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Determination of true temperature of opaque matter based on its thermal radiation spectrum: Using relative emissivity and the Wien displacement law

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Abstract. Two methods for determining of the true (thermodynamic) temperature via thermal radiation spectrum of an opaque heated object are presented. The first method is based on the relative emissivity. It is shown that in many cases, the range of the true temperature values may be narrowed down using the "convex–concave" criterion. As shown, that any relative spectral emissivity dependence can be approximated by the same parametric model. The second method is based on the use of the Wien displacement law for real materials. This method is effective when the radiation of the object close to the gray-body radiation in the region of the spectral emission maximum. It is shown that these two methods complement each other.

1. Introduction

Radiation thermometers are characterized by high performance and require no direct contact with the measured object [1, 2]. These features are of particular importance for registration of fast processes at high temperatures and for investigation of the thermophysical properties of matters (materials) [3]. It was assumed that the spectral intensity (radiances) of the free-emitted radiation and, hence, the emissivity are continuous functions of the variables wavelength and true temperature T. The object temperature is constant during the measurement process. The environment where the measured object is contained is transparent for the thermal radiation; radiation from outside is absent. The value of the directional spectral emissivity, $\epsilon(\lambda_i, T)$, of material is unknown. The registered radiation spectrum consisting of a set of spectral intensities $I_c(\lambda_i)$ at m wavelengths is used as an input data.

There are several approaches for determination of true temperature of opaque materials via the registered thermal radiation spectrum [1, 2, 4, 5]. Two new approaches (and two methods, respectively) are considered. The first method based on relative emissivity of material [6]. The second method is based on temperature determination of opaque materials via the spectral thermal radiation maximum [7]. It is shown that the area of the use of these approaches depends on the temperatures level and emissivity dependence on wavelength. It is shown that these approaches complement each other.

The problem of determining the object true temperature is proposed to solve in two stages.

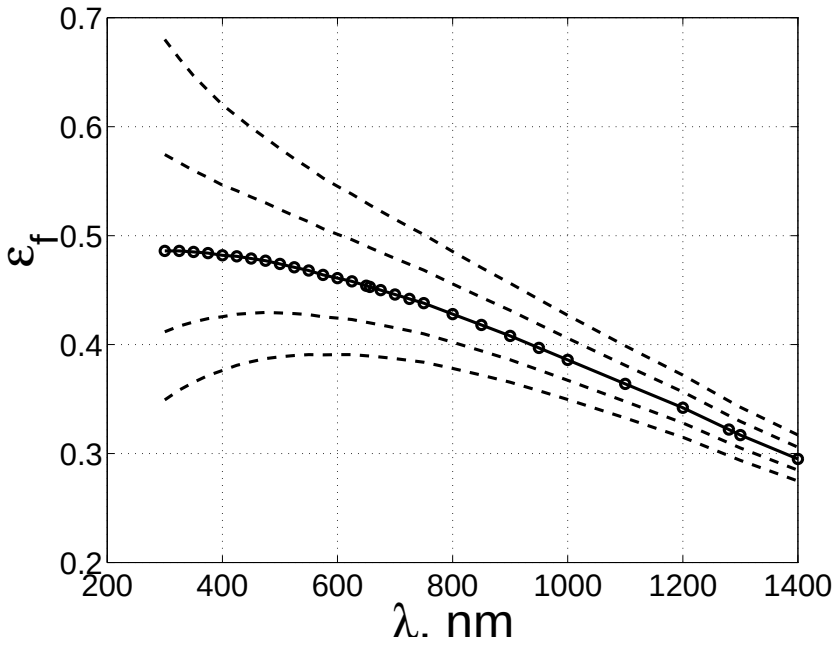

Figure 1. Dependence of ϵ_f on λ for tungsten at change the reference temperature, T_f, from 1190 to 1210 K in steps of 5 K: solid line—data at $T = 1200$ K [8]; dashed lines—the same data at reference temperatures $T_f = 1190$ (the upper dashed line), 1195, 1205 and 1210 K (the lower dashed line), respectively.

2. Basic relationships and results

The first stage. This method is based on using of the relative emissivity, $\epsilon_f(\lambda, T_f)$, where T_f is the reference temperature [6]. For the fixed wavelength λ_i, in accordance relationship for $I_c(\lambda_i) = \epsilon(\lambda_i, T) I_0(\lambda_i, T)$, where I_0 is the black-body intensity, we obtain

$$\epsilon_f(\lambda_i, T_f) = I_c(\lambda_i)/I_0(\lambda_i, T_f) = \epsilon(\lambda_i, T) f_P, \tag{1}$$

where according to the Planck formula

$$I_0(\lambda_i, T) = \frac{C_1/\pi}{\lambda_i^5[\exp\frac{c_2}{\lambda_i, T} - 1]},$$

C_1 and c_2 are the first and second radiation constants, respectively ($c_2 = 1.4388 \times 10^{-2}$ K $\times$ m);

$$f_P = \frac{\exp(\frac{c_2}{\lambda_i T_f}) - 1}{\exp(\frac{c_2}{\lambda_i T}) - 1},$$

T is the thermodynamic temperature. Within the validity range of the Wien formula,

$$f_P = f_W = \exp(p/\lambda_i), \tag{2}$$

where $p = c_2(1/T_f - 1/T)$.

Dependence of $\epsilon_f(\lambda_i, T_f)$ on λ for tungsten at $T = 1200$ K in vacuum [8] is shown in figure 1. The reference temperature, T_f, changes from 1190 to 1210 K in steps of 5 K.

