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TECHNICAL NOTE

Terms related to Planckian radiation temperature for light sources

CIE TN 013:2022

A CIE Technical Note is a concise technical paper summarizing information of fundamental importance to CIE members and other stakeholders.

This Technical Note has been prepared by CIE Division Reporter 2-88 of Division 2 “Physical Measurement of Light and Radiation". The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by all with an interest in excellence in light and lighting. The information provided here is advisory, and not mandatory.

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Terms related to Planckian radiation temperature for light sources

Summary

There are several terms which describe the Planckian radiation temperature for light sources, including radiance temperature, colour temperature, correlated colour temperature, distribution temperature and ratio temperature. This document provides descriptions of these terms, information on their applicability, and highlights relationships between them so that they may be consistently applied in all applications.

Definitions and additional explanatory information for each term are given in this document. Obviously, the greater the difference between the radiation considered and a Planckian radiator, the more tenuous the interpretation of the temperature attribution. Guidelines as to agreed reasonable limits of applicability, if any, are therefore also given, together with information on the calculation of the associated measurement uncertainties where relevant.

1 Introduction

This document is written sequentially, in that quantities that form the basis of dependent quantities are mentioned first, so reading the entire document is recommended.

Radiation from an incandescent lamp has a relative spectral power distribution which is reasonably close to that of a Planckian radiator (also known as a blackbody or full radiator). Since a single parameter, temperature, can be used with Planck’s formula to define a complete spectral power distribution of a blackbody, it is often convenient to describe incandescent radiation, especially from tungsten lamps, in terms of the temperature of an equivalent Planckian radiator.

Several terms as listed above, used in optical radiation measurement, make use of this concept to assign a temperature measure to a spectral power distribution. The difference between the terms is in the way in which the corresponding Planckian radiator is selected. Values for all of these terms are expressed in the unit of kelvin as a positive real number above absolute zero, the theoretical point at which particles have zero energy.

2 Thermodynamic temperature

2.1 Symbol

T

2.2 Definition

positive state quantity proportional to the kinetic energy of the chaotically moving particles that constitute a physical system being locally in equilibrium

[SOURCE: IEC 60050-113:2011 (Electropedia, Subject area 113), 113-04-14, online: http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=113-04-14, modified – notes to entry omitted]

2.3 Additional information

The definition in 2.2 is accurate only at temperatures well above zero kelvins, which is the case for all foreseeable application of this document.

The thermodynamic temperature is an absolute measure of the average total energy of the particles comprising a solid material, liquid or gas, i.e. the total internal energy of a substance or an object.

2.4 Limits to applicability

The thermodynamic temperature gives no information with respect to the radiation emitted from or by an object (other than a blackbody) and is therefore not relevant for photometry, spectroradiometry or other radiometric applications. In the specific case of a blackbody, the thermodynamic temperature determines its optical radiation emission (see Clause 3).

3 Planckian radiator temperature / Blackbody temperature

3.1 Symbol

T_p

3.2 Definition

thermodynamic temperature of a Planckian radiator (blackbody)

Note 1 to entry: A Planckian radiator is defined as an "ideal thermal radiator that absorbs completely all incident radiation, whatever the wavelength, the direction of incidence or the polarization" (CIE 2020, 17-24-004).

3.3 Additional information

The Planckian radiator temperature applies only to a theoretical Planckian radiator, also called a blackbody. A blackbody emits a spectral power distribution according to Planck's law (CIE 2020, 17-24-005). The relative spectrum of emission, $S_\mathrm{p}(\lambda, T_\mathrm{p})$ (relative spectral radiance, relative spectral irradiance, etc.), depends solely on the blackbody temperature, T_p, and is given by Planck's law:

$$S_\mathrm{p}\left(\lambda, T_\mathrm{p}\right) = K\,\lambda^{-5}\left(\mathrm{e}^{\frac{c_2}{\lambda\,T_\mathrm{p}}} - 1\right)^{-1} \tag{1}$$

where

c_2 is the second radiation constant (NIST 2022a, BIPM 2019);

λ is the wavelength;

K is a constant that depends only on the measurement geometry used (can be omitted, i.e. $K = 1$, for relative spectral power distribution calculations);

subscript p indicates the Planckian radiator (blackbody).

