Spectral irradiance model for tungsten halogen lamps in 340–850 nm wavelength range

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We have developed a physical model for the spectral irradiance of 1 kW tungsten halogen incandescent lamps for the wavelength range 340–850 nm. The model consists of the Planck's radiation law, published values for the emissivity of tungsten, and a residual spectral correction function taking into account unknown factors of the lamp. The correction function was determined by measuring the spectra of a 1000 W, quartz-halogen, tungsten coiled filament (FEL) lamp at different temperatures. The new model was tested with lamps of types FEL and 1000 W, 120 V quartz halogen (DXW). Comparisons with measurements of two national standards laboratories indicate that the model can account for the spectral irradiance values of lamps with an agreement better than 1% throughout the spectral region studied. We further demonstrate that the spectral irradiance of a lamp can be predicted with an expanded uncertainty of 2.6% if the color temperature and illuminance values for the lamp are known with expanded uncertainties of 20 K and 2%, respectively. In addition, it is suggested that the spectral irradiance may be derived from resistance measurements of the filament with lamp on and off. © 2010 Optical Society of America

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1. Introduction

High-temperature blackbodies are used as radiation sources in primary spectral irradiance scale realizations in several National Metrology Institutes (NMIs) [1–4]. The emissivity of a blackbody is predictable and spectrally constant. It is thus possible to extrapolate spectral irradiance values, measured with, e.g., filter radiometers, to other wavelengths using the Planck's radiation law. One disadvantage of high-temperature blackbodies is that they are quite expensive and large, and may not be feasible for smaller NMIs. Using detector-based methods, the spectral irradiance scale can also be realized in tungsten halogen incandescent lamps [5–8]. In contrast to black bodies, incandescent lamps are not perfect Planckian radiators. The spectra are affected by spectrally varying emissivities. For extrapolation of the spectral irradiance, knowledge of the spectral behavior of the lamp emissivity is required.

The lamp emissivity is mainly determined by the emissivity of the tungsten filament. Emissivity of tungsten has been measured and published by e.g., de Vos [9] and Larrabee [10]. The effective emissivity of a lamp is further influenced by the transmittance of the glass bulb, the absorption of the halogen or other filling gas, and possible impurities of the filament. The emissivity of an incandescent tungsten lamp is typically modeled using an Nth-degree polynomial [5,7,11–13]. The degree N used typically varies between 3 and 7. Polynomial emissivity models require several spectral irradiance data points to avoid oscillations between the wavelengths of the measured points. Polynomial models cannot be used for extrapolation. The modeled effective emissivities of different lamp specimens are typically close to

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each other [13] and do not need to be modified due to ageing of the lamp [14].

In this paper we present a physical model for the lamp irradiance for the extended visible wavelength region, 340–850 nm. The model is based on the Planck's radiation law, published values for the emissivity of tungsten [9] in polynomial form [15], and a residual correction function taking into account unknown factors of the lamp.

In Section 2, we present the details of the model. In Section 3, we present the measurements conducted to determine the residual correction function. We first calibrate a spectroradiometer with a blackbody. The spectra of a 1 kW FEL lamp are then measured at various temperatures, and a common solution for the correction function explaining all measured spectra is determined. In Section 4, the model is validated with measurement results of the Helsinki University of Technology (TKK) and the National Physical Laboratory (NPL) for several lamps of types: 1000 W, quartz-halogen, tungsten coiled filament (FEL) and 1000 W, 120 V quartz halogen (DXW). The uncertainty of the new model is discussed in Section 5. The final uncertainty consists of the uncertainty of the spectral irradiance values used and the additional uncertainty caused by extrapolation with the model. We study how the latter is influenced by the selection of the data points. In Section 6, we study whether the spectral irradiance of a lamp can be derived from its photometric and electrical properties only. It turns out that, using photometric properties, reasonable expanded uncertainties of the order of 2% to 3% can be achieved. The conclusions of this work are presented in Section 7.

