Combined Method of Radiation Pyrometry in Material Science

Konstantin Ludanov

Institute for Problem of Material Science NAS of Ukraine
3 Krzhizhanovsky str., Kyiv-142, Ulraine, 03680

Abstract: Mathematical modeling is proposed measurement procedure combined method for radiation pyrometry stalemate. Patent UA number 63080A, which includes the joint determination of the true temperature and emissivity integral substances, which makes it possible to determine the point of phase transitions and structural transformations.

Keywords: pyrometric method, brightness temperature, color temperature, radiation temperature, energy of partial radiation, quasi series surface.

Introduction

In modern materials science is a very important task of measuring high temperatures, such as in determining the melting points of refractory materials and their compounds. If for this purpose cannot be used thermionic thermometers (thermocouples), the only possibility - pyrometry [1,2,3]. However, all the traditional methods of measuring high temperature pyrometer have one fundamental drawback: the measurement result is not the absolute temperature, and a certain "quasi temperature" ("radiation", "brightness" or "color"), for which the conversion to absolute temperature (true) must a priori have a value of surface emissivity. Most of these data are not available or they are extremely unreliable, so the pyrometric measurements melting temperature refractory materials must also determine emissivity $\bar{\varepsilon}(T)$ of the surface. Existing methods for measuring the emissivity of the very complex and expensive, so is a very topical problem of the development of combined methods pyrometry, which simultaneously determines the two unknown quantities: the absolute temperature (true) surface and its actual problem is the development of combined methods of pyrometry, which simultaneously determines the two unknown quantities: the absolute temperature (true) surface and its emissivity**.**

Author of this article received a patent of Ukraine "Combined method radiation pyrometry" for number 63080A in which this problem is solved by conducting two parallel pyrometric measurements:

1) "radiation" temperature - the full energy spectrum of radiation and

2) energy "partial radiation" - a limited part of the spectrum of radiation from the surface: 0 to λ_L. These two measurements are necessary and sufficient to solve the problem with two unknowns: T (K) and $\bar{\varepsilon}(T)$.

This article presents the mathematical modeling of the measurement procedure "Combined radiation pyrometry method", which is a so-called "indirect way to measure", i.e. way to the joint determination of two values: valid surface temperature and its emissivity.

Literature review

Theoretical basis of radiation pyrometry became Stefan-Boltzmann law $E(T) = \sigma T^4$, Stephen empirically established in 1879 and theoretically grounded Boltzmann in 1884, [4]. However, the first pyrometer, invented by Le Chatelier in 1892, was not based on the integral, and spectral patterns of thermal radiation, although Wien's formula to be used as a theoretical basis for such pyrometers, was installed later, in 1896, already use optical Le Chatelier pyrometer showed that optical pyrometer (however, as well as radiation) as a result of measurements allows to obtain not the absolute value of the temperature, and a kind of "pseudo-temperature": brightness, color or radiation ($T_R = {}^4\sqrt{(E_\infty/\sigma)}$), to convert that into true need a priori knowledge emissivity ε. First attempt to solve this problem by using the missing equation to close the system of equations in the form of the dispersion curve of emissivity of the flame (in accordance with the Bouguer law) was first raised in 1889 Angstrom when assessing the true temperature of the flame of candles.

When measuring temperatures by radiation pyrometry radiating surface is usually presented as a "gray" with $\varepsilon(\lambda) \equiv$ const. Last dependence can also be interpreted as the missing dispersion equation and the methods of optical pyrometry and if the method is to use "color" pyrometry (including measurement of the brightness of radiation at two wavelengths), one can easily determine the true temperature of the surface, not exactly knowing the absolute value of emissivity ε. Although known materials which can be called is "gray" (for example, silicon carbide, for which $\varepsilon(\lambda) \cong$ const $\cong 0,8$), but in general, the vast majority of surface materials emits selectively and at best can be interpreted only as "quasi series", i.e. one for which the equality $\bar{\varepsilon}(0\text{-}\lambda_q) \cong \bar{\varepsilon}_\infty$.

