

The definition analyses of radiation temperature measurement area

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Abstract: In the research of primary spectrum pyrometry, this paper discussed the definition problem of radiation temperature measurement area based on the measurement coordinates. For the linear spectrum emissivity model and improved monotonic spectrum emissivity model, the characteristics of radiation temperature measurement area restricted by the measurement coordinates were theoretically analyzed, through the investigations of the temperature and emissivity coordinate axes. Choosing the specific primary spectrum pyrometer as an example in applications, the theoretical area of radiation temperature measurement of this pyrometer was given and it was verified through blackbody experiments. The discussions of this paper will provide the necessary foundation for the theory research development of primary spectrum pyrometry and the realization of technical applications.

Key words: temperature; emissivity; radiation temperature measurement; the measurement coordinates

1 Introduction

Planck's Law, which reveals the quantitative mathematical relationship between blackbody radiation and its temperature, is one of the fundamentals of non-contact radiation temperature measurement. In applications, the calibrations aroused by the complexity of practical object emissivity and the field measurement has become the key issue of theoretic and technological research on radiation temperature measurement, which produced many measurement methods^[1-9]. Aiming at the mentioned key point, we have already put forward the primary spectrum pyrometry^[10] based on the narrow waveband measurement, the linear emissivity model and the normalization process, which realized the true temperature field measurement without the emissivity calibration and the spatial calibration. And we established the measurement coordinates formed by the temperature and emissivity coordinate axes^[11], which was an important theoretical and application characteristic of primary spectrum pyrometry differing from other methods. The Ref. [12] investigated the division and definition of object radiation color area in the chromaticity coordinates within the visible waveband range. However, in the research of primary spectrum pyrometry based on the measurement coordinates, the definition of radiation temperature measurement area was al-

so concerned. Therefore, on the base of previous studies, the paper will analyze the effective radiation temperature measurement area defined by the measurement coordinates for different emissivity models, and determine the measurable area scope of objects to provide the foundation for further theoretical research and technical applications of primary spectrum pyrometry.

2 Principle of primary spectrum pyrometry

The measurement equation of primary spectrum pyrometry is expressed by

$$V_i = \psi \int_{\lambda_a}^{\lambda_b} F_i(\lambda) \cdot \varepsilon(\lambda, T) \cdot I_b(\lambda, T) d\lambda, \quad i = 1, 2, 3 \quad (1)$$

Where V_i is the measured signal intensity in channel i , and also called as the spectrum values; ψ is the geometrical factor independent of wavelength and temperature; (λ_a, λ_b) is the spectrum response range of the sensor; $F_i(\lambda)$ is the spectral response function of the sensor i ; $\varepsilon(\lambda, T)$ is the spectrum emissivity function; $I_b(\lambda, T)$ is the spectral radiance distribution of an ideal blackbody at the same temperature. In the narrow measurement waveband, the spectrum emissivity may be described as^[13]

$$\varepsilon(\lambda, T) = a(T) \cdot (1 + m(T) \cdot \Lambda) \quad (2)$$

Where the non-dimension wavelength $\Lambda = (\lambda -$

λ_a)/ $(\lambda_b - \lambda_a)$, the parameters of the emissivity model satisfies such physical constraints: $a(T) > 0$ and $m(T) \in [-1, \infty)$. Take the spectrum emissivity function into Eq. (1), and normalize (V_1, V_2, V_3) as the spectrum value (x, y) ,

$$x = \frac{V_1}{V_1 + V_2 + V_3} = \frac{\int_{\lambda_a}^{\lambda_b} F_1(\lambda) \cdot (1 + m\Lambda) \cdot I_b(\lambda, T) d\lambda}{\sum_{i=1}^3 \int_{\lambda_a}^{\lambda_b} F_i(\lambda) \cdot (1 + m\Lambda) \cdot I_b(\lambda, T) d\lambda}$$

$$y = \frac{V_2}{V_1 + V_2 + V_3} = \frac{\int_{\lambda_a}^{\lambda_b} F_2(\lambda) \cdot (1 + m\Lambda) \cdot I_b(\lambda, T) d\lambda}{\sum_{i=1}^3 \int_{\lambda_a}^{\lambda_b} F_i(\lambda) \cdot (1 + m\Lambda) \cdot I_b(\lambda, T) d\lambda} \quad (3)$$

Eq. (3) shows the implicit corresponding relationship between the measured data and the parameters of temperature and emissivity $(x, y) \Leftrightarrow (m, T)$; thereby establishing the principle of primary spectrum pyrometry, which is applicable to objects with continuous radiation characteristics and the above emissivity expression in the narrow measurement waveband.

3 Measurement coordinates

In the measurement coordinates^[11], there are two specific coordinate axes: the temperature coordinate axis and the emissivity coordinate axis.

According to Eq. (3), the temperature T may be expressed by

$$T = \xi(x, y, m) \quad (4)$$

The temperature T is relative to the spectrum value (x, y) and the emissivity parameter m . For a certain emissivity parameter m_* , the locus formed by (x, y) is looked upon as the temperature coordinate axis \mathbf{T} (isom locus) in the measurement coordinates.

