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NEW FACILITES OF RADIATION THERMOMETRY IN HEATING AND COOLING DYNAMIC

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Abstract: The new method of measurement of true temperature and emissivity is considered. The method is based on use of redundancy of the information of Plank's radiation and changes of properties of substance finding the reflection in change of emissivity factor from temperature. The simultaneous application of relative spectroreflectometry allows to reduce quantity of used spectral components and to determine emissivity's meanings, including surfaces, which are not following Lambert law. It is shown, that the method allows to build a thermodynamic temperature scale without using of black body.

Keywords: radiation, thermodynamic-temperature scale, emissivity, true temperature, relative spectroreflectometry.

1 INTRODUCTION

The new method of measurement of true temperature and emissivity is considered. The method is based on use of redundancy of the information of Plank's radiation and changes of properties of substance finding the reflection in change of emissivity factor from temperature. The simultaneous application of relative spectroreflectometry allows to reduce quantity of used spectral components and to determine emissivity's meanings, including surfaces, which are not following Lambert law. It is shown, that the method allows to build a thermodynamic temperature scale without using of black body.

In [1] the method, allowing to determine the true temperature with the exception of the influence of thespread function and emissivity is described.

This method is based on the optimal using of the redundancy of the information of the spectrum of self thermal radiation of the object under it's heating or cooling. Physically this method is using the changes of the substance's properties as a function of the changes of emissivity's factors of the components of spectrum with temperature.

Reflectometry considerably reduced the requirements to signal/noise ratio and this is an advantage of this method.

Moreover this method allows to exclude the principal difficulties of the thermometry's application concerning the necessity of Lambert law execution.

Because it is important to have only the temperature depend factor of reflection but not the reflection factor it self.

Really, under the Kirchgof law for opaque bodies, emissivity factor

$\varepsilon(\lambda_\iota,T_{j+1})$ on wave length λ_ι, at temperature T_{j+1}, will be:

$$\varepsilon(\lambda_\iota,T_{j+1})=1-\rho(\lambda_\iota,T_{j+1})=1-[\rho(\lambda_\iota,T_j)+\alpha_\iota(T_{j+1}-T_j)+\beta_\iota(T_{j+1}{}^2-T_j{}^2)+\ldots+\gamma_\iota,(T_{j+1}{}^n-T_j{}^n)],$$

Where: $\rho(\lambda_\iota,T_{j+1})$ and $\rho(\lambda_\iota,T_j)$ - factors of reflection on wave length λ_ι at temperatures T_{j+1} and T_j accordingly;

α,β,γ - factors of a polynom, which approximate a temperature dependence of factor of reflection.

If the surface does not follow Lambert law:

$$\rho(\lambda_\iota,T_{j+1}) = x_\iota\rho^*(\lambda_\iota,T_{j+1}) \quad \text{and} \quad \varepsilon(\lambda_\iota,T_{j+1}) = 1- x_\iota\rho^*(\lambda_\iota,T_{j+1}),$$

Where: x_ι for given wave length λ_ι is determined by the character of a surface of radiation and by the angle of the reflection (close to normal).

If for the given surface the Lambert law is existed, $x_1=1$. But the temperature dependence determined by a polynom of the degree n with the same factors $\alpha_\iota,\beta_\iota,\ldots,\gamma_\iota$, will be not changed[*/].

So, the difference of reflection factors, at any degree of a roughness of a surface, determines the dependence emissivity by temperature.