The published studies on the experimental determination of the phase transitions of new refractory materials by the method of thermal analysis [5,6,7] typically use the fact that at the transition point of the liquid to the solid phase transition latent heat is released, and the cooling curve of the sample at this point has characteristic "shelf" T_m = const, which is fixed and luminance pyrometer (usually λ = 0,65 µm). However, in many latent heat phase transition phase transition little or no. Therefore the problem of finding new ways of contactless temperature measurement phase and structural transformations refractory materials based on the use of other physical mechanisms for their registration.

Statement of the problem

In materials science is a very topical problem of accurate determination of phase transition temperatures and structural transformations of new refractory materials and the problem of controlling the process parameters implement highly accelerated thermal treatment regimens their surface. At the moment [8] in the world uses the International Temperature Scale ITS-90, which includes eleven major reference points (melting point of pure substances, which are known for the exact values of temperature), and describes the temperature range up to 10 000K. In accordance with the ITS-90 temperature scale primary standard for temperatures above the melting point of gold (1064.4 °C) passed laws of blackbody radiation (BB), although the standard thermocouples domestic production (for example, tungsten-rhenium) can measure temperatures up to 2.5 000°C.

Radiation pyrometers can be used for measuring high temperatures up to ~3.5 000°C. They are divided into pyrometers total (complete) and the radiation pyrometer of partial radiation pyrometer first type of heat sink to absorb the whole wavelength range of the radiation, and the second - just a part thereof, e.g. in the wavelength range $0-\lambda_q$. As radiation detectors radiation pyrometers are used thermionic batteries (thermopile) and bolometers (RTD), receiving surface which has a strongly absorbing coating, usually cobalt oxide. To create a bandwidth $0-\lambda_q$ in the partial radiation pyrometer uses special filters, for example, well-known fact [9] that the bandwidth of un cooled S-Hb photo resistor located in the spectral range from λ = 0–3.5 µm.

In accordance with the Stefan-Boltzmann law for the total radiation $E_\infty = \sigma T^4$, E_q same dependence for a blackbody is much more complex:

$$E_q = 15\sigma(T/\pi)^4 \int_0^{\lambda_q} e(\lambda T)d\lambda, \qquad e(\lambda T) = C_1/\{\lambda^5[exp(C_2/\lambda T) - 1]\}.$$

Since the integral on the right-hand side of this expression is not "taken" as if $e(\lambda T)$ use the exact expression of Planck, it is usually used here approximate formula wines, which gives an error of less than 1% if $\lambda \cdot T \leq 3,0$ mm·K. In this case, the expression of the E_q is integrated, and the result of integration is obtained in "quadrature", he has the following form:

$$E_q = 15\sigma(T/\pi)^4[(C_2/\lambda T)^3 + 3(C_2/\lambda T)^2 + 6(C_2/\lambda T) + 6]exp(-C_2/\lambda T).$$

For the spectral range of $2 - 5$ microns, and a temperature range of 500 - 800 K the $E_q = f(T)$ was investigated in [10], and as a local approximation for this expression was adopted dependence $E_q \sim const \cdot T^p$, which has been previously this purpose [9]. Author [9] showed experimentally in the study as a filter S-Pb un cooled photo-resistance $\lambda \approx 3,5$ µm, in the formula p > 4. Has been found that at temperatures of 200 - 1000 °C the value of p = 8 ÷ 12. So, the methodical error of temperature measurement method for detecting partial radiation $\delta T = 1 - \sqrt[p]{\varepsilon}$, where ε − emissivity) is smaller than the total radiation method. However, the most widely used as a radiation pyrometers partial radiation filters which have band width, $\lambda_1 - \lambda_2$ where $\lambda_1 \neq 0$. In this case, the ΔE_q can be expressed analytically in the approximation of wines as follows:

$$\Delta E_q = 15\sigma(T/\pi)^4\{[(C_2/\lambda_2 T)^3 + 3(C_2/\lambda_2 T)^2 + 6(C_2/\lambda_2 T) + 6]exp(-C_2/\lambda_2 T) -$$
$$- [(C_2/\lambda_1 T)^3 + 3(C_2/\lambda_1 T)^2 + 6(C_2/\lambda_1 T) + 6]exp(-C_2/\lambda_1 T)\}$$

Analysis of the above expressions for the E_q of different spectral regions shows that they are all quite complex and present them in the form of analytical inverse function required to calculate the temperature of the partial energy radiation, ie as $(\lambda T)/C_2 = \varphi(E_q)$ is not possible. In this situation use a combination of the two measurements (patent 63080A): measurement of the entire spectrum of energy and energy "partial radiation" calculating their relationship $E_q/E_\infty = F_{0-\lambda T}$ - and determining the true temperature T based on the analysis of the expression $F_{0-\lambda T}(\lambda T)$. Thus, the aim of this work is to solve the problem of constructing an algorithm accurately

calculate the true temperature T and ε on the results of two parallel measurements of the radiation flux from the heated surface (the full range of energy and energy "partial radiation"), emissivity which a priori unknown.