The emissivity parameter m is also expressed by,

$$m = \zeta(x, y, T) \quad (5)$$

The emissivity parameter m is relative to the spectrum value (x, y) and the temperature T . For a certain temperature T_* , the locus formed by (x, y) is looked upon as the emissivity coordinate axis \mathbf{m} (isothermal locus) in the measurement coordinates.

Spectral response functions are indispensable in primary spectrum pyrometry, and is simulated with Gaussian distribution,

$$F(\lambda; a, c, \omega) = c \cdot \exp\left\{ -4 \ln 2 \cdot \left[\frac{\lambda - a}{\omega} \right]^2 \right\} \quad (6)$$

where the parameter a is the mean wavelength, c is the peak transmission, ω is here defined as the full-

width at half maximum (FWHM) value of the peak. Assuming the integral waveband of the pyrometer $(\lambda_a, \lambda_b) = (380 \text{ nm}, 780 \text{ nm})$, the parameters of the Gaussian distribution $c_1 = c_2 = c_3 = 1$, $a_1 = 480 \text{ nm}$, $a_2 = 580 \text{ nm}$, $a_3 = 680 \text{ nm}$, $\omega_1 = \omega_2 = \omega_3 = 70 \text{ nm}$, the distribution curves of three response functions are shown in Fig. 1.

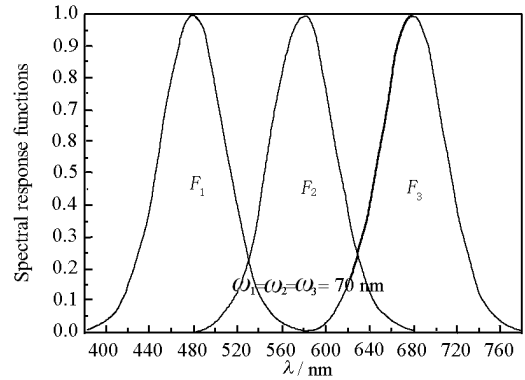


Fig. 1 Spectral response functions

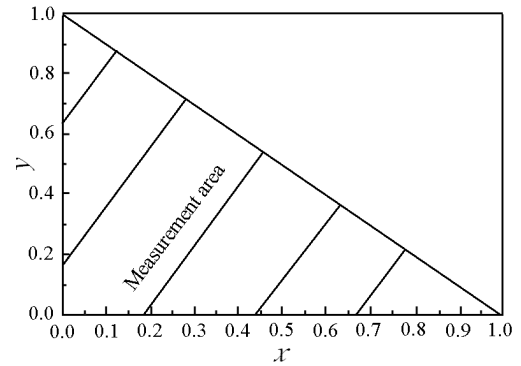


Fig. 2 The measurement area restricted by spectral response functions

Under different response wavelength, three non-correlative spectral response functions are normalized

$$\text{as } \left[\frac{F_1(\lambda)}{F_1(\lambda) + F_2(\lambda) + F_3(\lambda)}, \frac{F_2(\lambda)}{F_1(\lambda) + F_2(\lambda) + F_3(\lambda)} \right]$$

The area formed by spectral response functions in $x - y$ measurement coordinates is illustrated in Fig. 2 (diagonal line area). And the measurement points described in Eq. (3) are also limited in the diagonal line area.

4 Radiation temperature measurement area

In the measurement area (Fig. 2), the temperature and emissivity axes follow the specific distribution rules^[11]. The radiation temperature measurement coordinates don't fulfill the whole measurement area, which means that not all points in the measurement area correspond to the temperature measuring points.

Therefore, according to the distribution of the temperature and emissivity measurement coordinates under different spectrum emissivity models, how to clearly define the effective area of radiation temperature measurement may provide the necessary guidelines for the inversion calculation and the error analysis of radiation temperature measurement.

4.1 Radiation temperature measurement area based on the linear emissivity model

The linear emissivity model is $\varepsilon = a_0 + a_1\Lambda$. Assume the parameters range: temperature T range $[1\ 000\ \text{K}, \infty)$, emissivity parameter m range $[-1, \infty)$. Solid line locus in Fig. 3 is the border of radiation temperature measurement area based on linear emissivity. And the correlative descriptions of the locus are illustrated in Table 1.

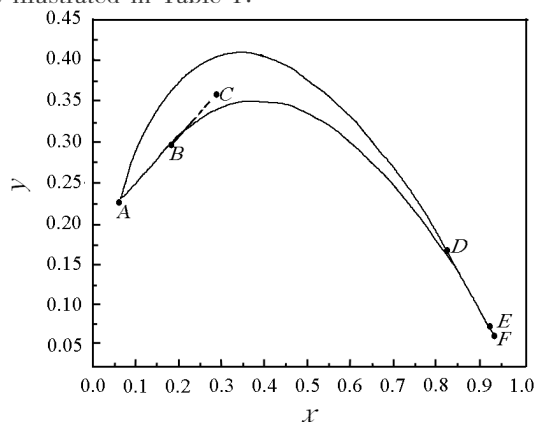


Fig. 3 Radiation temperature measurement area based on linear emissivity

Table 1 The description of the locus in Fig. 3

Locus	Type	Parameter	Line shape
ABC	Emissivity axis (isothermal locus)	$T = \infty$	Straight line segment
DEF	Emissivity axis (isothermal locus)	$T = 1\ 000\ \text{K}$	Straight line segment
AD	Temperature axis (iso-mlocus)	$m = -1.0$	Curve segment
BE	The envelope line of isotherm cluster		Curve segment