2. Lamp Model

The spectral irradiance $E(\lambda, T)$ of an incandescent lamp is modeled as

$$E(\lambda, T) = B(T)\varepsilon_W(\lambda, T)\varepsilon_\Delta(\lambda)\frac{2hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]}, \quad (1)$$

where λ is the wavelength in vacuum, T is the temperature of the filament, $\varepsilon_W(\lambda, T)$ is the emissivity of tungsten, $\varepsilon_\Delta(\lambda)$ is the residual correction factor for the emissivity of the lamp, h is the Planck constant, c is the speed of light in vacuum, and k is the Boltzmann constant. For the spectral emissivity of tungsten ribbon, we use the emissivity determined by de Vos [9] in polynomial form [15]. Parameter $B(T)$ is a geometrical factor and takes into account the measurement distance and the dimensions of the filament. The irradiance levels and temperatures of different lamp specimens vary, although the lamps are operated with constant current or constant power. Temperature affects $B(T)$ only through thermal expansion of the dimensions of the filament.

The residual correction factor, $\varepsilon_\Delta(\lambda)$, accounts for the effects of all factors in addition to the nominal spectral emissivity of tungsten. These include the transmittance of the quartz bulb, the transmittance of the filling gas, the difference of the properties of the tungsten used in the lamp filament and in the nominal emissivity determination, and the light recycling effect in the coiled filament [16,17].

We have chosen the data of de Vos for the nominal emissivity of tungsten [9] because we know from earlier experience that it is rather close to the emissivity of the lamps we use. Furthermore, these data are available in polynomial form [15]. The emissivity in [9] has been determined using tungsten metal in a strip form. In lamps of type FEL or DXW, the filament is double-coiled. The light recycling in the coil increases the effective emissivity of the filament, especially in the IR region [16,17]. The emissivity of tungsten may vary upon its physical preparation, and other data sets in addition to [9] have been published as well [18]. Using some other published values for the nominal emissivity of tungsten would lead to a slightly different residual correction.

3. Measurement of the Residual Emissivity Correction

To determine $\varepsilon_\Delta(\lambda)$, the spectra of a 1 kW tungsten halogen lamp were measured at different temperatures in the wavelength range 340–850 nm. The measured spectral irradiances of the lamp are shown in Fig. 1. The different burning temperatures were obtained by adjusting the operating current of the lamp. The lamp was operated with 8.1, 7.5, 7, 6.5, and 6 A currents. The measurements were started from the highest current, and the current was then adjusted downward. After setting the operating current, the lamp was allowed to stabilize for 30 min before starting the measurement.

The lamp current was monitored with help of a precision resistor and a high-accuracy digital voltmeter. The distance between the reference plane of the lamp and the detector was 500 mm. The measurements were carried out using a Bentham DTMc300 spectroradiometer with a fiber and diffuser as the sensing head and a photomultiplier tube as the sensing element. The spectroradiometer was calibrated by

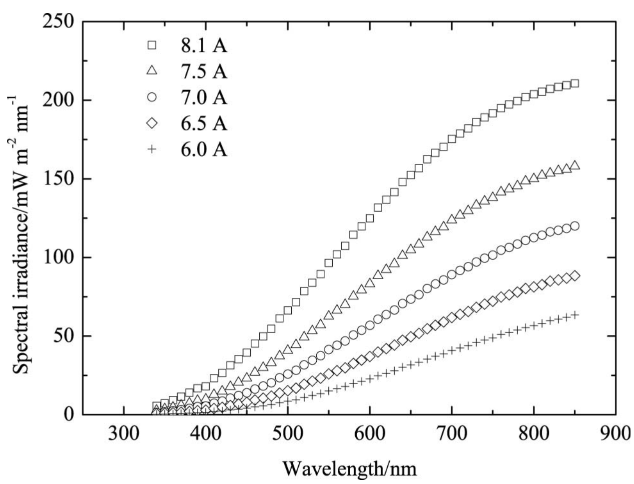

Fig. 1. Measured spectral irradiances of the lamp at different operating currents.

measuring a blackbody operated at 1770 K. The blackbody was used in the calibration in order to obtain a reference spectrum with constant emissivity close to unity.

The temperature of the lamp filament at each current level was first obtained by fitting parameter T in Eq. (1), with $\varepsilon_\Delta(\lambda) = 1$. The factor $B(T)$ was modeled as

$$B(T) = B_0[1 + b(T)], \tag{2}$$

where B_0 is a geometrical factor and $b(T)$ is the relative correction for the thermal expansion of the filament. Factor B_0 was assumed to be constant and was determined at the current of 7.0 A. Thermal expansion was calculated with respect to these conditions. Equations for calculating the thermal expansion of tungsten at high temperatures were taken from [19,20]. To simplify the calculation of $B(T)$ in the limited temperature range, the correction $b(T)$ was approximated to be linear between the highest and lowest obtained temperatures, as

$$b(T) = 0.000016\,\mathrm{K}^{-1}(T - T_0), \tag{3}$$

where $T_0 = 2770\,\mathrm{K}$ is the approximate midpoint of the temperature interval. The maximum of $|b(T)|$ was 0.0044 for the current of 8.1 A.