That's why reflectometer allows to receive this temperature dependence for given wave length λ_ι as:

$$L_{1,1}= [\rho^*(\lambda_\iota,T_1) -\rho^*(\lambda_\iota,T_2)]\ x_1^{-1}= [\alpha_\iota(T_2-T_1)+\beta_\iota(T_2^2-T_1^2)+\ldots+\gamma_\iota(T_2^n-T_1^n)]\ x_1^{-1}$$

$$L_{1,2}= [\rho^*(\lambda_\iota,T_2) -\rho^*(\lambda_\iota,T_3)]\ x_1^{-1}= [\alpha_\iota(T_3-T_2)+\beta_\iota(T_3^2-T_2^2)+\ldots+\gamma_\iota(T_3^n-T_2^n)]\ x_1^{-1}$$

It is obvious, that the application of a reflectometry allows to have only two unknowns: $-\xi_\iota\varepsilon(\lambda_\iota,T_j)$ and $x_1\varepsilon(\lambda_\iota,T_j)$, in the expression for each spectral intensity of Plank's radiation, at temperature T_j. For the definition by the radiation, of the meanings of true temperature without any preliminary calibration, it is necessary not less, than at three meanings of temperature $T_1<T_2<T_3$ to carry out measurements not less than of three spectral components with wave lengths [**/] λ_1,λ_2 and λ_3.

In this case we receive nine equations with nine unknowns: $\xi_1\varepsilon\ (\lambda_1,T_2)$; $\xi_2\varepsilon\ (\lambda_2,T_2)$; $\xi_3\varepsilon\ (\lambda_3,T_2)$; $x_1\varepsilon\ (\lambda_1,T_1)$; $x_2\varepsilon\ (\lambda_2,T_2)$; $\varepsilon\ (\lambda_3,T_2)$; T_1; T_2; T_3.

$$U(\lambda_1,T_1) = \xi_1 C_1\lambda_1^{-5}\varepsilon\ (\lambda_1,T_2)[1-L_{1,1} / x_1\varepsilon\ (\lambda_1,T_2)][(\exp C_2/\lambda_1 T_1) -1]^{-1}$$

$$U(\lambda_1,T_2) = \xi_1 C_1\lambda_1^{-5}\varepsilon\ (\lambda_1,T_2)[(\exp C_2/\lambda_1 T_2) - 1]^{-1}$$

$$U(\lambda_1,T_3) = \xi_1 C_1\lambda_1^{-5}\varepsilon\ (\lambda_1,T_2)[1+L_{1,2} / x_1\varepsilon\ (\lambda_1,T_3)][(\exp C_2/\lambda_1 T_3) -1]^{-1}$$

$$U(\lambda_2,T_1) = \xi_2 C_1\lambda_2^{-5}\varepsilon\ (\lambda_2,T_2)[1-L_{2,1} / x_2\varepsilon\ (\lambda_2,T_2)][(\exp C_2/\lambda_2 T_1) -1]^{-1}$$

$$U(\lambda_2,T_2) = \xi_2 C_1\lambda_2^{-5}\varepsilon\ (\lambda_2,T_2)[(\exp C_2/\lambda_2 T_2)-1]^{-1}$$

$$U(\lambda_2,T_3) = \xi_2 C_1\lambda_2^{-5}\varepsilon\ (\lambda_2,T_2)[1+L_{2,2} / x_2\varepsilon\ (\lambda_2,T_2)][(\exp C_2/\lambda_2 T_3) -1]^{-1}$$

$$U(\lambda_3,T_1) = \xi_3 C_1\lambda_3^{-5}\varepsilon\ (\lambda_3,T_2)[1-L_{3,1} / x_3\varepsilon\ (\lambda_3,T_2)][(\exp C_2/\lambda_3 T_1) -1]^{-1}$$

$$U(\lambda_3,T_2) = \xi_3 C_1\lambda_3^{-5}\varepsilon\ (\lambda_3,T_2)[(\exp C_2/\lambda_3 T_2)-1]^{-1}$$

$$U(\lambda_3,T_3) = \xi_3 C_1\lambda_3^{-5}\varepsilon\ (\lambda_3,T_2)[1+L_{3,2} / x_3\varepsilon\ (\lambda_3,T_2)][(\exp C_2/\lambda_3 T_3) -1]^{-1}$$

