XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22–27, 2003, Dubrovnik, Croatia

DYNAMIC METHOD OF MEASURING THE TRUE TEMPERATURE AND EMISSIVITY BY DIRECTIONAL REFLECTED AND SELF-RADIATION

Dariy Svet

Institute of High Temperatures,
Russian Academy of Sciences (IVTAN), Moscow, Russia

Abstract: The paper deals with the method of on line radiation measurement of the true temperature and emissivity in the process of heating or cooling. The method may be realized without any precalibration. The realization of the method is based on simultaneous measurement of the intensities of self-radiation and of directional reflected radiation on two wavelengths for three values of temperature. The method involves the use of relative directional reflectometry which does not require the validity of the Lambert law for radiating surface. For the method to be realized in practice, the accuracy of radiometric and reflectometric measurements must be significantly increased.

1. INTRODUCTION

The main problem associated with radiation pyrometry of real bodies is the elimination of the effect of emissivity on the measurement results.

Present-day metrologists reduced the error of measurement in the range of two and more thousand Kelvin's to tens of millikelvins; however, in practical thermometry, when performing radiation measurements of real nonblack bodies, this error increases hundreds and thousands times. At present, two ways are known of solving this problem.

The first way is based on the use of an outside source of radiation, and the second way is based on the utilization of the redundancy of information contained in the spectrum of thermal radiation of the body.

To some extent, the method treated in this presentation covers both ways.

In [1, 2], we have demonstrated the fundamental possibilities of measuring the true temperature of a real nonblack body by its radiation on the processes of heating or cooling. The main difficulty of practical realization of this method consists in the need for a very high signal-to-noise ratio.

In [3, 4], the use of relative laser reflectometry in this method was described; as a result, the required number of spectral components could be drastically reduced (to just two, as a matter of fact), and a fairly simple way was suggested for on-line measurement of spectral emissivity.

In this presentation, a possible development of this method is considered. In particular, it is shown that it may be realized for measuring the emissivity without precalibration. Moreover, the values of true temperature may be determined simultaneously with those of emissivity in the case when the temperature dependence of the latter is linear and the accuracy of radiometric and reflectometric measurements is high enough.

Note that known publications, for example, [5, 6], have demonstrated the presence of the linear dependence of emissivity, at least, for metals in fairly wide temperature ranges.

The error of radiometric measurements (ca. $\sim 10^{-5}$--10^{-4}), recently reached in metrology, is also sufficient for the method of temperature measurement under consideration.

2. METHOD

From the physical standpoint, the method of [1] is based on the utilization of the variations of the properties of substances, which are embodied in the variation of the emissivity of the components of thermal radiation spectrum with temperature.

We will write the radiometric signals $U(\lambda_\iota,T_j)$ from the surface of unknown emissivity $\varepsilon(\lambda_\iota,T_j)$ for two wavelengths λ_1 and λ_2 and three unknown values of temperature $T_1<T_2<T_3$ in the Wien region, i.e., at $\lambda_{max}T_{max} \leq 3000$ mcm deg.

$$U(\lambda_1,T_1) = \xi_1\lambda_1^{-5}\, C_1\varepsilon(\lambda_1,T_1)\exp-(C_2 / \lambda_1T_1)$$

$$U(\lambda_2,T_2) = \xi_1\lambda_1^{-5}\, C_1\varepsilon(\lambda_1,T_2)\exp-(C_2 / \lambda_1T_2)$$

$$U(\lambda_1,T_3) = \xi_1\lambda_3^{-5}\, C_1\varepsilon(\lambda_1,T_3)\exp-(C_2 / \lambda_1T_3)$$

$$U(\lambda_2,T_1) = \xi_2\lambda_2^{-5}\, C_1\varepsilon(\lambda_2,T_1)\exp-(C_2 / \lambda_2T_1)$$

$$U(\lambda_2,T_2) = \xi_2\lambda_2^{-5}\, C_1\varepsilon(\lambda_2,T_2)\exp-(C_2 / \lambda_2T_2)$$

$$U(\lambda_2,T_3) = \xi_2\lambda_2^{-5}\, C_1\varepsilon(\lambda_2,T_3)\exp-(C_2 / \lambda_2T_3)$$

where ξ_1 and ξ_2 - are instrument constants.