NOTE Footnote 7 on page 39 of CIE 015:2018 (CIE 2018) states that the c_2 value from the International Temperature Scale of 1990 (ITS-90) must be used when calculating the chromaticity coordinates of the Planckian radiator. This is different to the currently accepted value of c_2 found in (NIST 2022a, BIPM 2019). CIE Division 1 has been made aware of this discrepancy, and a future revision of CIE 015 may change this. The numerical difference can be seen here: 0,014 388 m·K (ITC-90); 0,014 387 768 77... m·K (BIPM 2019).

3.4 Limits to applicability

Real objects have an emissivity, ε (quotient of the radiant exitance of a radiator and the radiant exitance of a Planckian radiator at the same temperature (CIE 2020, 17-24-009, online https://cie.co.at/eilvterm/17-24-009)), of less than unity. An object that features a constant emissivity with respect to wavelength and temperature is termed a grey body, featuring an emission of the same relative spectral power density as a blackbody, but of lower absolute radiance. For a perfect grey body (a non-selective thermal radiator (CIE 2020, 17-24-011)) the relative spectral power distribution can be described exactly using the temperature of the equivalent blackbody. For most sources encountered in photometry and spectroradiometry, however, the emissivity depends on the wavelength (corresponding to a selective thermal radiator (CIE 2020, 17-24-010)) but the radiation spectrum might also be affected by optical components (e.g. a glass envelope). These spectral differences from a Planckian distribution mean it is more appropriate to use one of the temperature measures detailed below.

4 Radiance temperature

4.1 Symbol

T_r

4.2 Definition

thermodynamic temperature of the Planckian radiator for which the radiance at the specified wavelength has the same spectral concentration as for the thermal radiator considered

[SOURCE: CIE S 017:2020, 17-24-016, online: https://cie.co.at/eilvterm/17-24-016, modified – "temperature" replaced with "thermodynamic temperature", notes to entry omitted]

4.3 Additional information

Based on the definition, the radiance temperature of a light source (e.g. tungsten strip lamp) at a specified wavelength λ_s, $T_{\mathrm{r},\lambda_\mathrm{s}}$, is determined (NIST 1998) from the spectral radiance emitted by the source at that wavelength as

$$T_{\mathrm{r},\lambda_\mathrm{s}} = \frac{c_2}{\lambda_\mathrm{s} \cdot \ln\left(1 + \varepsilon_{\lambda_\mathrm{s}} \cdot c_{1L} / \left(\lambda_\mathrm{s}{}^5 \cdot L_{\lambda_\mathrm{s}}\right)\right)} \tag{2}$$

where

$T_{\mathrm{r},\lambda_\mathrm{s}}$ is the radiance temperature at the specified wavelength λ_s;

$\varepsilon_{\lambda_\mathrm{s}}$ is the emissivity at wavelength λ_s;

c_{1L} is the first radiation constant in radiance form (NIST 2022b);

c_2 is the second radiation constant;

L_{λ_s} is the spectral radiance at wavelength λ_s.

NOTE 1 (NIST 1998) includes the refractive index of air, which has been removed in this Technical Note for consistency with other equations. Equation (2) therefore refers to emission in a vacuum.

NOTE 2 (NIST 1998) omits parentheses which are required; Equation (2) includes them to correct this error.

Based on Equation (2) the radiance temperature, $T_{\mathrm{r},\lambda_\mathrm{s}}$, at a specified wavelength, λ_s, of a real object with an emissivity $\varepsilon_{\lambda_\mathrm{s}}$ at that wavelength relates to the thermodynamic temperature T as:

$$T_{\mathrm{r},\lambda_\mathrm{s}} = \left(\frac{1}{T} - \frac{\lambda_\mathrm{s}}{c_2}\ln\left(\varepsilon_{\lambda_\mathrm{s}}\right)\right)^{-1} \tag{3}$$

where

T is the object thermodynamic temperature.

4.4 Limits to applicability

Radiance temperature at a specified wavelength λ_s depends on the spectral radiance at that wavelength. It is primarily used for transferring the thermodynamic temperature scale of a blackbody source to another blackbody or grey body source through spectral radiance measurement. Radiance temperature gives no information with respect to the total radiation or spectral radiance emitted from or by an object at other wavelengths unless the emissivity is the same (spectrally constant) at these wavelengths. Therefore, it can provide information on neither the thermodynamic temperature of the filament of a real tungsten lamp nor its spectral power distribution. Such information may be obtained with knowledge of spectral emissivity of the filament and spectral transmittance of the glass envelope but it is not the purpose of radiance temperature. Thus, it is not relevant for photometry, spectroradiometry or other radiometric applications, except in the specific cases of a blackbody or grey body (see Clause 3).

