Radiation Measurement of the Real Temperature Based on Specific Wavelength

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Abstract. The method of radiation thermometry has many advantages such as the wide temperature measurement range, the needless of establishing heat balance and has a good applicable prospect in aerospace as well as remote sensing. The theory of measuring real temperature in radiation thermometry is studied in this article by using mathematical analysis. This article establishes radiation thermometry model and points out the condition of measuring real temperature. A phenomenon is revealed through the analysis of radiation thermometry model that the real temperature of objects can be measured at specific wavelength even if the set emissivity function of pyrometer is different from object’s emissivity function. According to the phenomenon, a new radiation thermometry method—-the multi-wavelength thermometry based on specific wavelength is proposed in this paper. This new method relaxes the limits of object’s emissivity function from traditional multi-wavelength thermometry methods, which can measure the real temperature of the object as long as the specific wavelength can be found. According to the simulation experiment, the author proves that the multi-wavelength radiation thermometry based on specific wavelength can measure the real temperature of the object, and points out that specific wavelength has numerically uncertain property. Finally, the author indicates the problems existing in the multi-wavelength thermometry based on specific wavelength and the future direction of the radiation thermometry development.

Introduction

Radiation thermometry method has many advantages such as the needless of establishing heat balance, without destroying object temperature field, wide temperature measurement range[1] and short response time. The radiation thermometry method has broad application prospects in aerospace and remote sensing fields[2]. At present, commonly used radiation thermometry methods include brightness thermometry[3], colorimetric thermometry[4], multi-wavelength thermometry[5] and primary spectrum pyrometry[6]. In order to accurately measure the real temperature of the object, scholars have proposed nonlinear regression[7], orthogonal polynomial regression[8], neural networks[9,10], iterative algorithms[11], and other temperature measurement data processing methods. Scholars also have analyzed the effect of the selection of measurement wavelength[12] and ambient background radiation on the measurement of real temperature[13]. The purpose of this article is to provide a new approach for radiation measurement of real temperature through mathematics analysis and to study how to achieve real temperature measurement in radiation thermometry.

This article proposes a radiation thermometry model and points out that there are two technical methods to measure the real temperature of the object by radiation thermometry: “the same order” and “the same wavelength”. This article also reveals the phenomenon that the real temperature of the object can be measured by radiation thermometry at specific wavelength, and therefore proposes the multi-wavelength thermometry based on specific wavelength. According to the experiment case of temperature measurement of tungsten, the author proves the conclusions proposed in this paper, and indicates the uncertainty of the specific wavelength, problems existing in the multi-wavelength thermometry based on specific wavelength, as well as the future direction of the radiation thermometry development.
Radiation Thermometry Model

During the development history of radiation thermometry, although there are brightness thermometry, colorimetric thermometry, multi-wavelength thermometry and etc., but there is no radiation thermometry model for objects and pyrometers, this makes it hard to do radiation thermometry analysis by means of mathematics. Thus, it is necessary to build radiation thermometry model first, see below expression (1). Out of below expression,  \( I_b(\lambda, T) \) is the function of black body radiation,  \( \epsilon(\lambda, T) \) and  \( f(\lambda, T_p) \) are two functions represent the emissivity of actual object and the set emissivity of pyrometer, \( T \) is object’s real temperature, \( T_p \) is the pyrometer temperature (pyrometer temperature refers to the temperature data obtained from pyrometer during measurement). The left of expression is the radiation intensity function of actual object, which represent the radiation information of measured object, and also represent measurement value pyrometer actually received; the right of expression is the function of pyrometer measurement, this function is used to compute temperature data during measurement.

\[
I_b(\lambda, T) \cdot \epsilon(\lambda, T) = I_b(\lambda, T_p) \cdot f(\lambda, T_p)
\]  

(1)

The above model does not define the form of the set emissivity function of pyrometer, thus, by changing the expression of function, the model can represent other thermometry methods, such as brightness thermometry, colorimetric thermometry and multi-wavelength thermometry. If the set emissivity function of pyrometer equal to 1 (black emissivity), or a constant which has nothing to do with wavelength (grey emissivity), or make function related to wavelength and temperature.