The correction function $\varepsilon_\Delta(\lambda)$ was calculated from the measured spectral irradiances E_{meas} in Fig. 1 and the temperatures obtained, as

$$\varepsilon_\Delta(\lambda) = \frac{E_{\mathrm{meas}}(\lambda, T)}{L(\lambda, T)\varepsilon_{\mathrm{W}}(\lambda, T)B(T)}, \tag{4}$$

where $L(\lambda, T)$ is the blackbody radiance. An eighth degree polynomial was fitted to the average of the correction functions, and it was taken into use as the new $\varepsilon_\Delta(\lambda)$. The fitting of T in Eq. (1) and the calculation of $\varepsilon_\Delta(\lambda)$ was repeated twice. In the two last iterations, the values of T and $\varepsilon_\Delta(\lambda)$ did not change by more than 0.001% and 0.01%, respectively.

The final correction functions and the eighth degree polynomial fit are shown in Fig. 2. The absolute level of the correction is determined by factor B_0, and only the spectral shape of the correction functions is significant in Fig. 2. We have therefore chosen to normalize the data so that their average is unity. As can be seen, the spectral shape of the correction function is almost the same for all currents, which indicates that the model has converged to a physical solution. The magnitude of the correction required is ±2.5%.

It appears as if something would absorb visible radiation. The spectral shape of the residual correction cannot be explained by the transmittance of the quartz bulb. The absorption effect might be due to the filling gas, which is presumably a mixture of bromium, chlorine, phosphorus, and hydrocarbons. An absorption maximum in the mid-visible wavelength range has been reported for iodine, sometimes used as filling gas [21]. The other halogen gases may absorb the visible radiation in a similar manner. Another factor contributing to the spectral shape is the light recycling in the filament [16,17], which increases the emissivity. The tungsten of which the filament has been coiled might also have different surface properties as compared with the tungsten that de Vos [9] used in his measurements.

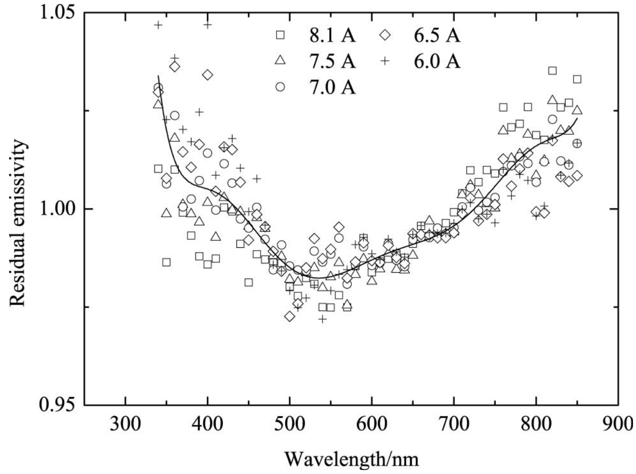

Fig. 2. Residual corrections, after the spectral irradiances measured at different operating currents have been divided by the blackbody radiance and the emissivity of tungsten. The residual corrections have been normalized in such a way that their average is 1. The solid line is an eighth degree polynomial fitted to the average of the residual corrections.

The final temperatures corresponding to the different operating currents, and the voltages measured over the lamp during operation, are given in Table 1. The coefficients of the eighth degree polynomial of $\varepsilon_\Delta(\lambda)$ are listed in Table 2.

4. Verification Measurements

After fixing the $\varepsilon_\Delta(\lambda)$ function, the model presented has only two free parameters, B_0 and T. The realization of a spectral irradiance scale could thus be carried out using a minimum of two measurements of a lamp. In practice, it is preferable to use data at three wavelengths in order to reveal possible errors in measurements. One point could be selected from each of the red, green, and blue wavelength regions.