When a small step by T_f is given in the diagram of spectral dependences of $\epsilon_f(\lambda, T_f)$, we can see dependence of $\epsilon_f(\lambda, T_{f,k})$ which coincides within experimental accuracy with the desired

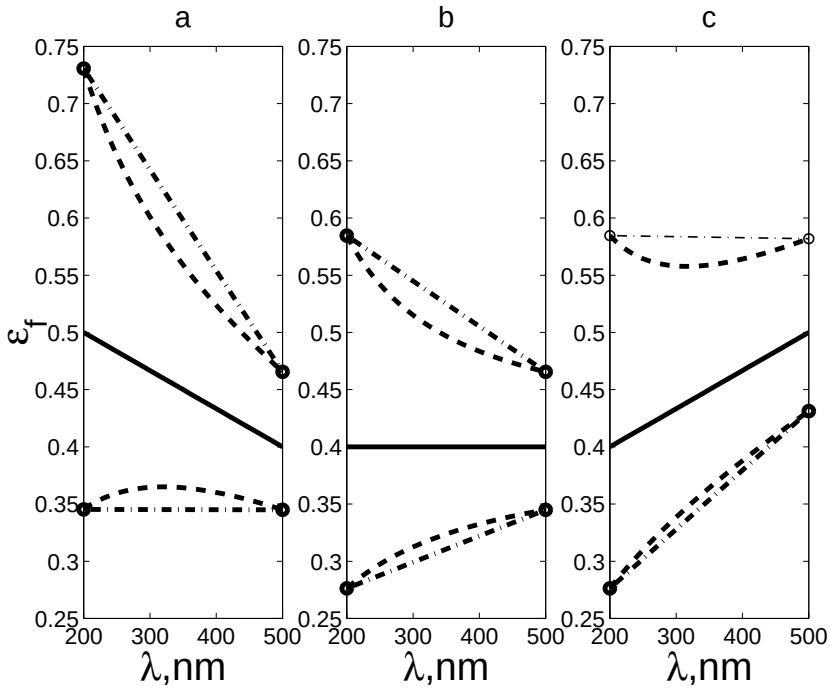

Figure 2. Function of $\epsilon_f(\lambda, T_f)$ on λ for different values of T_f. Initial data: linear dependences of material emissivity, $\epsilon(\lambda, T = 2400$ K), (solid lines, the convexity is absent), $\epsilon_f(\lambda, T_f = 2370$ K) (the upper dashed lines, convex downwards), $\epsilon_f(\lambda, T_f = 2430$ K) (the lower dashed lines, convex upward). Dash-dotted lines indicate the chord, which tighten the ends of the respective curves.

spectral dependence of emissivity, $\epsilon(\lambda, T)$, at desired temperature $T_{f,k} \cong T$. However, this requires the choice criterion.

This criterion can be obtained without solving the corresponding system of equations, if in any significant spectral range the function of $\epsilon(\lambda, T = \text{const})$ depends linearly on λ.

As known, dependence of ϵ_f on λ in the chosen spectral range will be convex upwards, if $T_f > T$ and, hence, $(\epsilon_f)''_\lambda < 0$, and it will be convex downwards, if $T_f < T$, $(\epsilon_f)''_\lambda > 0$, and it will be linear, if $T_f = T$, $(\epsilon_f)''_\lambda = 0$ in this range.

The results of computer simulations confirm this pattern (see figure 2).

The criterion "convex-concave" allows to narrow temperature range to which belongs the desired temperature T.

The relative emissivity is $\epsilon_f(\lambda, T_f) = \epsilon(\lambda, T) f_P$. Parametric form of the f_P function is known. That is why, any dependence of $\epsilon_f(\lambda, T_f)$ at the selected value of T_f can be approximated by the same parametric model. To determine the unknown parameters the least squares technique (LST) was used.

The second stage is based on the use of the Wien displacement law for real materials. As follows from [7]

$$x_{\max} = (5 - \rho_{\max})[1 - \exp(-x_{\max})], \tag{3}$$

where $x_{\max} = c_2/(\lambda_{\max} T)$, $\rho_{\max} = \lambda_{\max}(\ln\epsilon)'_{\lambda=\lambda_{\max}} = c_2(\ln\epsilon)'_{\lambda=\lambda_{\max}}/(x_{\max} T)$.

According to (3) each of these values might be determined if the other two are known. The corresponding equation was solved numerically by iteration method. Numerical examples are given in [9], can be solved exactly by using (3). It is shown that the "peak-method" [9] based on the direct use of the Wien displacement law tends to significant methodological errors. By means of a computer experiment, it is shown that, for selectively radiating materials such as tungsten

at 2600–3000 K, determination of the true temperature according to the Wien displacement law leads to a deviation from the true temperature by more than 200 K [7].

3. Conclusions

True temperature of the opaque material surface was determined in two stages. In the first stage, a registered spectral radiance array belonging to the given spectral region is used as the source data. This array is converted to the relative spectral emissivity array at the proposed surface temperature. It is shown that this transformation has several advantages. First, the resulting relative spectral emissivity (or its logarithm) dependence can be represented graphically, particularly, at the temperature close to the true temperature. Secondly, will select the spectral interval in which the desired emissivity determined by a small number of parameters, in particular, such as a linear function of the wavelength. Initially, for the linear case, the desired dependence of $\epsilon(\lambda, T)$ is determined by a change of convexity (concavity) of the $\epsilon_f(\lambda, T_f)$ curve when the proposed temperature T_f varies. Then, for the given spectral interval, a parametric model of $\epsilon(\lambda, T)$ were chosen and the unknown model parameters and the true temperature T are determined by LST.

In the second stage the surface true temperature T was calculated from obtained data of the first stage again by solving the equation of the form (3).

Thus, both the true temperature values were obtained on the first and second stages, respectively. Finally, that value was chosen, which had the lowest uncertainty.

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