We can exclude the spread function, multiplied by emissivity factor from the written equations and receive six equations with six unknowns:

$$U(\lambda_1,T_1) / U(\lambda_1,T_2) = [1-L_{1,1} / x_1\varepsilon\ (\lambda_1,T_2)]\ \{[\exp\ (C_2/\lambda_2 T_2)-1] / [\exp\ (C_2/\lambda_1 T_1)-1]\}$$

$$U(\lambda_1,T_3) / U(\lambda_1,T_2) = [1+L_{1,2} / x_1\varepsilon\ (\lambda_1,T_2)]\ \{[\exp\ (C_2/\lambda_2 T_2)-1] / [\exp\ (C_2/\lambda_1 T_3)-1]\}$$

$$U(\lambda_2,T_1) / U(\lambda_2,T_2) = [1-L_{2,1}/ x_2\varepsilon\ (\lambda_2,T_2)]\ \{[\exp\ (C_2/ \lambda_2 T_2) -1] / [\exp\ (C_2/\lambda_2 T_1)-1]\}$$

$$U(\lambda_2,T_3) / U(\lambda_3,T_2) = [1-L_{2,2} / x_2\varepsilon\ (\lambda_2,T_2)]\ \{[\exp\ (C_2/ \lambda_2 T_2) -1] / [\exp\ (C_2/\lambda_2 T_3)-1]\}$$

$$U(\lambda_3,T_1) / U(\lambda_3,T_2) = [1-L_{3,1} / x_3\varepsilon\ (\lambda_3,T_2)]\ \{[\exp\ (C_2/ \lambda_3 T_2) -1] / [\exp\ (C_2/\lambda_3 T_1) -1]\}$$

$$U(\lambda_3,T_3) / U(\lambda_3,T_2) = [1-L_{3,2} / x_3\varepsilon\ (\lambda_3,T_2)]\ \{[\exp\ (C_2/\ \lambda_3 T_2) -1] / [\exp\ (C_2/\lambda_3 T_3) -1]\}$$

To increase the accuracy, it is necessary to shift spectral intervals. The written equations are transcendental and are simply solved with the help of the computer . However, in special cases they can be solved analytically.

[*/] That temperature dependence is determined by electrical conduction, dielectric constant and magnetic permeance on the radiation frequency.

[**/] Instead of one spectral components one the full radiation be can use, described by Stefan-Boltzman law.

Let's assume, that at three unknown meanings of temperatures the measurement will be made in two spectral intervals in Wien's region and two in intervals of Rayleigh-Jeans region, i.e. we will have 12 equations and 9 unknowns.

With six spectral components of Wien's region for T_1,T_2 and T_3 we shall take the logarithms of the relations (1) - (4):

$$\ln[U(\lambda_1,T_1) / U(\lambda_1,T_2)] =-[L_{1,1} / x_1\varepsilon(\lambda_1,T_2)]-[(T_1-T_2)C_2/T_1T_2\lambda_1] \quad (1)$$

$$\ln[U(\lambda_1,T_2) / U(\lambda_1,T_3)=+[L_{1,2} / x_1\varepsilon(\lambda_1,T_2)]-[(T_2-T_3)C_2/T_1T_2\lambda_1] \quad (2)$$

$$\ln[U(\lambda_2,T_1) / U(\lambda_2,T_2)=-[L_{2,1} / x_2\varepsilon(\lambda_2,T_2)]-[(T_1-T_2)C_2/T_1T_2\lambda_2] \quad (3)$$

$$\ln[U(\lambda_2,T_2) / U(\lambda_2,T_3)=+[L_{2,2}/x_2\varepsilon(\lambda_2,T_2)]-[(T_2-T_3)C_2/T_2T_3\lambda_2] \quad (4)$$