Results

1. Combined method of radiation pyrometry

In "quasi series" approximation ratio of the energy spectrum of the E_q to the total energy spectrum E_∞ thermal radiation selectively radiating surface than $F_{0-\lambda T} = E_q/E_\infty$ – partial fraction of the energy of radiation in the flow of the total radiation blackbody. Function $F_{0-\lambda T}$ is a function of blackbody radiation in the spectral range. This is a standard blackbody, it is tabulated and given in almost all textbooks of radiative heat transfer. Moreover, fundamental publication [8] are approximations $F_{0-\lambda T} - \mu$ for two spectral ranges variable $\vartheta = C_2/\lambda T$: $\vartheta \in (0-2)$ and $\vartheta_2 \in (2-\infty)$ – which recommends Wilbert polynomials, for example, for $\vartheta < 2$:

$$F_{o-\lambda T} = 1 - 15(\vartheta^3/\pi^4)[1/3 - \vartheta/8 + \vartheta^2/60 - \vartheta^4/5040 + \vartheta^6/272160 - \vartheta^8/13305000],$$

$$F_{o-\lambda T} = 15/\pi^4 \sum_{m=1,2}^{\infty} m^{-4} exp(-m\vartheta)\{[(m\vartheta + 3)m\vartheta + 6]m\vartheta + 6\}, \quad \vartheta \geq 2.$$

These expressions do not allow us to obtain an analytical dependence $\lambda T/C_2 = \vartheta^{-1} = \varphi(F_{0-\lambda T})$ explicitly, but the analysis shows that for unambiguous dependence $T = f(E_q)$ must not take the absolute value of the E_q and the ratio of the $E_q/E_\infty = F_{0-\lambda T}$ and thus it is now easy to understand the idea of combined radiation pyrometry method patented in number 63080A. For unambiguous dependence $\lambda T/C_2 = \varphi(F_{o-\lambda T})$ - is necessary and sufficient to carry out only two pyrometric measurement: partial radiation flux E_q (with a light filter) and total radiation flux E_∞ (without filter) and calculate the ratio of the $E_q/E_\infty = F_{o-\lambda T} \equiv F_q$. In this case it is possible to obtain an unambiguous relationship for T:

$$T = (C_2/\lambda_q) \cdot \varphi(F_q).$$

As has been shown above that by elementary transformations to obtain a simple expression for the $\varphi(F_q)$ is not possible, you can take the next step: to expand the function $F_{o-\lambda T}$ in Taylor series. It seems that the most appropriate as the coordinates of the expansion is the inflection point graphics $F_{o-\lambda T} = f(\lambda T)$, which corresponds to the maximum of the Planck blackbody radiation, since it is at an inflection point, the second derivative is zero function. Coordinates of the inflection point of the following $F_{o-\lambda T} = 0,25$ and $(\lambda_q T) = b$, where the latter - Wines constant, b = 2,8978 mm·K. So here is justified instead zoom $C_2 = 14,388$ mm·K use constant Wines, in this case a number is written:

$$\lambda_q T/b = 1 + a_1 \cdot X + a_2 \cdot X^2 + ...,$$

where the variable expansion is selected as: $X = ln[0,75/(1-F_q)]$.

This expansion has been used only three members of the series, and it is obvious that the coefficient of the variable X is equal to the first power unit: $a_1 = 1$, and if the square of the variable X^2 is zero: $a_2 = 0$. Therefore, in terms of final formula of the patent is only the first two member of the series, in this case, the expression $T = f(F_q)$ acquires a very compact form:

$$T = \frac{b}{\lambda_q} \{1 + ln[0,75/(1 - F_q)]\}.$$

This expression describes the acceptable accuracy range of the $F_q \in (0,2 - 0,75)$, "hit" which provided an appropriate choice of values λ_q filter, so it was used as part of the measurement procedure, the patent number 63080A. His analysis shows that at the expansion of $F_q = 0,25$ (X = 0) the exact result: $T = b/\lambda_q$.