A. Tests with Helsinki University of Technology Calibrated Lamps

The model was tested with four incandescent lamps of type FEL and four of type DXW calibrated earlier by TKK. Filter radiometer measurements at wave-

Table 1. Operating Currents, Corresponding Voltages, and Final Burning Temperatures of an FEL Lamp

Current/A	Voltage/V	Temperature/K
8.1000	109.55	3045.9
7.5000	95.92	2895.8
7.0000	84.33	2766.7
6.5000	73.76	2635.4
6.0000	63.83	2501.4

Table 2. Coefficients for the Eighth Degree Polynomial Modeling the Residual Emissivity

	Coefficient
c_8	$1.6701 \times 10^4\ \mu\text{m}^{-8}$
c_7	$-8.1549 \times 10^4\ \mu\text{m}^{-7}$
c_6	$1.7210 \times 10^5\ \mu\text{m}^{-6}$
c_5	$-2.0490 \times 10^5\ \mu\text{m}^{-5}$
c_4	$1.5044 \times 10^5\ \mu\text{m}^{-4}$
c_3	$-6.9719 \times 10^4\ \mu\text{m}^{-3}$
c_2	$1.9906 \times 10^4\ \mu\text{m}^{-2}$
c_1	$-3.2007 \times 10^3\ \mu\text{m}^{-1}$
c_0	2.2290×10^2

lengths of 380, 570, and 800 nm were used to determine parameters T and B_0.

The test results are presented in Figs. 3 and 4. The agreement is within $\pm 0.71\%$ for the FEL lamps, the standard deviation being 0.35%. The corresponding values for the DXW lamps are $\pm 0.83\%$ and 0.40%. As can be seen, the interpolated values are well within the expanded uncertainties of the TKK calibration. The spectral structure of the difference is similar for both FEL and DXW lamps, and it is caused mainly by the seventh degree interpolation polynomial used in the earlier calibrations [7]. The relatively high degree of the polynomial causes oscillation within uncertainties that has been noted in several intercomparisons, e.g., CCPR-K1.a [22]. When using the new model, this structure relative to the true spectral irradiance should be smaller. The uncertainty of the calibration is somewhat larger for the DXW lamps than for the FEL lamps because the calibrations have been carried out using slightly different measurement setups. The discontinuity point at 760 nm is due to a discontinuity in the polynomial model of the emissivity of tungsten [15].

B. Tests with National Physical Laboratory Calibrated Lamps

Two of the FEL lamps have also been calibrated by NPL as part of the international key comparison CCPR-K1.a [22]. The spectral irradiance values at wavelengths 380, 555, and 800 nm were used for testing the model. The deviation between the spectral irradiance values obtained with the model and the NPL calibration is presented in Fig. 5. The agreement of the new model is within $\pm 1.0\%$, and the standard deviation is 0.29%.

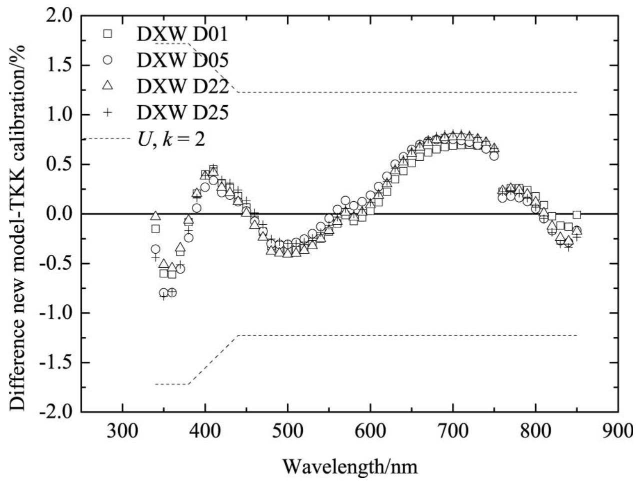

Fig. 4. Deviation of the modeled spectral irradiances from earlier TKK calibrations for four DXW type lamps. The dashed lines represent the expanded uncertainties of the calibration of the lamps.