Excluding the members with the differences of back meanings of temperatures from the equations (1) - (4), we receive two equations with two unknowns: $x_1\varepsilon(\lambda_1,T_2)$ and $x_2\varepsilon(\lambda_2,T_2)$:

$$\lambda_1\ln[U(\lambda_1,T_1) / U(\lambda_1,T_2)]+\lambda_2\ln[U(\lambda_2,T_2) / U(\lambda_1,T_1)] = [L_{2,1}/ x_2\varepsilon (\lambda_2,T_2)]-[L_{1,1}/ x_1\varepsilon (\lambda_1,T_2)] =A$$

$$\lambda_1\ln[U(\lambda_1,T_2) / U(\lambda_1,T_3)]+\lambda_2\ln[U(\lambda_2,T_3) / U(\lambda_2,T_2)] = [L_{1,2}/ x_1\varepsilon (\lambda_1,T_2)]-[L_{2,2}/ x_2\varepsilon (\lambda_2,T_2)] =B$$

Solving these equations we can determine $x_1\varepsilon (\lambda_1,T_2)$ and $x_2\varepsilon (\lambda_2,T_2)$:

$$x_1\varepsilon (\lambda_1,T_2) = [(L_{2,1}L_{1,2} -L_{2,2}L_{1,1})\lambda_1] / (AL_{2,2}+BL_{2,1})$$

$$x_2\varepsilon (\lambda_2,T_2) = [(L_{2,1}L_{1,2} -L_{2,2}L_{1,1})\lambda_2] / (AL_{1,2}+BL_{1,1})$$

In Rayleigh-Jeans region the relation of signals can be written , as:

$$U(\lambda_3,T_1) / U(\lambda_3,T_2) = \{1-L_{3,1} / [x_3\varepsilon (\lambda_3,T_2)]\}\ T_1/ T_2$$

$$U(\lambda_3,T_3) / U(\lambda_3,T_2) = \{1+L_{3,2} / [x_3\varepsilon (\lambda_3,T_2)]\}\ T_3/T_2$$

$$U(\lambda_4,T_1) / U(\lambda_4,T_2) = \{1-L_{4,1} / [x_4\varepsilon (\lambda_4,T_2)]\}\ T_1/T_2$$

$$U(\lambda_4,T_3) / U(\lambda_4,T_2) = \{1+L_{4,2} / [x_4\varepsilon (\lambda_4,T_2)]\}\ T_3/T_2$$

Excluding the relation of temperatures T_1/T_2 and T_3/T_2 from the written expressions we shall receive two equations for D and E:

$$\begin{aligned}\{x_4\varepsilon (\lambda_4,T_2)\ [x_3\varepsilon (\lambda_3T_2) -L_{3,1}]\} / \{x_3\varepsilon (\lambda_3,T_2)\ [x_4\varepsilon (\lambda_4,T_2) -L_{4,1}]\}\\ = [U (\lambda_3,T_1)U (\lambda_4,T_2)] / [U (\lambda_3,T_2)U (\lambda_4,T_1)] = D\end{aligned}$$

$$\begin{aligned}\{x_4\varepsilon (\lambda_4,T_2)\ [x_3\varepsilon (\lambda_3,T_3)+L_{3,2}]\} / \{x_3\varepsilon (\lambda_3,T_2)[x_4\varepsilon (\lambda_4,T_2)+L_{4,2}]\}\\ = [U (\lambda_3,T_1)U (\lambda_4,T_2)] / [U (\lambda_3,T_2)U (\lambda_4,T_3)] = E\end{aligned}$$

Solving together the equations for D and E, we determine the meanings $x_3\varepsilon(\lambda_3,T_2)$ and $x_4\varepsilon(\lambda_4,T_2)$ in Rayleigh-Jeans region as:

$$x_3\varepsilon (\lambda_3,T_2) = [DL_{4,1}+EL_{4,2}L_{3,1}] / [DL_{4,1}+L_{4,2}(1-D)]E$$

and

$$x_4\varepsilon (\lambda_4,T_2) = [Dx_3\varepsilon (\lambda_3,T_2)L_{4,1}] / [x_3\varepsilon(\lambda_3,T_2)(1-D)] -L_{3,1}$$