Further studies have found two more terms at the series, which significantly increase the accuracy of calculation of the temperature and increase the range of variation of F_q. The resulting trinomial is of the form:

$$T = \frac{b}{\lambda_q} \{1 + ln[0,75/(1 - F_q)] + a_4 \cdot ln^4[0,75/(1 - F_q)]\},$$

where $a_3 = 0$, $a_4 = 1,5 \cdot 10^{-2}$ – coefficients of the 3rd and 4th degree variable. Range 1% approximation of the formula expanded to $F_q \leq 0,9$.

Example 1. If the filter radiation thermometer was used S-Pb photo resistor with $\lambda_q = 3,5$ µm and as a result of the two measurements (one - with a light filter, and more - without) found flux values partial and full E_q radiation E_∞, attitude which is equal to the $E_q/E_\infty = F_q = 0,94$, we obtain the value of the above formula true temperature T = 2700 K. If the radiation temperature, calculated from the flow E_∞ is: $T_R = 2500$ K, $\bar{\varepsilon} = (T_R/T)^4 = 0.734$. The error in determining the true temperature is here $\delta T= 1\%$.

If the same filter as in this case, used glass window $\lambda_q = 2,7$ µm, then $F_q = 0,9$ we obtain T = 3500 K.

2. Integral emissivity "quasi series" surface materials

In the general case, the integral emissivity of the heated surface is expressed analytically through spectral follows:

$$\bar{\varepsilon} = [\int_{o}^{\infty} \varepsilon(\lambda)e(\lambda T)d\lambda]/(\sigma_o T^4) \leq 1,$$

where f = $e(\lambda T)$ - the Planck function, σ - Stefan-Boltzmann constant.

Integral emissivity surface $\bar{\varepsilon}$(T) can be determined experimentally, knowing the actual value of the absolute temperature T and the surface radiation received "quasi temperature" T_R on the testimony of the total radiation pyrometer, according to the formula $\bar{\varepsilon} = (T_R/T)^4$.

I must say that the results obtained (for T and $\bar{\varepsilon}$) have sufficient accuracy only if the spectral characteristics of the radiating surface is within the "quasi series" approximation. The concept of "quasi series" approximation for the case when its spectral characteristics $\varepsilon(\lambda)$ in the full spectral range is defined by a step function, defined in Harrison [2] the expression of the integral characteristic $\bar{\varepsilon}$ as follows:

$$\bar{\varepsilon}_{o-\infty} = \varepsilon_{o-1}F_1 + \varepsilon_{1-2}(F_2 - F_1) + \varepsilon_{2-3}(F_2 - F_3) + ... + \varepsilon_{i-\infty}(F_i - F_\infty)$$

For the case of incomplete spectral range, with a similar task emissivity, $\varepsilon(\lambda)$ integral characteristic $\bar{\varepsilon}$ follows:

$$\bar{\varepsilon}_{o-\lambda} = \frac{1}{F_{\lambda T}} [\varepsilon_{o-1}F_1 + \varepsilon_{1-2}(F_2 - F_1) + \varepsilon_{2-3}(F_2 - F_3) + ... + \varepsilon_{i-\lambda}(F_i - F_{\lambda T})]$$

These formulas can "roll" and conditions "quasi series" approach expressed in a compact form:

$$\bar{\varepsilon}_{o-\lambda} = \frac{1}{F_q} \sum_{i=1,2}^{i=q} \varepsilon_i \Delta F_i \cong \sum_{i=1,2}^{\infty} \varepsilon_i \Delta F_i = \bar{\varepsilon}_{o-\infty}$$

If there is not ideal speed, and continuous spectral characteristics, $\varepsilon(\lambda)$ passing to the limit $\Delta F \to dF$ marked, in our notation $\sum$, the definition of "quasi series" approximation is possible to mathematically rigorous express in integral form:

$$\bar{\varepsilon}_q = \frac{1}{F_q} \int_{0}^{F_q} \varepsilon(F)dF \cong \int_{0}^{1} \varepsilon(F)dF = \bar{\varepsilon}_\infty$$

Thus, having a table for $F(\lambda T)$ (which is tabulated as "a function of blackbody radiation") and knowing the spectral characteristic, $\varepsilon(\lambda T)$ can be summed expression $\sum \varepsilon_i \Delta F_i$ and obtain a numerical estimate for the integrated radiative ability $\bar{\varepsilon}$.