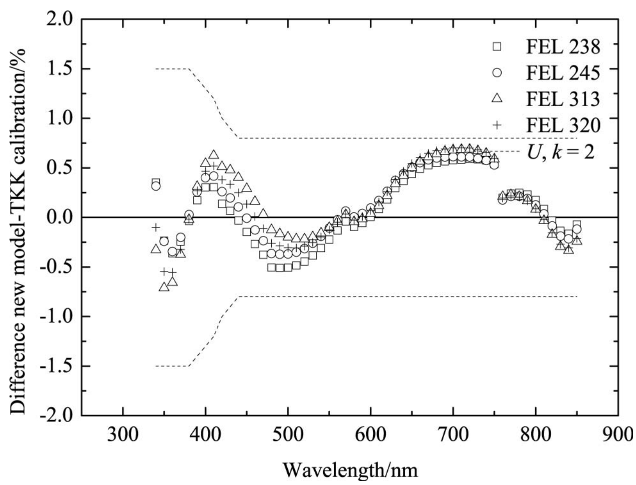

Fig. 3. Deviation of the modeled spectral irradiances from earlier TKK calibrations for four FEL type lamps. The dashed lines represent the expanded uncertainties of the calibration of the lamps.

5. Uncertainty of the Model

The uncertainty budget of the model of Eq. (1) is presented in Table 3. The uncertainty of the model consists of three basic types of uncertainties: the uncertainty of the spectral irradiance measurement, the deviation of the polynomial model of $\varepsilon_\Delta(\lambda)$ from the measured values, and the uncertainty due to the selection of the measurement points. At TKK, the expanded uncertainty ($k = 2$) of the spectral irradiance varies between 1.4% and 0.7% [7]. The corresponding uncertainty at NPL is between 1.2% and 0.32% [22]. The uncertainty of the $\varepsilon_\Delta(\lambda)$ model is calculated as the standard deviation between the

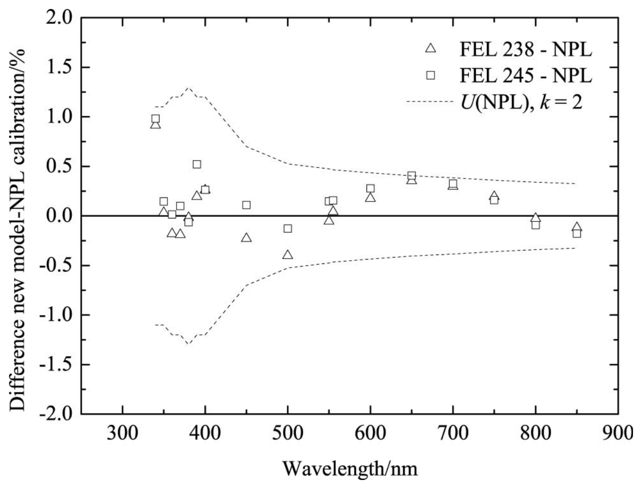

Fig. 5. Deviation between the model and the NPL calibrations. The dashed lines represent the expanded uncertainties of NPL.

Table 3. Uncertainty Budget of the Lamp Model

	Relative Uncertainty/%					
Wavelength/nm	340	380	440	570	700	800
Uncertainty of irradiance measurement	0.68	0.54	0.35	0.32	0.32	0.34
Spectral dependence of irradiance (Standard deviation of the residual correction)	0.60	0.32	0.32	0.32	0.32	0.32
Selection of points, 3-point fit	0.46	0.35	0.23	0.11	0.17	0.22
Combined standard uncertainty	1.02	0.72	0.53	0.47	0.48	0.52
Expanded uncertainty ($k = 2$)	2.03	1.44	1.05	0.93	0.97	1.03

determined correction functions and the fitted polynomial. This component describes the uncertainty due to spectral dependence of irradiance, and it is independent on the selection of nominal spectral emissivity of the tungsten filament.

To determine the uncertainty component related to the selection of the measurement points, we tested the model with five different combinations of results at three wavelengths, and with ten combinations of results at two wavelengths. The measurement points were at the wavelengths of 366, 380, 440, 570, 700, and 800 nm. The points were chosen such that they were from different regions of the visible spectrum: one from the blue, one from the green, and one from the red wavelength region. In the two-point combinations, one of the regions was left out for each calculation. With three wavelengths, the relative standard deviation between the different measurement point combinations varied from 0.46% in the UV region to 0.11% in the visible region and 0.22% in the NIR region. With two wavelengths, the corresponding standard deviations are 0.50%, 0.14%, and 0.26%. The results show that the model can also extrapolate the spectral irradiance with reasonable uncertainties outside the outermost filter radiometer wavelengths.

The overall expanded uncertainties of the model are between 0.93% and 2.03%. If this method is applied by another user, the uncertainties of the measurement points with which the scale is realized at the three wavelengths need to be taken into account.