Substituting the meaning $x_3\varepsilon(\lambda_3,T_2)$ in the initial equations for the relations of signals in Rayleigh-Jeans region, for example, in the equation for $[U(\lambda_3,T_2)] / [U(\lambda_3,T_3)]$ we receive the meaning of the relation of temperatures T_2/T_3

$$T_2/ T_3 =\{1+\{L_{3,2}[DL_{4,1}+L_{4,2}(1-D)]E\}/(DL_{4,1}+EL_{4,2}L_{3,1})\}\}[U(\lambda_3,T_2)/U(\lambda_3,T_3)]=G \quad (5)$$

To calculate the unknown meanings of temperatures we re write the equation (2) for the Wien's region and devoid numerator and denominator of the member, which represents the difference of the back meanings of T_2, T_3 on T_3 :

$$\ln[U(\lambda_1,T_3)/U(\lambda_1,T_2)] - [L_{1,2}/x_1\varepsilon(\lambda_1,T_2)] = -[(T_3-T_2)C_2/T_2T_3\lambda_2] = [(1-T_2/T_3)C_2]/T_2\lambda_2$$

We put the meaning $T_2/T_3=G$ from (5) in this equation and find T_2 and T_3:

$$T_2 = [(1-G)C_2]/\lambda_2\{\ln[U(\lambda_1,T_3)/U(\lambda_1,T_2)] - [L_{1,2}/x_1\varepsilon(\lambda_1,T_2)]\}$$

$$T_3 = [(1-G)C_2]/\lambda_2\{\ln[U(\lambda_1,T_3)/U(\lambda_1,T_2)] - [L_{1,2}/x_1\varepsilon(\lambda_1,T_2)]\}G$$

getting T_2 in equation (1) the meaning of T_1:

$$T_1 = [(1-G)C_2]/\{\lambda_2[\ln[U(\lambda_1,T_3)/U(\lambda_1,T_2)] - L_{1,2}/x_1\varepsilon(\lambda_1,T_2)] + \lambda_1/\lambda_2(1-G) \\ \times\{\ln[U(\lambda_1,T_1)/U(\lambda_1,T_2)] + L_{1,1}/x_1\varepsilon(\lambda_1,T_2)\}\{\ln[U(\lambda_1,T_3)/U(\lambda_1,T_2)] - L_{1,2}/x_1\varepsilon(\lambda_1,T_2) \\ \}^{-1}$$

So, the method allows to determine the true temperature of object with the unknown spectral emissivity. The preliminary calibration of pyrometer is excluded. That's why this method can design the thermodynamic temperature scale without using of the black body.

If is interesting, that in "such form" the method cannot determine neither spread function nor spectral emissivity.

To do this the relative reflectometry can be used.
Really let:

$$\varepsilon(\lambda_1,T_1) = \varepsilon(\lambda_1,T_2) + {}_{\Delta}\varepsilon_{1,1}$$

$$\varepsilon(\lambda_1,T_3) = \varepsilon(\lambda_1,T_2) + {}_{\Delta}\varepsilon_{1,2}$$

$$A_1 = 1-[\rho^*(\lambda_1,T_1)/\rho^*(\lambda_1,T_2)] = {}_{\Delta}\varepsilon_{1,2}/[1-\varepsilon(\lambda_1,T_2)] \qquad (6)$$

$$A_2 = 1-[\rho^*(\lambda_1,T_3)/\rho^*(\lambda_1,T_2)] = {}_{\Delta}\varepsilon_{1,2}/[1-\varepsilon(\lambda_1,T_2)] \qquad (7)$$

$$B_1 = 1-[\rho^*(\lambda_2,T_1)/\rho^*(\lambda_2,T_2)] = {}_{\Delta}\varepsilon_{2,1}/[1-\varepsilon(\lambda_2,T_2)] \qquad (8)$$

$$B_2 = 1-[\rho^*(\lambda_2,T_3)/\rho^*(\lambda_2,T_2)] = {}_{\Delta}\varepsilon_{2,2}/[1-\varepsilon(\lambda_2,T_2)] \qquad (9)$$