If known the emissivity function are consecutive, giving arbitrary wavelength \( \lambda_0 \) to perform partial Taylor expanded to get consecutive emissivity expression(2), due to unknown property of object’s emissivity, we have no way to determine the value of object emissivity’s multinomial order \( n \). According to emissivity expression, this paper selects \( m \) order equation (3) as the set emissivity function of pyrometer.

\[
\epsilon(\lambda, T) = \sum_{i=0}^{n} \epsilon^{(i)}(\lambda_0, T) \left( \frac{\lambda - \lambda_0}{\lambda_0} \right)^i
\]  

(2)

\[
f(\lambda, T_p) = \sum_{i=0}^{m} f^{(i)}(\lambda_0, T_p) \left( \frac{\lambda - \lambda_0}{\lambda_0} \right)^i
\]  

(3)

The purpose of radiation thermometry is to get temperature data, therefore the first key point is to solve the problem of obtaining pyrometer temperature. Refer to the model (1), take the left function of equation as pyrometer received measurement value \( V_j \), \( V_j \) equals to object’s radiation intensity(  \( V_j = I_b(\lambda_j, T) \cdot \epsilon(\lambda_j, T) \) ) which is under measured wavelength \( \lambda_j \). Apply emissivity equation (3) to model (1) can obtain equation (4), due to the right part of equation (4) contains \( f^{(i)}(\lambda_0, T_p) \) and pyrometer temperature \( T_p \), overall \( m+2 \) unknown variables, thus, according to multi-wavelength thermometry method, select \( m+2 \) different measurement wavelengths will be able to get pyrometer temperature.

\[
V_j = I_b(\lambda_j, T_p) \times \sum_{i=0}^{m} f^{(i)}(\lambda_j, T_p) \left( \frac{\lambda_j - \lambda_0}{\lambda_0} \right)^i, \quad j = 1, 2, \cdots, m + 2
\]  

(4)

In order to get temperature data, multi-wavelength thermometry needs to manually select \( m+2 \) different measured wavelengths. After obtain temperature data (pyrometer temperature), we need to pay more attention to the relationship with real temperature and pyrometer temperature, as well as how to make pyrometer temperature equals to real temperature.
Real Temperature Measurement in Radiation Thermometry Model

In model (1), replace Planck’s law with Wein’s law, and take logarithm from both sides, this way will help to get temperature error expression (5). Based on temperature error expression, pyrometer temperature equals to real temperature \( T_p = T \), and the set emissivity of pyrometer equals object’s emissivity \( \varepsilon(\lambda, T) = f(\lambda, T_p) \), one is sufficient condition for the other one. Thus, when make the set emissivity of pyrometer equals to object’s emissivity, the pyrometer can measure object’s real temperature.

\[
\frac{1}{T} - \frac{1}{T_p} = \frac{\lambda}{C_2} \ln \frac{\varepsilon(\lambda, T)}{f(\lambda, T_p)}
\]

(5)

Use (2) and (3) to represent object's emissivity and the set emissivity of pyrometer, we can get (6), which represent the condition of real temperature. When pyrometer meets real temperature condition, temperature measured by pyrometer is the object’s real temperature.

\[
\sum_{i=0}^{n} \varepsilon^{(i)}(\lambda_0, T) \left( \frac{\lambda - \lambda_0}{i!} \right) - \sum_{i=0}^{n} f^{(i)}(\lambda_0, T_p) \left( \frac{\lambda - \lambda_0}{i!} \right) = 0
\]

(6)

Real Temperature Measurement under the Same Order

For equation (6), when the set emissivity of pyrometer function equals to object’s emissivity function (m=n), equation can changed to (7). Because pyrometer emissivity’s coefficient \( f^{(i)}(\lambda_0, T_p) \) obtained from measured value through fitting, therefore, if want to keep real temperature condition stays valid under arbitrary wavelength \( \lambda \), then just need to make \( \varepsilon^{(i)}(\lambda_0, T) = f^{(i)}(\lambda_0, T_p) \). When setting pyrometer’s emissivity function order equals to actual object’s, pyrometer can measure and get real temperature of real object under arbitrary wavelength. This is the first path to get real temperature of object through radiation thermometry. Under traditional multi-wavelength thermometry, as long as make pyrometer’s emissivity order equals to objects’, then the pyrometer temperature is the real temperature of object. In order to get object’s emissivity order, scholars proposed a few different know of ways, such as automatic order finding, gradually fitting, and orthogonal polynomial regression.