6. Practical Applications

A. Determining the Spectral Irradiance Using Color Temperature and Illuminance Values of a Lamp

The developed model can be used to determine the spectral irradiance of a lamp using the color temperature and illuminance values of the lamp. Color temperature may be obtained, e.g., with a colorimeter, or it may be known from the manufacturer's specifications or calibration certificate. Illuminance may be measured with a luxmeter. To determine the physical temperature of the tungsten filament from the color temperature, the methods and equations presented in [23] can be applied.

The model was tested using the color temperature known with an expanded uncertainty of 20 K and a measured illuminance value with an expanded uncertainty of 2% to fix B_0 and T for an FEL lamp. The obtained spectrum was compared with the spectral irradiance values measured as in Fig. 3. The temperature and illuminance values were then varied within their uncertainties to see how the difference behaves. Figure 6 shows the four extreme conditions where T and B_0 have been deflected to their negative and positive standard uncertainties. The expanded uncertainty of 20 K in the color temperature results in a standard deviation of 0.8% in the spectral irradiance values. The 2% expanded uncertainty in illuminance results in an uncertainty of 2% in the absolute level of the spectral irradiance. With the uncertainty of the residual correction from Table 3 included, the spectral irradiance of a lamp may thus be obtained with an expanded uncertainty of 2.6% from its color temperature and illuminance.

B. Determining the Spectral Irradiance from the Electrical Properties of a Lamp

Finally, we consider determination of the physical temperature of the lamp filament based on electrical properties of the lamp. The resistance values of the filament at room temperature and at the burning temperature were measured. The temperature of the filament may then be obtained from the known temperature dependence of the resistance of tungsten [24–26]. With fixed filament temperature, the spectral irradiance can be determined using an

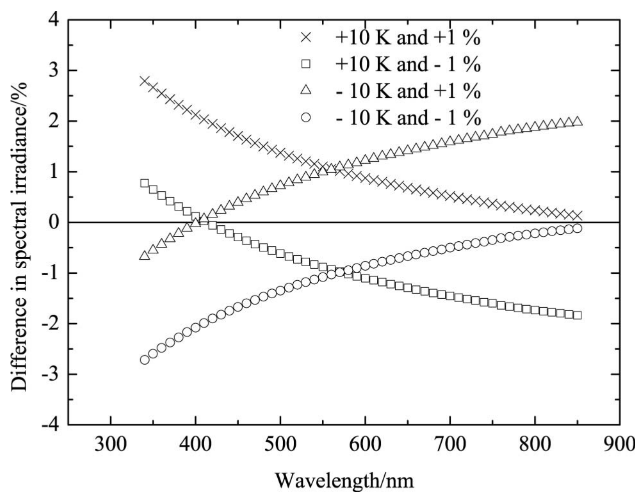

Fig. 6. Deviation in the spectral irradiance values using a color temperature with ±10 K deflection and an illuminance value with ±1% deflection from the nominal values.

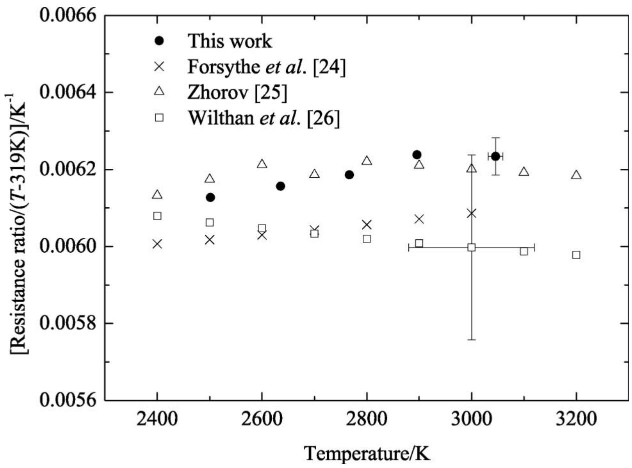

Fig. 7. Ratio of the hot resistance to the room temperature resistance, scaled by $T - 319\,\mathrm{K}$. The resistance ratio was corrected for the contribution of the weakly glowing stem by −0.25%. The uncertainty of this correction is assumed to have a rectangular distribution with a full width of 0.5%. The uncertainty bars correspond to the expanded uncertainties ($k = 2$) of the resistance ratio and temperature measurements.

illuminance measurement and the model developed as in Subsection 6.A.