The logarithms of the ratios of these signals will be

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

$$\ln[U(\lambda_1,T_2) / U(\lambda_1,T_3)]= = -C_2 / \lambda_1[(T_3-T_2) /(T_2T_3)]+\ln[\varepsilon(\lambda_1,T_2) / \varepsilon (\lambda_1,T_3) \quad (2)$$

$$\ln[U(\lambda_2,T_1)/U(\lambda_2,T_2)]=$$
$$=-C_2/\lambda_2[(T_2-T_1)/(T_1T_2)]+\ln[\varepsilon(\lambda_2,T_1)/\varepsilon(\lambda_2,T_2)] \quad (3)$$
$$\ln[U(\lambda_2,T_2)/U(\lambda_2,T_3)]=$$
$$=-C_2/\lambda_2[(T_3-T_2)/(T_2T_3)]+\ln[\varepsilon(\lambda_2,T_2)/\varepsilon(\lambda_2,T_3)] \quad (4)$$

We raise each one of Eqs. (1)-(4) to the power with the exponent equal to the dimensionless value corresponding to the wavelength (λ_{01} or λ_{02}), after which we can write the ratios of the difference of expressions (1), (3) and (2), (4) in the form

$$\ln[U(\lambda_1,T_1)/U(\lambda_1,T_2)]^{\lambda01}-\ln[U(\lambda_2,T_1)/U(\lambda_2,T_2)]^{\lambda02}=I_1$$

$$\ln[U(\lambda_1,T_3)/U(\lambda_1,T_2)]^{\lambda01}-\ln[U(\lambda_2,T_3)/U(\lambda_2,T_2)]^{\lambda02}=I_2$$

After opening the left-hand parts of these two equations, we can write

$$\lambda_{01}\ln[\varepsilon(\lambda_1,T_1)/\varepsilon(\lambda_1,T_2)]-\lambda_{02}\ln[\varepsilon(\lambda_2,T_1)/\varepsilon(\lambda_2,T_2)]=I_1 \quad (5)$$

$$\lambda_{01}\ln[\varepsilon(\lambda_1,T_3)/\varepsilon(\lambda_1,T_2)]-\lambda_{02}\ln[\varepsilon(\lambda_2,T_3)/\varepsilon(\lambda_2,T_2)]=I_2 \quad (6)$$

A laser reflectometer built in such a bichromatic pyrometer measures, on the same wavelengths, the coefficients of directional reflection $\rho^*(\lambda_1,T_1)$, $\rho^*(\lambda_1,T_2)$, $\rho^*(\lambda_1,T_3)$, $\rho^*(\lambda_2,T_1)$, $\rho^*(\lambda_2,T_2)$, $\rho^*(\lambda_2,T_3)$ and enables one to form the following relations:

$$\rho^*(\lambda_1,T_1)/\rho^*(\lambda_1,T_2)=x_1\rho(\lambda_1,T_1)/x_1\rho(\lambda_1,T_2)$$

$$\rho^*(\lambda_1,T_2)/\rho^*(\lambda_1,T_3)=x_1\rho(\lambda_1,T_2)/x_1\rho(\lambda_1,T_3)$$

and

$$\rho^*(\lambda_2,T_1)/\rho^*(\lambda_2,T_2)=x_2\rho(\lambda_2,T_1)/x_2\rho(\lambda_2,T_2)$$

$$\rho^*(\lambda_2,T_3)/\rho^*(\lambda_2,T_2)=x_2\rho(\lambda_2,T_3)/x_2\rho(\lambda_2,T_2)$$

Here, $\rho(\lambda_1,T_1)$, $\rho(\lambda_1,T_2)$, $\rho(\lambda_1,T_3)$, $\rho(\lambda_2,T_1)$, $\rho(\lambda_2,T_2)$ и $\rho(\lambda_2,T_3)$ are coefficients of normal reflection, and x_1 and x_2 are coefficients defined by the surface roughness.

If the surface satisfies the Lambert law, $x_1 = x_2 = 1$.

Based on the Kirchhoff law for nontransparent surface,

$$\rho^*(\lambda_\iota,T_1)/\rho^*(\lambda_\iota,T_2)=[1-\varepsilon(\lambda_\iota,T_1)]/[1-\varepsilon(\lambda_\iota,T_2)]=1-$$
$$-{}_\Delta\varepsilon_\iota/[1-\varepsilon(\lambda_\iota,T_2)]$$

where ${}_\Delta\varepsilon_\iota=\varepsilon(\lambda_1,T_1)-\varepsilon(\lambda_1,T_2)$

Now, we can write

$$A_1=1-\rho^*(\lambda_1,T_1)/\rho^*(\lambda_1,T_2)={}_\Delta\varepsilon_1/[1-\varepsilon(\lambda_1,T_2)] \quad (7)$$

$$A_2=1-\rho^*(\lambda_1,T_2)/\rho^*(\lambda_1,T_3)={}_\Delta\varepsilon_2/[1-\varepsilon(\lambda_1,T_2)] \quad (8)$$

$$B_1=1-\rho^*(\lambda_2,T_1)/\rho^*(\lambda_2,T_2)={}_\Delta\varepsilon_3/[1-\varepsilon(\lambda_2,T_2)] \quad (9)$$

$$B_2=1-\rho^*(\lambda_2,T_2)/\rho^*(\lambda_2,T_3)={}_\Delta\varepsilon_4/[1-\varepsilon(\lambda_2,T_2)] \quad (10)$$

We have derived six equations (5)-(10) for determining six unknown values of emissivity,

$$\varepsilon(\lambda_1,T_1),\ \varepsilon(\lambda_1,T_2),\ \varepsilon(\lambda_1,T_3) \quad \text{and}$$
$$\varepsilon(\lambda_2,T_1),\ \varepsilon(\lambda_2,T_2),\ \varepsilon(\lambda_2,T_3)$$

Naturally, a computer is used for solution.