\[
\sum_{i=0}^{n} \left[ \varepsilon^{(i)}(\lambda_0, T) - f^{(i)}(\lambda_0, T_p) \right] \left( \frac{\lambda - \lambda_0}{i!} \right) = 0
\]

(7)

Due to unknown characteristic of object’s emissivity, we cannot pre-setting pyrometer’s emissivity order m equals to object’s emissivity order n, thus we cannot guarantee pyrometer to obtain object’s real temperature under arbitrary wavelength, this is the issue to be solved for multi-wavelength thermometry. Without knowing actual object’s emissivity order, the only way we can do is to maximum pyrometer’s emissivity order, leave opportunity for finding m=n. Therefore, after multi-wavelength thermometry commonly used, the order of the set emissivity of pyrometer keep increasing, gradually developed three-wavelength pyrometer, four-wavelength pyrometer and six-wavelength pyrometer. Unknown order of object emissivity is one of the key reason that multi-wavelength thermometry cannot measure object’s real temperature.

Real Temperature Measurement under Specific Wavelength

Due to the unknown of object emissivity, most of time we face the situation that pyrometer and object have different emissivity order (m≠n), traditional multi-wavelength thermometry method considers that under such situation, pyrometer will have relative bigger temperature error, but, this does not apply to all, sometimes, there is still a method to measure and get the real temperature of object.
When pyrometer’s emissivity order and object’s emissivity order are not equal, real temperature condition expression (6) change to (8). Because none of consecutive function’s derivative \( \varepsilon^{(i)}(\lambda, T) \) equals to 0, thus, expression (8) is a univariate n-th order equation with respect to wavelength, and the solution in this equation is called specific wavelength. From expression (8), the condition of real temperature stays valid at specific wavelength. Thus when pyrometer’s emissivity order and object’s emissivity order are not equal, the real temperature of objects can be measured at specific wavelength. Expression (8) is the equation to get specific wavelength, as long as knowing all emissivity derivatives from object and pyrometer, we can get specific wavelength through (8). Look closely to equation (8), this equation has n specific wavelength solutions \( \lambda^*_j (j = 1, 2, \ldots, n) \). As long as the number of specific wavelength meets the condition that pyrometer temperature is able to be solved, i.e., \( n \geq m + 2 \), pyrometer can measure and get object’s real temperature, this is the second path to get the real temperature of object through radiation thermometry. Thus, a new method is proposed ---- multi-wavelength thermometry based on specific wavelength. No matter if pyrometer’s emissivity order equals object’s emissivity order, as long as find specific wavelength, this new method can get real temperature of object.

\[
\sum_{i=m+1}^{n} \varepsilon^{(i)}(\lambda_0, T) \frac{(\lambda - \lambda_0)^i}{i!} + \sum_{i=0}^{m} \left[ \varepsilon^{(i)}(\lambda_0, T) - f^{(i)}(\lambda_0, T_p) \right] \frac{(\lambda - \lambda_0)^i}{i!} = 0 \tag{8}
\]

We’ve already known that in colorimetric thermometry method, when objects’ emissivity are equal at 2 selected measurement wavelength, colorimetric thermometry can measure real temperature of object. Colorimetric thermometry becomes one of exceptional case of radiation thermometry based on specific wavelength, as long as find specific wavelength that satisfies the real temperature condition, multi-wavelength thermometry can measure and get real temperature. Compare to colorimetric thermometry, multi-wavelength thermometry based on specific wavelength add wavelength item to the set emissivity function of pyrometer, which is more close to object’s emissivity, thus has better adoptability.