The resistance of the FEL lamp filament was measured at the room temperature of 22 °C, using a four-wire setup at measurement currents between 1 and 10 mA. The resistance was $R(295\,\mathrm{K}) = 0.798\,\Omega$ with a standard uncertainty of $0.002\,\Omega$. The filament of the studied lamp also included molybdenum stems. We measured the resistance of the molybdenum parts of a similar filament of a broken lamp. The relative contribution of the molybdenum parts to the room temperature resistance of the lamp, $(0.50 \pm 0.25)\%$, is included in the resistance value above.

Spectral irradiance standard lamps are typically operated with constant current, and the voltage over the lamp is monitored. During the measurements, the lamp current was recorded with a standard uncertainty of 0.1 mA, and the voltage with a standard uncertainty of 0.05 V. The resistance of the hot filament was obtained from the current and voltage measurements with the lamp on (see Table 1). The uncertainties in the current and voltage measurements result in a standard uncertainty of $0.006\,\Omega$ in resistance. Figure 7 presents the ratio of the hot resistance to the room temperature resistance, scaled by $T - 319\,\mathrm{K}$. The intercept temperature of 319 K was selected for illustration purposes to remove the slope in the temperature dependence of the resistance ratio. Corresponding data from [24–26] are also shown in Fig. 7.

The relative standard uncertainty of 0.38% of our resistance ratio is determined from the standard uncertainties of the room temperature and hot filament measurements. The standard uncertainty of the temperature of the filament is 6 K. This value was estimated on the basis of uncertainties in Table 3: a change of the ratio of irradiances at 340 nm and 800 nm by 1.5% requires a 6 K change in temperature.

As seen in Fig. 7, the data obtained from different tungsten samples agree within expanded uncertainties given in this work and in [25]. This is a quite satisfactory result and encourages us to suggest a method for spectral irradiance determination on the basis of resistance and illuminance measurements. In the temperature range of this study, the temperature of the filament can be calculated from the hot resistance $R(T)$ and the room temperature resistance $R(295\,\mathrm{K})$ as

$$T = \frac{R(T)}{0.0062\,\mathrm{K}^{-1} R(295\,\mathrm{K})} + 319\,\mathrm{K}. \qquad (5)$$

If the data of this work in Fig. 7 can be confirmed for a larger number of tungsten lamps, another user could measure the room temperature resistance and burning resistance of his lamp and determine the physical temperature of the filament by Eq. (5). With known lamp temperature and illuminance, the model of Eq. (1) gives the spectral irradiance.

7. Conclusions

A physical model for 1 kW tungsten halogen incandescent lamps of types FEL and DXW was developed for the wavelength range 340–850 nm. The model consists of Planck's radiation law, spectral emissivity of tungsten, a geometrical factor, and a measured spectral residual correction. The residual correction function was determined by measuring the spectra of an FEL lamp at different temperatures.

The model was tested with four lamps of type FEL and four lamps of type DXW calibrated at TKK and two FEL lamps calibrated by NPL. The model followed the measured spectral irradiance points with standard deviations of the order of 0.35%.

The model can be used to predict the spectral irradiance of an incandescent lamp between 340 and 850 nm wavelengths from two measured spectral irradiance values only. Use of three points with decent wavelength separation is recommended to increase the reliability. The model could be extended from both of its endpoints: The lower end of our model was limited to 340 nm, because the polynomial forms of the emissivity of tungsten given in [15] do not reach lower wavelengths. Extension of the model would require further evaluation of the tungsten emissivity data published by de Vos [9]. In the UV region, the polynomial representation for the emissivity of tungsten could be extended toward lower wavelengths. In the IR region, our measurements were limited to 850 nm due to the detector of the spectroradiometer. Measurements could be extended by using, e.g., an extended InGaAs detector.

We have shown that the known correction function $\varepsilon_\Delta(\lambda)$ allows the spectral irradiance of a lamp to be determined from the color temperature or even from the electrical properties of the lamp. The absolute level may be determined using an illuminance measurement. Expanded uncertainties of the order of 2% to 3% can be achieved, with typical measurement uncertainties of 20 K and 2% for the color temperature and illuminance, respectively. In order to develop a simple scale, it is suggested that the spectral irradiance of a tungsten lamp can be determined from the resistance and illuminance measurements.

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