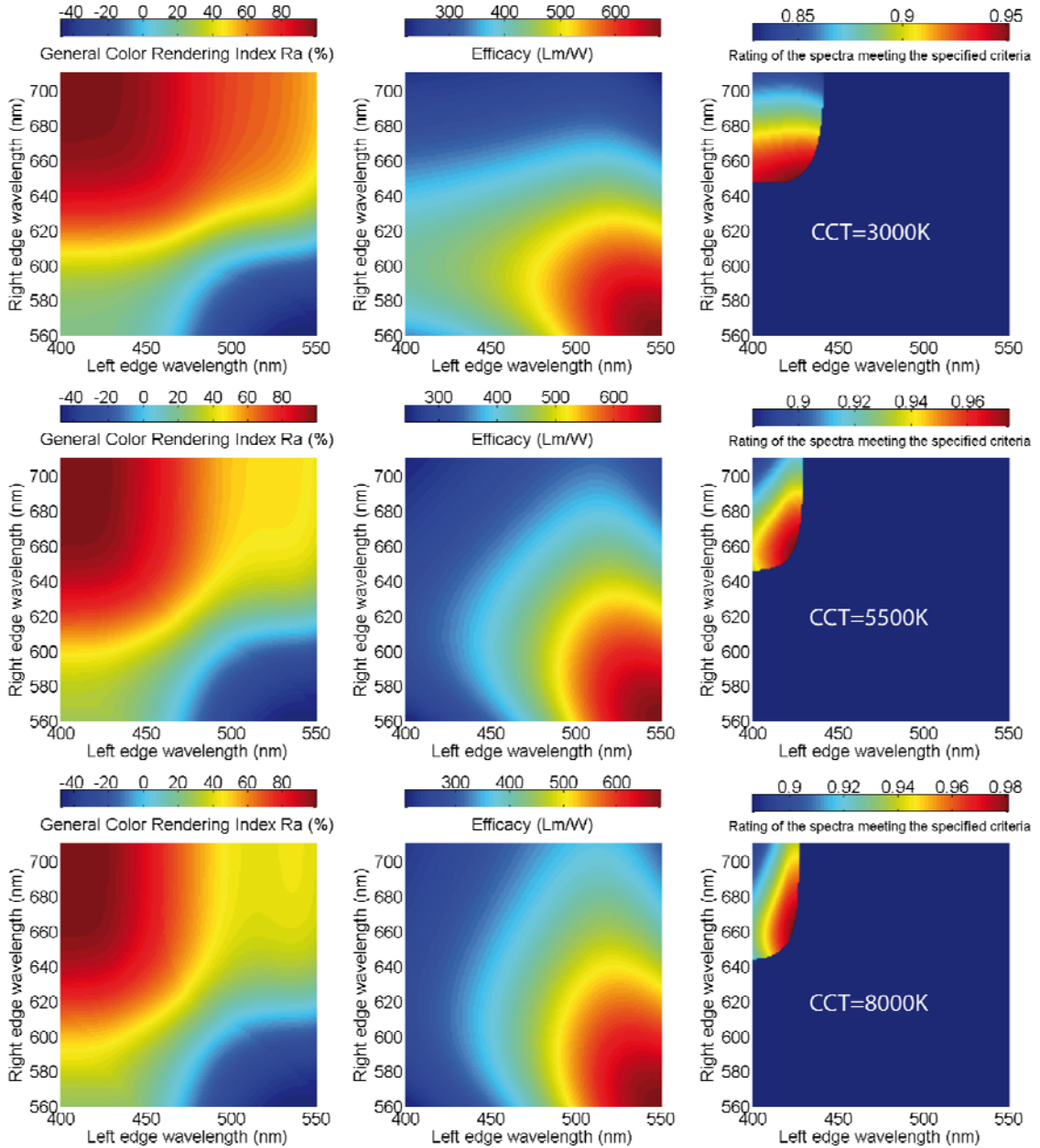


Fig. 2: Trade-off relationship between efficacy and CRI in RVS blackbody sources for 3000K, 5500K and 8000K. As expected, the efficacy is higher (approaching 683 lm/W) when the left and right edges are closer to 555 nm, but at that point CRI is negative. The plot on the right is the score obtained when a spectrum satisfies user-defined criteria (CRI>90, Efficacy>200 lm/W and $\Delta_{uv}<0.0054$) in equation 1.