Based on the analysis of real temperature condition, we raise a method that can measure the real temperature of object under specific wavelength. This method has no require to the set emissivity function of pyrometer, as long as the specific wavelength can be found, pyrometer can measure and get real temperature. Considering multi-wavelength thermometry based on specific wavelength has no request to the set emissivity function of pyrometer, for easier computing, choose the simplest function (9) as the set emissivity function of pyrometer. And expression (10) can be obtained by applying expression (9) to model (1), which is three-wavelength thermometry based on specific wavelength, when find 3 specific wavelengths, pyrometer can measure and get real temperature.

\[
f (\lambda, T_p) = f (\lambda_0, T_p) + f' (\lambda_0, T_p) (\lambda - \lambda_0) \tag{9}
\]

\[
I_b (\lambda_j, T) \cdot \varepsilon (\lambda_j, T) = I_b (\lambda_j, T_p) \cdot [f (\lambda_0, T_p) + f' (\lambda_0, T_p) (\lambda_j - \lambda_0)], \quad j = 1, 2, 3 \tag{10}
\]

This section proposes the condition to get real temperature in radiation thermometry model, and forms two conclusions through analysis: when pyrometer and object have same emissivity function (m=n), pyrometer can measure and get real temperature of object at arbitrary wavelength; when pyrometer and object has different emissivity function (m≠n), pyrometer can measure and get real temperature of object at specific wavelength \( \lambda^*_j \). Normally, tradition multi-wavelength thermometry method measure and get real temperature through finding the set emissivity function of pyrometer which matched measured object’s, actually there is another real temperature measurement method according to above conclusion: when pyrometer and object have different emissivity functions, if the measurement can be conducted under specific wavelength, pyrometer can get real temperature as well. This is the method that this article proposed: multi-wavelength thermometry based on specific
wavelength, and this method has no demand to object’s emissivity, do not need to find the set emissivity function of pyrometer which matched measured object’s, as long as having enough specific wavelength, pyrometer can measure and get real temperature of object.

Simulation Experiment

In order to describe how to measure object’s real temperature in multi-wavelength thermometry based on specific wavelength and reveal the problems appeared in finding specific wavelength, simulation experiment about tungsten’s temperature measurement is adopted.

The emissivity data of tungsten in the wavelength range of 0.35 to 1.05μm at 1800K and 2000K was obtained through searching reference[14], see fig 1. Applying least square method to tungsten’s emissivity data and conduct 7 orders fitting, get fitting curve \( \varepsilon(\lambda,1800) \) and \( \varepsilon(\lambda,2000) \), see fig 1, see the expression of \( \varepsilon(\lambda,1800) \) and \( \varepsilon(\lambda,2000) \) in (11). The R-square of both the fitting curve and the original emissivity data exceeds 0.99, indicating that the fitting curve and the original data fit well. Thus, we use fitting curve \( \varepsilon(\lambda,1800) \) and \( \varepsilon(\lambda,2000) \) as object’s emissivity to compute the specific wavelength during tungsten temperature measurement experiment.

\[
\begin{align*}
\varepsilon(\lambda,1800) & = 74.112\lambda^7 - 412.4\lambda^6 + 958.78\lambda^5 - 1205.6\lambda^4 \\
& +883.94\lambda^3 - 377.35\lambda^2 + 86.613\lambda - 7.7543 \\
\varepsilon(\lambda,2000) & = 81.103\lambda^7 - 453.79\lambda^6 + 1058.5\lambda^5 - 1332.1\lambda^4 \\
& +975.19\lambda^3 - 414.74\lambda^2 + 94.667\lambda - 8.4604
\end{align*}
\] (11)

Figure 1. The emissivity data and fitting curves of Tungsten at 1800K and 2000K.

Steps of Multi-wavelength Thermometry Based on Specific Wavelength

As above mentioned, the simulation experiment is conducted at specific wavelength by choosing three-wavelength thermometry method described in (10), and the set emissivity function of pyrometer can be expressed as (12), \( a_0 \) and \( a_i \) are two to be defined coefficient, \( a_0 = f(\lambda_0, T_p) + f'(\lambda_0, T_p)\lambda_0, \quad a_i = f'(\lambda_0, T_p) \).

\[
f(\lambda, T_p) = a_0 + a_i\lambda \] (12)

a) Picking any two wavelengths \( \lambda_1 \) and \( \lambda_2 \) from tungsten’s emissivity curve, applying them along with the value of correspondent tungsten’s emissivity to equation (12) to get to be calculated \( a_0 \) and \( a_i \), thus, a group of set emissivity function of pyrometer will be obtained. Because the wavelength can be arbitrarily chosen, different group of wavelength will get different pyrometer's emissivity functions which are called "cluster of emissivity functions".

b) Picking any of emissivity function from a cluster of emissivity functions, applying it to equation (8) to get specific wavelength, and compare to see if the quantity of specific wavelength meets the
requirement that pyrometer temperature can be obtained, if the quantity of specific wavelength meet the requirements, then the picked set emissivity function of pyrometer can be used to radiation thermometry of real temperature, else the picked set emissivity function of pyrometer cannot be used to measure and get real temperature, thus, we must continue to select the other emissivity function from the cluster of emissivity functions, till find the one which meet the requirements.

c) Apply the values of specific wavelength to expression (10) and get temperature of objects.