4.2 Radiation temperature measurement area based on the monotonic emissivity model

The monotonic emissivity model is $\varepsilon = a_0 + a_1\Lambda^n$. For the fixed waveband interval (λ_a, λ_b) , the applicability of linear emissivity model is generally limited. Hence, the curvature index n is introduced to modify this emissivity model described in Eq. (2):

$$\varepsilon(\lambda, T) = a(T) \cdot [1 + m(T) \cdot \Lambda^n] \quad (7)$$

Under the monotonic emissivity in practical situa-

tions, there are also the emissivity axis (isothermal locus) and the temperature axis (iso-m locus) similar to those under the linear emissivity model. The fitting results of emissivity experiments in Ref. [13] demonstrate that in narrow waveband, most of objects with monotonic emissivity have the curvature index within $n \in [0.5 \sim 2.0]$. Fig. 4 illustrates the radiation temperature measurement area in the specific interval based on the monotonic spectrum emissivity function. The physical description of this locus is the similar to that shown in Table 1. In comparison with Fig. 3, the temperature measurement areas are overlapping, which means that one spectrum value (x, y) will correspond to different temperature solutions due to different values of the curvature index. The temperature deviation resulting from this may be estimated through the adjustment of the curvature index.

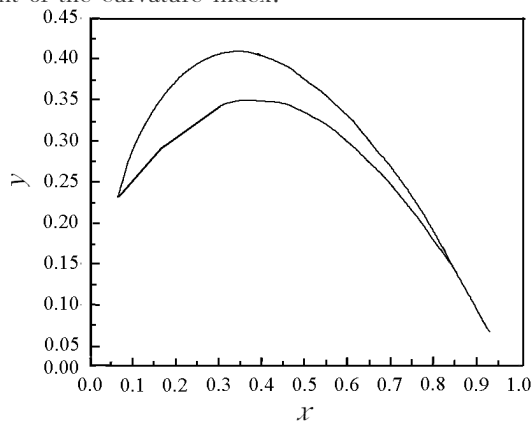


Fig. 4 Radiation temperature measurement area based on monotonic emissivity ($n \in [0.5 \sim 2.0]$)

4.3 Applications and examples

Based on the specified CCD (charge coupled device), a three-channel primary spectrum pyrometer was developed, and its comprehensive spectral response functions were calibrated by monochromatic spectrum experiments. According to above theoretical analyses, we present the distribution of radiation temperature measurement area applicable to the pyrometer (Fig. 5). Color images of blackbody source were captured with this pyrometer at different temperatures within $(1\ 600\ \text{K}, 2\ 200\ \text{K})$, and were analyzed. The temperature measurement error was only within 1%. All measuring coordinate points of high-temperature blackbody were distributed within the radiation temperature measurement area (circles in Fig. 5), adjacent to edges of the area.

5 Conclusions

The measurement coordinates formed by tempera-

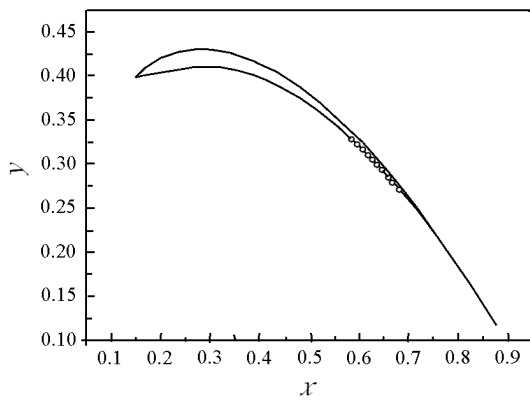


Fig. 5 The temperature measurement area of the specific pyrometer (the linear emissivity)

ture axis and emissivity axis are an important feature of primary spectrum pyrometry. In the research of primary spectrum pyrometry based on the measurement coordinates, the paper discusses the theoretical definition of radiation temperature measurement area in the coordinates. On the base of linear emissivity model and improved monotonic emissivity model, considering the distribution rules of measurement coordinates, the radiation temperature measurement area is investigated for different spectrum emissivity model. The analyses show that the radiation temperature measurement area is very limited in measurement coordinates, and the area border is arc. The linear emissivity model and the monotonic emissivity model respectively correspond to different areas, but the areas are partially overlapped. Choosing the specific primary spectrum pyrometer as an example, we present the theory area of radiation temperature measurement applicable for this pyrometer, which is verified through blackbody experiments. The research on the definition of radiation temperature measurement area will provide a necessary foundation for the theory research development and the technical applications of primary spectrum pyrometry.

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