However, given the ratio between the wavelengths of λ_1, λ_2 and $\lambda_2/\lambda_1=2$, the analytical solution for emissivity has the form of quadratic equation.

For example, for $\varepsilon(\lambda_2,T_2)$,

$$\varepsilon(\lambda_2,T_2)^2[I_1(1-B_1)^2+I_2A_1/A_2(1+B_2)^2-(1+A_1/A_2)]+$$
$$+\varepsilon(\lambda_2,T_2)[2I_1B_1(1-B_1)-2A_1/A_2B_2(1+B_2)+(I_1B_1^2+I_2A_1/A_2B_2)=0 \quad (11)$$

On determining all six values of emissivity from Eqs. (1)-(4), we can readily find the differences of the reciprocal temperature values,

$$\theta_1=(T_2-T_1)/T_1T_2 \quad (12)$$

$$\theta_2=(T_3-T_2)/T_2T_3 \quad (13)$$

We write the above-formulated condition of linearity of the temperature dependence of emissivity as

$${}_\Delta\varepsilon_1=\alpha_1(T_2-T_1)$$

$${}_\Delta\varepsilon_2=\alpha_1(T_3-T_2)$$

$${}_\Delta\varepsilon_3=\alpha_2(T_2-T_1)$$

$${}_\Delta\varepsilon_4=\alpha_2(T_3-T_2)$$

Then, any of the relations

$${}_\Delta\varepsilon_1/{}_\Delta\varepsilon_2=(T_2-T_1)/(T_3-T_2)=P \quad (14)$$

or

$${}_\Delta\varepsilon_3/{}_\Delta\varepsilon_4=(T_2-T_1)/(T_3-T_2)=P \quad (15)$$

may be used simultaneously with Eqs. (12) and (13) to determine the true vales of temperatures T_1, T_2, and T_3 from the following three equations:

$$T_2=(\theta_1-\theta_2P)/\theta_1\theta_2(1+P) \quad (16)$$

$$T_1=T_2/(1+\theta_1T_2) \quad (17)$$

$$T_3=[\theta_1T_2^2(1+P)+PT_2]/(P-\theta_1T_2) \quad (18)$$

One can readily demonstrate that, given the correlation $|\alpha_\iota(T_3-T_1)|<<1$, Eqs. (14) and (15) may be derived from expressions for self-radiation as well. These equations may be used for some check of the "correctness" of the measurements performed.

In view of the rather weak temperature dependence of emissivity, in realizing this method one must take into account the effect of the temperature-induced variation of the values of effective wavelengths on the results of measurements.

It was demonstrated in [3] that, based on the findings of [7, 8], this effect may be eliminated.

3. CONCLUSIONS

1. In [3, 4], examples of tungsten, tantalum, and rhenium were used to demonstrate that, with precalibration, the suggested method employing a built-in reflectometer enables one to determine the spectral emissivity with an error of < 6-8%. In the absence of precalibration, the requirements of the signal-to-noise ratio are significantly toughened.
2. A computer check of the method reveals that, for a signal-to-noise ratio of $>5\cdot10^3$, the suggested method enables one to determine the true temperature in the range of 2000 K with an error of ≤1%.

REFERENCES

[1] D.Ya.Svet, “ A Radiation Method for the Determination of the True Temperature and emissivity of Materials, and Realization of the Thermodynamic Temperature Scale without Use of a Black Body”, *Doklady Physics,* 1999, v.4 no 8 p.552 (Official English Translation of Doklady Academy Nauk v.367, no.4-6 August 1999).

[2] D.Ya.Svet Trans.IMEKO-15 World Congress 1999, v.7, tc-12, p.167, Osaka.

[3] D.Ya. Svet, Doklady Physics 2000, v.45, # 6, p.281 (Translated from Doklady Academy Nauk 2000, v.372, #5, p.622).

[4] D.Ya. Svet, Proceedings 8-th International Symposium on Temperature and Thermal Measurements in Industry and Science, v.1, p.289, Berlin.

[5] Radiating Properties of Materials (Edited by A.E.Sheindlin), Moscow, Nauka 1974.

[6] Y.S.Toulookian Thermophisical Properties of High Temperatures Solid Materials N.Y.MacMillan Co. 1967, v.1

[7] P.B.Coates, Metrologia, 1977, 13, 1.

[8] D.Ya.Svet and O.R.Popova, Metrologia (Russia), 1986, #3, p.56.

Author: Dariy Ya. Svet, Professor, Dr. of Engineering, Head of Laboratory of Radiation Pyrometry at the Institute of High Temperatures, Russian Academy of Sciences, Moscow, Russia.
Address: Apt.17, Building 3, Fersmana str, Moscow, 117312, Russia
Phone: (095) 124 83 75
Fax: (095) 9537100
E-mail: **svet_dya@mtu-net.ru**