5 Colour temperature

5.1 Symbol

T_{c}

5.2 Definition

thermodynamic temperature of a Planckian radiator whose radiation has the same chromaticity as that of a given stimulus

[SOURCE: CIE S 017:2020, 17-23-067, online https://cie.co.at/eilvterm/17-23-067, modified – "temperature" replaced with "thermodynamic temperature", notes to entry omitted]

5.3 Additional information

If the stimulus is a blackbody, the colour temperature is equivalent to the thermodynamic temperature. This equivalence is a means to determine the temperature of blackbodies using tristimulus colorimeters without the need for spectral measurements.

5.4 Limits to applicability

In practice, chromaticities are regarded as the "same" if their difference is within reasonable limits. This Technical Note recommends, as a guide, a chromaticity difference, ΔC, of less than or equal to 5×10^{-4} is acceptable:

$$\Delta C = \left[\left(u'_{\mathrm{t}} - u'_{\mathrm{p}} \right)^2 + \frac{4}{9} \left(v'_{\mathrm{t}} - v'_{\mathrm{p}} \right)^2 \right]^{\frac{1}{2}} \leq 5 \times 10^{-4} \qquad (4)$$

where

$u'_{\mathrm{t}}, v'_{\mathrm{t}}$ are the chromaticity coordinates of the stimulus source;

$u'_{\mathrm{p}}, v'_{\mathrm{p}}$ are the chromaticity coordinates of the nearest point on the Planckian locus.

This means that the concept only applies to grey bodies, near-grey bodies, Planckian radiators, or near-Planckian radiators. For other artefacts the correlated colour temperature (see Clause 6) should be used instead.

6 Correlated colour temperature (CCT)

6.1 Symbol

T_{cp}

6.2 Definition

thermodynamic temperature of the Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution on a modified 1976 UCS diagram where u', 2/3 v' are the coordinates of the Planckian locus and the test stimulus

[SOURCE: CIE S 017:2020, 17-23-068, online https://cie.co.at/eilvterm/17-23-068, modified – "temperature" replaced with "thermodynamic temperature, notes to entry omitted]

6.3 Additional information

The CCT can be calculated by a simple minimum search computer program that tries various Planckian temperatures and finds the one that provides the smallest chromaticity difference between the stimulus chromaticity and the Planckian locus:

$$T_{\mathrm{cp}} = \left\{ T_{\mathrm{p}} \;\middle|\; \min_{T_{\mathrm{p}} \in \mathbb{R}} \left(\left(\left(u'_{\mathrm{t}} - u'_{\mathrm{p}} \right)^2 + \frac{4}{9} \left(v'_{\mathrm{t}} - v'_{\mathrm{p}} \right)^2 \right)^{\frac{1}{2}} \right) \right\} \tag{5}$$

where

$u'_{\mathrm{t}}, v'_{\mathrm{t}}$ are the chromaticity coordinates of the stimulus source,

$u'_{\mathrm{p}}, v'_{\mathrm{p}}$ are the chromaticity coordinates of the Planckian radiator.

NOTE Equation (5) should be read as: T_{cp} is equal to the value of T_{p} that satisfies the expression to the right of the $|$ symbol. In this case the expression is a minimization that explicitly alters T_{p} only during the iterations and states T_{p} must be a real number.

Practical methods to calculate T_{cp} using spreadsheet functions with minimum value search facilities or similar approaches are available (e.g. Robertson 1968, AFNOR 2016, Ohno 2014, Li et al. 2016). Differences between these approaches are small, but where they are significant it is recommended that recent methods are used.

The chromaticity coordinates along a line normal to the Planckian locus in the (u', 2/3 v') chromaticity diagram share the same CCT, hence forming iso-temperature lines as shown in Figure 1.