3. Questions pyrometric determination of the melting points of substances

Sveht and Talensky in 1960, [11] with the registration oscilographical radiation intensity is very clean (unoxidized) Armco iron bath surface (under argon) recorded a sharp increase in brightness ("flash") at its phase transition (crystallization). Metal part characterized by a weak dependence of the spectral emissivity of the temperature, which leads to a small difference in the nature of spectral distribution, $\varepsilon(\lambda T)$ for the liquid and solid metal mirror. Therefore, in all parts of the spectrum at the time of crystallization on the waveform was recorded "splash" brightness. Quantitatively, the increase in brightness depending on the wavelength and the crystallization conditions reached 100%. The authors of this is due to the fact that the liquid metal "short range order", which determines the dependence on wavelength ε retained and solidified due to the formation of grains (crystals), the mirror surface becomes rough. In this case we can predict that the solidification of the metal surface dramatically increases its brightness and total radiation, resulting in an abrupt increase in radiative flux $E_\infty = \bar{\varepsilon}\sigma \cdot T^4$.

Thus, a joint temperature and emissivity of a heated surface of the combined method of radiation pyrometry this phase transition can be locked [12] by an abrupt change of the emissivity as in this case, not only the surface roughness, but also the electrical resistivity of the material.

Emissivity of the surface roughness Agababov investigated [13] and theoretically obtained the formula:

$$\bar{\varepsilon}_{ш} = \{1 + [(\ \bar{\varepsilon}_{гл}\ )^{-1} - 1]S_F\}^{-1},$$

where S_F - factor "smoothness" of the surface, $S_F = F_{sm}/F_{sh} \leq 1$. However, the expression for the factor of "smoothness" of the surface is generally unknown and Agababov defined it experimentally (by radiation thermometer), so the estimates in the first approximation, we can use a simplified dependence for real cases, which is recommended in reference [8]: $\bar{\varepsilon}_m = 0.2 + 0.8\ \bar{\varepsilon}_{ch}$, where $\bar{\varepsilon}_{ch}$ - emissivity of a smooth surface.

For optically smooth metal surface is known [4] dependence Ashkinass for thermal radiation in the normal direction $\bar{\varepsilon}_{ch} = 0.576\sqrt{(r_e T)}$, where r_e - electrical resistivity, T - absolute temperature, K. In this formula appears r_e, and there are data that the electrical resistivity of pure substances in the phase transition can vary greatly, for example, metal germanium (Ge) in ~ 20 times [14], while the nonmetal silicon (Si) in ~ 30 times!

Therefore, abrupt changes ("spike") radiant flux from the surface of the liquid metal when it solidifies expression can be written expression: $\Delta E = (\ \bar{\varepsilon}_{ml} - \ \bar{\varepsilon}_{ms})\sigma_o T^4_m \cong 0.8(\ \bar{\varepsilon}_{ml} - \ \bar{\varepsilon}_{ms})\sigma_o T^4_m$.

Given that the pyrometer registers mainly normal emissivity surface, resulting in a formula may substitute the value of $\bar{\varepsilon}_{ch}$ Ashkinass formula, wherein obtain:

$$\delta E = \Delta E_\infty/(\ \bar{\varepsilon}_{ml}\sigma_o T^4) \cong 0.8\cdot[1 - \sqrt{(r_{ms}/r_{ml})}].$$

So racing surface emissivity at the phase transition is determined not only by changing its roughness (S_F), but also a significant change in electrical resistivity (r_e) substances at this point, due to the transformation of their structure.

Example 2. For example solidification "mirror" of the liquid metal (copper) a qualitative estimate of the "jump" of the total radiant flux from the surface, detected radiation pyrometer.

Emissivity of copper in the liquid state 0.13 ($t_p = 1083^o$C) and $r_{ms}/r_{ml} = 2.04$ for Cu [14]). Substituting these values into the formula found above, we obtain: $\delta E \cong 0.8\cdot[1-\sqrt{(r_{ms}/r_{ml})}] = 0.8\cdot[1-\sqrt{(2.04)^{-1}}] = 0.24$ (24 %).