For each CCT, this set includes spectra that have the same functional dependence as a blackbody radiator of the same temperature, but only have luminous power in the central region of the spectrum, where the human eye is most sensitive. Figure 2 shows a quantification of the inverse relationship existing between efficacy and color rendering and the third plot defines the intersection where a used-defined criterion for CRI (Ra), efficacy and Δ_{uv} is met. The

color scale is mapped through the definition of a score function as,

$$S = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{R_a}{R_a^*}\right)^2 + \left(\frac{Eff}{Eff^*}\right)^2} \quad (1)$$

where $R_a^*=100$ and Eff^* is the target efficacy, that is, for a particular CCT, the highest efficacy in the set that satisfies the restriction over Δ_{uv} . Note that in order to

obtain the highest score, $S=1$, both efficacy and color rendering quantities should be well rated. Even sunlight would poorly score ($S\sim 0.7$) because of its IR and UV content.

Finally, we present additional data for the best rated spectra in Table 1. General CRI (R_a) has been computed for a complete set of 1269 Munsell samples with known reflectivity. Since the score, as defined by equation 1, only takes into account R_a , the best rated spectra poorly reproduce some saturated colors such as that represented by R_9 (saturated red). This deficiency seems to diminish with increasing CCTs but at the expense of an abrupt decrease in efficacy.

This visual representation of a color rendering metric over a large color set is a useful concept that eliminates the difficulties of a single CRI number, which cannot quantify all the subtleties from the spectrum[3]. In this method, a graphical representation of the information is visually assessed, and deficiencies in the reproduction of colors can be directly identified by inspection.

3. CONCLUSIONS

We have investigated the theoretical limits for a blackbody radiator of specific color temperatures with regards to efficacy and color quality. Efficacy has been increased by

reducing the spectral content around 555 nm and a method to rate all the resulting

spectra in terms of efficacy and color quality has been developed. Results show that by sacrificing less than a 10% in CRI ($R_a > 90$), the efficacy of an artificial light emulating the best rated spectrum can be increased by 1700%. The best rated spectra have been tested along a complete set of 1269 reflective samples to further check the color rendering capabilities of the resulting source.

Since these values are extracted directly from reduced blackbody spectra, they represent the most "natural" light emulation possible, having only reduction of spectral content in the tails of the luminosity function (V_λ), where human vision is largely insensitive. Any color-fidelity-based approach that takes natural light as a reference should consider these as maximum values attainable for simultaneous optimization of efficacy and color quality.

REFERENCES

- [1] CIE 13.3: 1995, Method of Measuring and Specifying Colour Rendering Properties of Light Sources (1995).
- [2] CIE 17.4: 1987, International Lighting Vocabulary, (1987), 845-02-59
- [3] Wendy Davis, Yoshi Ohno, The color quality scale, *Opt. Eng.* 49(3) (2010) 033602

Table 1: Extended data and graphical representation of CRI over the Munsell set for the best rated spectra for CCTs of 3000K, 5500K and 8000K.

CCT	Target Efficacy (lm/W)	Highest Score Spectrum	Munsell set color assessment
3000K	364.41	Efficacy: 363 lm/W Ra: 90.5 S: 0.951 Duv: 5.37e-3 Wave range: [424,649] nm CCT: 3260 K R9: 39.1 R9-12: 76.0	
5500K	314.92	Efficacy: 313 lm/W Ra: 95.4 S: 0.975 Duv: 5.31e-3 Wave range: [424,658] nm CCT: 5490 K R9: 66.3 R9-12: 88.6	
8000K	289.34	Efficacy: 288 lm/W Ra: 96.6 S: 0.981 Duv: 5.32e-3 Wave range: [424,662] nm CCT: 7540 K R9: 78.8 R9-12: 91.5	