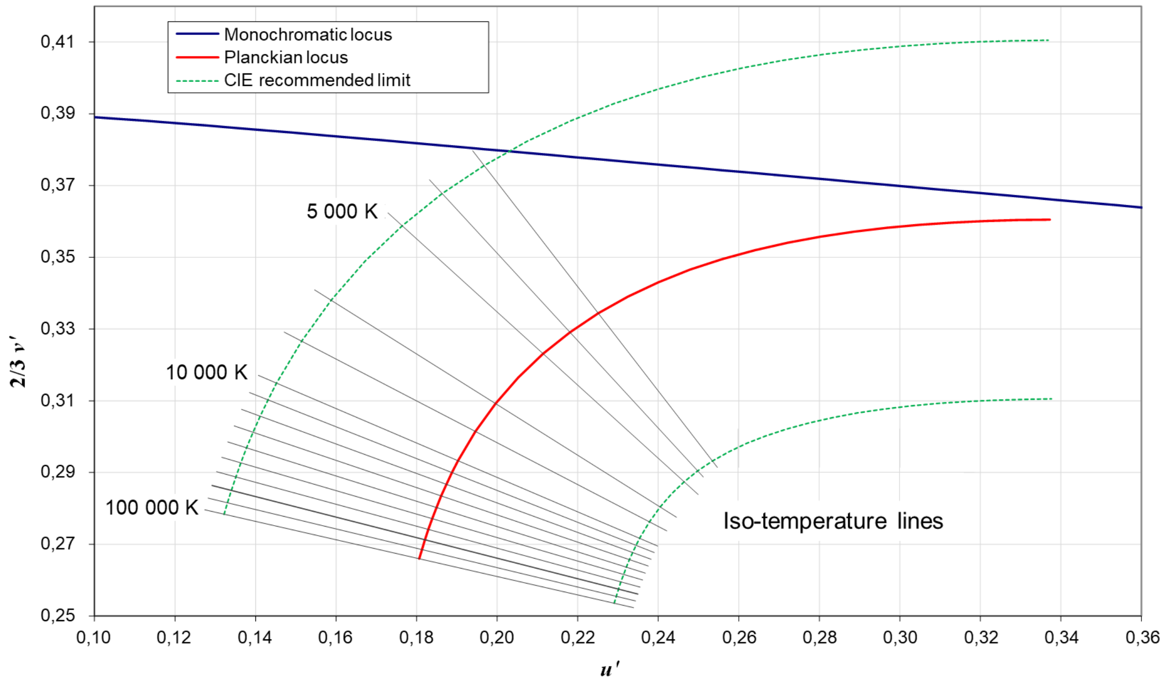

Figure 1 — (*u*', 2/3 *v*') chromaticity diagram showing the Planckian locus and recommended limits to calculation of CCT

6.4 Limits to applicability

The CCT is used to express the chromaticity of a light stimulus in one number, and is referred to in data sheets for all types of general lighting products (including LEDs and discharge lamps). It is also the basis for qualitative descriptions such as “warm white” and “cool white”. Based on the concept of CCT, this term applies only to white light stimuli and should not be used for coloured light sources. Since the boundary of white light is unclear, the concept of CCT should not be used if the chromaticity difference, ΔC, of the stimulus is spaced more than 5×10^{-2} (CIE 2018) from the Planckian locus (see Figure 1), i.e.

$$\Delta C = \left[\left(u'_{\mathrm{t}} - u'_{\mathrm{p}} \right)^2 + \frac{4}{9} \left(v'_{\mathrm{t}} - v'_{\mathrm{p}} \right)^2 \right]^{\frac{1}{2}} \leq 5 \text{ x } 10^{-2} \tag{6}$$

6.5 Uncertainties

There are no uncertainties associated with the Planck formula or CIE tables and therefore also no uncertainty associated with calculated u'_{p} or v'_{p}. However, there are uncertainties in measured u'_{t} and v'_{t}. These are generally significantly correlated and hence the covariance matrix, either determined or estimated, should be used to estimate the uncertainty in the CCT. There may also be some uncertainties in calculation programs using a specific algorithm for determining the CCT, which are usually insignificant for practical applications.

It should also be noted that the uncertainty associated with the measurement of the CCT depends greatly on the CCT value itself; for example, the same (constant) relative spectral uncertainty that gives a CCT uncertainty of 14 K at 3 000 K will give an uncertainty of 35 K at 6 000 K. This non-linearity in the CCT scale means it is also not good practice to use percentage for CCT uncertainty; the uncertainty for CCT should be reported as an absolute value in kelvin.