For spectral components we can write two equations, based on Wien's relations:

$$J_1=[U(\lambda_1,T_1)/U(\lambda_1,T_2)]/[U(\lambda_2,T_1)/U(\lambda_2,T_2)]^z=[1+{}_{\Delta}\varepsilon_{1,1}/\varepsilon(\lambda_1,T_2)]/[1+{}_{\Delta}\varepsilon_{1,2}/\varepsilon(\lambda_2,T_2)]^z \qquad (10)$$

$$J_2=[U(\lambda_1,T_3)/U(\lambda_1,T_2)]/[U(\lambda_2,T_3)/U(\lambda_2,T_2)]^z=[1+{}_{\Delta}\varepsilon_{1,2}/\varepsilon(\lambda_1,T_2)]/[1+{}_{\Delta}\varepsilon_{2,2}/\varepsilon(\lambda_2,T_2)]^z \qquad (11)$$

Where: $z = \lambda_2/\lambda_1$

The solution of the equations (6) - (11) can give the unknown meanings of the spectral emissivities, which together with the meanings of T_1, T_2 and T_3, determined above, can give the possibility to find the spread function or in the other words to calibrate the pyrometer.

The problem can be solved very simple, if for example, $\lambda_2=2\lambda_1$.

The meanings $\varepsilon(\lambda_1,T_2)$ and $\varepsilon(\lambda_2,T_2)$ could be found from square equation.

In one case, when temperature dependency of one of spectral emissivities of the surface in Wien region is linear, which means that $[\partial^2\varepsilon_1(\lambda_1,T)]/\partial T^2 = 0$ for finding 3 meaning of temperatures it is enough to make measurements in three spectral intervals of only Wien region.
Finding from (6) - (11) the meanings of emissivitie's factors and ${}_{\Delta}\varepsilon_1$ itself, we can write the following equation:

$$R=\ln\{[U(\lambda_1,T_1)/U(\lambda_1,T_2)][\varepsilon(\lambda_1,T_2)/\varepsilon(\lambda_1,T_1)]\}/\ln\{[U(\lambda_1,T_3)/U(\lambda_1,T_2)][\varepsilon(\lambda_1,T_3)/\varepsilon(\lambda_1,T_2)]\} \\ = [(T_2-T_1)/(T_3-T_2)](T_3/T_1)$$

From the other hand:

$${}_{\Delta}\varepsilon_{1,1} / {}_{\Delta}\varepsilon_{1,2} = \alpha_1(T_2-T_1) / \alpha_1(T_3-T_1)$$

Dividing the equations one by another we receive: ${}_{\Delta}\varepsilon_{1,1} / {}_{\Delta}\varepsilon_{1,2}$ R $= T_3 / T_1 =$ ð

Then using equations (1), (2) we can find the meanings of true temperatures:

$$T_3 = (\text{ð}-1)\text{Ñ}_2 / \lambda_1 \ln\{[U(\lambda_1,T_1)\varepsilon(\lambda_1,T_3)] / [U(\lambda_1,T_3)\varepsilon(\lambda_1,T_1)]\ ;$$

$$T_1 = \text{ð}^{-1} T_3\ ;$$

$$T_2 = T_1 / \{1+(\lambda_1 T_1) / C_2 \ln[U(\lambda_1,T_1)\varepsilon(\lambda_1,T_2) / U(\lambda_1,T_2)\varepsilon(\lambda_1,T_1)]\}$$

So it is clear, that this method can build the termodynamic temperature scale without black body, using only Wien's region.

We can remind, that for the construction of thermodynamic temperature scale of the black body using Woolfson's method [2], it is necessary to use the second region of Plank emission with $\lambda T>3000$ ìêì.ãðàä.

The proposed method is perspective for the measurements of the spectral emissivity.

This method can be extensively used for fast pulse radiation thermometry, where the capacity of the redundant temperature information is too large.

It is sense to realize this method with the lasers as an extraneous source.

The computer testing of this method gave positive results.

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