**The Result of Simulation Experiment**

We will give an example at below to illustrate how to measure the real temperature of 1800K tungsten at specific wavelengths. First, picking up two wavelengths whose values are 0.3809 and 0.6036μm; Applying these two wavelengths and correspondent 1800K tungsten’s emissivity values (0.3809, 0.4745), (0.6036, 0.4412) to equation (12), and get set emissivity function of pyrometer \( f_1(\lambda, T) = -0.151\lambda + 0.532 \); Applying pyrometer’s emissivity function \( f_1 \) and fitting curve of tungsten’s emissivity function \( \varepsilon(\lambda, 1800) \) to equation (8), and get 4 specific wavelengths: 0.3809, 0.4595, 0.6036, and 0.7195μm through computation. Due to the calculation of pyrometer temperature just need three measured wavelengths, therefore, the quantity of specific wavelength during temperature measurement should be enough and be able to provides 3 options: group 1 (0.3809, 0.4595, 0.6036), group 2 (0.3809, 0.4595, 0.7195) and group 3 (0.4595, 0.6036, 0.7195). Applying 4 specific wavelengths to 1800K tungsten emissivity fitting curve \( \varepsilon(\lambda, 1800) \) to get emissivity value under specific wavelength, and to 1800K tungsten’s radiation intensity function to obtain measurement value; then applying above mentioned data such as measurement value, specific wavelength and emissivity function \( f_1 \) to equation (10) to get pyrometer temperature by using MATLAB. Table1 is the result of simulation experiment, and this table indicates that multi-wavelength thermometry based on specific wavelength can measure and get real temperature of object.

| Real Temperature/K | Pyrometer Temperature/K | Relative error/% | Pyrometer Temperature/K | Relative error/% | Pyrometer Temperature/K | Relative error/% |
|-------------------|------------------------|-----------------|------------------------|-----------------|------------------------|-----------------|
| 1800              | 1800                   | 0               | 1800                   | 0               | 1800                   | 0               |

**Specific Wavelength Varies With the Change of Pyrometer Emissivity Function.** For 1800K tungsten, when the set emissivity function of pyrometer is \( f_1 \), the value of specific wavelength are 0.3809, 0.4595, 0.6036, and 0.7195μm, see figure 2(a). However, selecting another set emissivity function of pyrometer, such as \( f_2(\lambda, T) = -0.131\lambda + 0.52 \), the value of specific wavelength changes to 0.3641, 0.4967, 0.6065 and 0.6791μm, see figure 2(b). Thus, the phenomenon in figure 2 reveals the value of specific wavelength varies with the changes of pyrometer emissivity function.

![Figure 2](image-url)
Specific Wavelength Varies With the Change of Measured Object Temperature. For the set emissivity function $f_1$ of pyrometer, when applying $f_1$ to measure the real temperature of tungsten at 1800K, the value of specific wavelength are 0.3809, 0.4595, 0.6036 and 0.7195μm, see figure 3(a). However, when applying $f_1$ to measure the real temperature of tungsten at 2000K, the value of specific wavelength changes to 0.4, 0.4137, 0.5977 and 0.7679μm, see figure 3(b). The phenomenon in figure 3 indicates that the value of specific wavelength also varies with the change of measured object temperature.

The phenomena in Fig. 2 and Fig. 3 illustrates that specific wavelength has numerically uncertain property, the property can also be revealed from expression (8). Specific wavelength is the function of measured objects and the set emissivity of pyrometer, so the value of specific wavelength varies with the change of measurement objects and pyrometer.