7 Distribution temperature

7.1 Symbol

T_D

7.2 Definition

thermodynamic temperature of the Planckian radiator whose relative spectral distribution, $S_\mathrm{p}(\lambda,T_\mathrm{p})$, is the same or nearly the same as that of the radiation considered in the spectral range of interest for which the following integral is minimized by adjustment of a and T_p:

$$\int_{\lambda_1}^{\lambda_2} \left[1 - \frac{S_\mathrm{t}(\lambda)}{a\,S_\mathrm{p}(\lambda,T_\mathrm{p})}\right]^2 \mathrm{d}\lambda$$

where λ is the wavelength, $S_\mathrm{t}(\lambda)$ is the relative spectral distribution of the radiation being considered, $S_\mathrm{p}(\lambda, T_\mathrm{p})$ is the relative spectral distribution of the Planckian radiator at temperature T_p, and a is a scaling factor

Note 1 to entry: The scaling factor a is chosen to make the quotient $\frac{S_\mathrm{t}(\lambda)}{S_\mathrm{p}(\lambda,T_\mathrm{p})}$ equal to unity at a convenient wavelength which, in photometry and colorimetry is typically 560 nm. $S_\mathrm{p}(\lambda,T_\mathrm{p}) = \frac{P(\lambda,T_\mathrm{p})}{P(560\ \mathrm{nm},T_\mathrm{p})}$ with $P(\lambda,T_\mathrm{p}) = \lambda^{-5}\left(\mathrm{e}^{\frac{c_2}{\lambda T}} - 1\right)^{-1}$, where c_2 is the second radiation constant.

Note 2 to entry: Distribution temperature is a meaningful characteristic for radiators having a relative spectral distribution similar to that of a Planckian radiator, but only if calculated for an expanded wavelength range and for radiation whose spectral distribution of radiant flux is a continuous function of wavelength in that range.

Note 3 to entry: In photometry and colorimetry the wavelength range set by λ_1 and λ_2 is the visible spectral range, and in these cases the range from at least $\lambda_1 = 400$ nm to $\lambda_2 = 750$ nm is recommended.

Note 4 to entry: In practice, the integral is replaced by a summation. For incandescent lamps, equally spaced wavelength intervals of 10 nm will usually suffice. All values in the summation are treated with equal weight.

Note 5 to entry: The distribution temperature is expressed in kelvin (K).

Note 6 to entry: The definition can be stated mathematically more rigorously as:

$$T_\mathrm{D} = \left\{ T_\mathrm{p} \,\middle|\, \min_{a,T_\mathrm{p}\in\mathbb{R}} \left(\int_{\lambda_1}^{\lambda_2} \left[1 - \frac{S_\mathrm{t}(\lambda)}{a\ S_\mathrm{p}(\lambda,T_\mathrm{p})}\right]^2 \mathrm{d}\lambda \right) \right\}$$

The equation should be read as: T_D is equal to the value of T_p that satisfies the expression to the right of the | symbol. In this case the expression is a minimization that explicitly alters a and T_p only during the iterations and states that both a and T_p must be a real numbers.

[SOURCE: CIE S 017:2020, 17-24-017, online https://cie.co.at/eilvterm/17-24-017, modified – "temperature" replaced with "thermodynamic temperature", Note 6 to entry replaced with new note, Notes 7 and 8 to entry omitted]

7.3 Additional information

The definition in 7.2 is based on the information given in CIE 114/4 (CIE 1994).

The fundamental method of determining the distribution temperature of any radiation is based on measuring its spectral power distribution by spectroradiometry. The distribution temperature can then be determined by minimizing the integral given in the definition above. Any converging iterative method may be used to perform this minimization; one such method has been suggested and used by Robertson (1968) but any available method, e.g. a spreadsheet function with minimum value search facilities, is suitable to perform the calculation.

The wavelength range used in the calculation must always be specified. Normally the concept is limited to a range inside the visible spectrum and in this case, as stated previously, the wavelength range of at least 400 nm to 750 nm is recommended. For most incandescent sources this wavelength range will give a distribution temperature that is within a few kelvins from the CCT, which is in most cases not significant compared to the overall measurement uncertainty of many kelvins.

The distribution temperature is used to express the information of spectral power distribution of a near-Planckian light source in one number. The similar purpose can be met by use of the CCT when it is applied to incandescent lamps, though the CCT is intended to provide colour information and thus includes a significant spectral bias towards the peak wavelengths of the colour-matching functions. Both terms are used for incandescent lamps, but the use of the distribution temperature is limited to specific purposes, e.g. for correction of spectral (colour) mismatch of photometer-based measurements (CIE 2011), while the CCT is widely used for all white lighting products including incandescent lamps.