Thus, the assessment above shows that the radiation flux from the "mirror" of the liquid metal (in this case - copper) when it solidifies - increases abruptly almost a quarter.

Conclusions

It is shown that the "combined method of radiation pyrometer" (Pat. UA N63080A), which allows to determine jointly true absolute temperature T(K) and the emissivity of the surface, $\bar{\varepsilon}$ enables ceteris paribus increase the accuracy of measuring these quantities compared to other methods (due to the decrease in the standard error of $\sqrt{2}$). Furthermore, the article extended upper limit of 1% accuracy range in comparison with the approximation of the patent - until $F_q = 0.94$.

Introduced the concept of "quasi series" the body as such, to measure the temperature of which is possible to use the method pyrometry submitted patent number 63080A, formulated a condition mathematically correct use of "combined mode radiation pyrometry" and provide an analytical expression of the criterion of "quasi series" Body in integral form.

Found that the new combined method of radiation pyrometry perfect "fit" into the measurement procedure for experimental determination of the temperature dependence of the emittertion capacity of refractory substances and materials $\bar{\varepsilon}$ (T) in the framework of the "method of radiation thermometer" [15] and it can be used to determine $\bar{\varepsilon}$(T), almost all substances.

Proposed to use a known fact abrupt change in the emissivity of the surface material in the phase transition points for the determination of these temperatures, which is especially important in cases where the phase transformations take place without the thermal effect (second order phase transitions) and are difficult to fix within the known variants of the thermal analysis.

The analysis logging capabilities "jump" emittertion capacity of metals at the phase transition (by fixing the "surge" of the total flux of radiation) and estimate of the value of such a "jump" at the melting point of the metal depending on the ratio of specific electric resistance of the solid phase and the liquid showed that these effects are very important and can be the basis of a new variant of the thermal analysis of materials at high

temperatures - over the break (or fracture) curve $\overline{\varepsilon}=f(T)$ in the graph, both coordinates are determined by the "combined method radiation pyrometry."

References

[1]. *Ribot G.* Optical pyrometer. Leningrad: GT-TI, 1934.
[2]. *Harrison T.R.* Radiation pyrometry. New York: Wiley, 1964.
[3]. *Gordov A.N.* Basics pyrometry. Moscow: Metallurgy, 1971.
[4]. Magunov A.N. The spectral pyrometry. – M.: Physmathlit, 2012.- P. 248.
[5]. *Stegniy A.I., Shevchenko A.V., Shovels L.M.* Thermal analysis and other oxides using solar heating / / Dokl. - Ser. And, № 6. - 1979, pp. 484 - 487.
[6]. *Shevchenko A.V., Tkachenko V.D., Shovels L.M. etc.* Methods of determining the phase transition temperatures using solar heating / /Powder Metallurgy, 1986, №1, pp. 91 - 95.
[7]. *Asimov S.A., Rumi R.F., Sigalov L.M.* On the determination of phase transition temperatures on the radiant heating installations / / Heliotekhnika. 1985, № 6.
[8]. Temperature measurements. Handbook. Naukova Dumka, 1989.
[9]. *Harmer J.D., B.N.Watts.* - J. Sci. Instruments, 1955, 32, 167.
[10]. *Reinholds P.M.* Brit.– J. Appl. Phis., 1961, 12, 401.
[11]. *Sveht D.Y., Talensky O.N.* - Proceedings of the Institute of Metallurgy them. Baykova USSR Academy of Sciences, 1960, No.5, p.183.
[12]. *Shvarev K.M., Bayturan S.H., Baum B.A.* Integral emissivity alloys of Al–Ni in solid and liquid states / / Journal of Engineering Physics. 1983, V 44, № 2, S.322.
[13]. *Agababov S.G.* Influence of surface roughness of a solid body on its radiative properties and methods of experimental determination / / High Temperature. 1968, Volume 6, Issue 1.
[14]. Properties elements. Directory / / Ed. *G.V.Samsonov*, Part 2, M.: Metallurgy, 1976.
[15]. *Worthing A.G.* Emissivity of thermal radiation at / / Proc. articles "Methods for measuring the temperature," Part 2, Moscow: IL, 1954.