Conclusion and Expectation

This article proposes radiation thermometry model, which accurately describes the phenomenon of radiation thermometry and makes two conclusions about measuring real temperature of object by analyzing radiation thermometry method: when the pyrometer’s emissivity function equals measured object’s (m=n), pyrometer can measure real temperature of object at any wavelength; when pyrometer’s emissivity function does not equal to measured object (m≠n), pyrometer can also measure real temperature of object at specific wavelength. These conclusions reveal the phenomenon that radiation thermometry can obtain real temperature of object at specific wavelength, and provide a new approach for measuring real temperature by using radiation thermometry.

A new method of measuring object’s real temperature is presented in this paper based on above conclusions, which is multi-wavelength thermometry based on specific wavelength. And it is proved that object’s real temperature can be measured through multi-wavelength thermometry based on specific wavelengths according to the simulation experiment.

In tungsten simulation experiment, an obvious phenomenon was observed: specific wavelength varies when changing measured object’s temperature and the set emissivity function of pyrometer, this means the specific wavelength has numerically uncertain property. So when using multi-wavelength thermometry based on specific wavelength, the setting of measurement wavelength must be changed from original multi-wavelength method’s “fixed wavelength” to “variable wavelength”, i.e., pyrometer’s measurement wavelength shall be varied when measured object and the set emissivity function of pyrometer changed. Thus, next research will focus on “searching method”, which can automatically search specific wavelength based on expression (8), and guarantee the radiation thermometer works at specific wavelength.
Reference

[1] Wang Wenge. Survey of Radiation Thermometry Technology [J]. Journal of Astronautic Metrology and Measurement, 2005, 25(4): 20-24.

[2] Dai Jingmin. Survey of Radiation Thermometry [J]. Techniques of Automation & Applications, 2004, 23(3): 1-7.

[3] Yuan Zundong. Generalized Effective Radiance Temperature in Radiation Thermometry [J]. Chinese Journal of Scientific Instrument, 2012, 33(4): 721-726.

[4] Fu T., Zhao H., Zeng J., et al. Two-color optical charge-coupled-device–based pyrometer using a two-peak filter [J]. Review of Scientific Instruments, 2010, 81(12): 124903.

[5] Fu T., Wang Z., Cheng X. Temperature measurements of diesel fuel combustion with multicolor pyrometry [J]. Journal of Heat Transfer, 2010, 132(5): 051602.

[6] Cheng Xiaofang, Fu Tairan, Fan Xueliang. Principle of Primary Spectrum Pyrometry [J]. Science in China Ser. G Physics, Mechanics & Astronomy, 2004, 34(6): 639-647.

[7] Gardner J.L. Computer modelling of a multiwavelength pyrometer for measuring true surface temperature [J]. High Temperature-High Pressures, 1980, 12: 699-705.

[8] Li Qinan, Xu Xiaoxuan, Wu Zhongchen, et al. The Orthogonal Polynomial Regression Method of Multi-wavelength Radiation Thermometry [J]. Spectroscopy and Spectral Analysis, 2006, 26(12): 2173-2176.

[9] Yang Chunling, Yang Maohua, Hu Yan, et al. Application of Wavelet Neural Networks to Multi-wavelength Radiation Thermometry [J]. Acta Metrologica Sinica, 2003, 24(4): 303-306.

[10] Sun Xiaogang, Yuan Guibin, Dai Jingmin. Multi-Spectral Thermometry Based on GA-BP Algorithm [J]. Spectroscopy and Spectral Analysis, 2007, 27(2): 213-216.

[11] Zhang Fucai, Sun Xiaogang, Sun Bojun, et al. Theoretical Study of Multi-Spectral Radiation Temperature Measurement Based on Temperature Difference Model [J]. Spectroscopy and Spectral Analysis, 2017, 37(9): 2675-2679.

[12] Rodiet C., Rémy B., Degiovanni A., et al. Optimization of wavelengths selection used for the multi-spectral temperature measurement by ordinary least squares method of surfaces exhibiting non-uniform emissivity [J]. Quantitative InfraRed Thermography Journal, 2013, 10(2): 222-236.

[13] Fu T., Liu J., Duan M., et al. Temperature measurements using multicolor pyrometry in thermal radiation heating environments [J]. Review of Scientific Instruments, 2014, 85(4): 044901.

[14] Ge Shaoyan, Na Hongyue. Thermal Radiation Properties and Measurement [M]. Beijing: Science Press, 1989: 236-237.