7.4 Limits to applicability

The distribution temperature is a meaningful characteristic only for radiators having a relative spectral power distribution similar to that of a Planckian radiator, and only if calculated over a sufficient wavelength range and for radiation whose spectral power distribution is a continuous function of wavelength in that range. For this reason, its use should be limited to incandescent lamps such as tungsten filament or ribbon lamps and the relative deviation of the spectral power distribution from Planckian radiation at any wavelength in the given spectral range should be less than 10 %.

Spectral emission lines from contaminants (e.g. sodium) and spectrally selective absorptions in the lamp envelope can also cause substantial deviations from Planck’s law, which depend on manufacturing and hence differ between lamps even of the same type. The size of the deviations also depends on the measurement bandwidth (narrower bandwidths give larger deviations); the 10 % value above is for a 5 nm bandwidth.

Due to such deviations, the relative spectral power distribution of a real object can only be roughly reconstructed from a distribution temperature statement, e.g. by a spectral tolerance band of about 10 %. For an incandescent standard lamp these deviations from the corresponding Planckian radiator (mainly in the blue spectral region) are caused by: a non-constant spectral emissivity of the filament, an inhomogeneous filament temperature and the spectral transmission of the glass envelope.

Radiation from a tungsten filament lamp is generally somewhat yellower than from the equivalent Planckian radiator; the relative spectral radiance at 400 nm is 2 % to 5 % lower than the Planckian equivalent for most tungsten filament lamps. In these circumstances the assignment of a distribution temperature to the lamp is generally valid. However, for some types of luminance standard, which incorporate an integrating sphere or opal diffuser with the tungsten lamp, the spectral deviation from a Planck distribution can be much greater (generally from 10 % to as much as 50 %) and the distribution temperature should therefore not be used for this type of source.

7.5 Measurement and uncertainties

A detailed description about the calculation of the distribution temperature from spectral measurements, and associated uncertainties in values, is given in CIE 198-SP1.4:2011 (CIE 2011). Distribution temperature uncertainties require a knowledge or estimate of the covariance matrix, which contains spectral correlations as well as individual (uncorrelated) wavelength component uncertainties. CIE 198-SP1.4:2011 provides some examples, but the actual matrix for the measurement should be used in calculations.

8 Ratio temperature

8.1 Symbol

T_{br}

8.2 Definition

correlated colour temperature or distribution temperature established from a null method for transferring the temperature quantity from one lamp to another lamp of the same type and design

Note 1 to entry: In a null method the sources are deemed equivalent when the quantities measured are equal; there is no implication of equivalence if the measured quantities are different.

8.3 Additional information

The definition in 8.2 is based on the information given in CIE 114/4 (CIE 1994).

Where standards of colour temperature, CCT or distribution temperature determined by spectroradiometry are used, these are usually maintained in the form of incandescent tungsten filament lamps operated at a specified current or voltage. For lamps of the same type the (nominal) operation conditions for the assigned ratio temperature can be determined by adjusting their electrical current or voltage until the ratio of power in two specified spectral bands within the visible spectral range are the same as that of the reference standard. The adjustment is usually made using blue and red glass filters to produce two different spectral responsivities, $B(\lambda)$ and $R(\lambda)$, of a detector. These spectral responsivities could be narrow, essentially monochromatic, bands (e.g. at 460 nm and 660 nm) or they could be wide bands (Mori et al., 1964).

Two lamps equalized in this way are said to have equal ratio temperatures (sometimes called bilateral temperatures). It is usually assumed that when two thermal radiators have equal ratio temperatures, they also have equal CCTs or distribution temperatures, but this may not be the case, especially if the transfer is made to different types of incandescent lamps, e.g. with the respective lamp envelopes made from different glasses.

8.4 Limits to applicability

The use of the ratio temperature is not recommended except in situations where the relative spectral power distribution, $S(\lambda)$, of the thermal radiator in the spectral range of interest is the same or nearly the same as that of the object considered, e.g. as a null method for transferring the quantity of correlated colour temperature or distribution temperature from one lamp to another of the same type and design. With the widespread use of spectroradiometers, a direct determination of the CCT or the distribution temperature is possible; however, the ratio temperature method requires less effort regarding calibration and uncertainty estimation and can, for example, be used to confirm equivalence between spectral measurements and integral measures.

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