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Peak-Wavelength Method for Temperature Measurement

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Abstract Based on measurements of the spectrum emitted by a target, a new method for measuring temperature, the peak-wavelength method (PWM), is proposed and evaluated in this paper. The uncertainty and resolution of this method have been estimated theoretically, and it is shown that this method offers high resolution and accuracy. Moreover, several analyses have been done for various surfaces (non-blackbody) with a series of assumed spectral emissivities. The results show that better accuracy can also be obtained in these cases. Finally, an experimental setup using a Fourier transform infrared spectrometer was built and tested in our lab. Several experiments have been carried out that show the peak-wavelength method is feasible and practical.

Keywords Peak-wavelength method (PWM) · Temperature · Fourier transform infrared spectrometer (FTIR) · Spectrum

1 Introduction

Traditional radiation thermometers [1] based on Planck's law are widely used in many fields due to their fast response and non-contact measuring ability. There are various instruments available in the market, including single-band radiation thermometers, ratio pyrometers, and multi-wavelength pyrometers [2]. However, all of them must be calibrated via blackbody cavities before being used to measure the radiant intensity of a target. Their uncertainties of measurement are mainly dependent on the drift and noise of electronic circuits and on the transparency of the optical path.

Fourier transform infrared (FTIR) spectrometers have been well developed and are widely used in many fields [3,4]. With them, it has become cheaper and easier

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to measure the radiation spectrum of a surface with high wavelength resolution and accuracy. Based on the spectral measurement of a target, a new method for measuring temperature, the peak-wavelength method (PWM), is proposed and studied in this paper. The radiance spectrum of a surface is first measured by a spectrometer; then the peak wavelength of the spectrum, λ_{max}, can be easily found. Finally, the temperature, T, of the surface can be computed according to Wien's displacement law.

The uncertainty and resolution of this method are theoretically estimated. It is shown that this method has high temperature resolution and accuracy. Moreover, several analyses have been carried out for various surfaces (non-blackbody) with a series of assumed wavelength-dependent emissivities. The results show that the method (PWM) can also obtain reasonable accuracies for real surfaces.

Lastly, an experimental setup was built in our lab based around a Fourier transform infrared spectrometer. Several experiments were carried out that show the Peak wavelength method (PWM) to be both feasible and practical.

2 Principle of Measurement

The spectral distribution of the radiation emitted by a blackbody is well known, having been first derived by Planck from quantum mechanical considerations. The spectral radiance has the form,

$$L_b(\lambda, T) = c_1\lambda^{-5}[\exp(c_2/\lambda T) - 1]^{-1} \tag{1}$$

where the first and second radiation constants, c_1 and c_2, respectively, are $c_1 = 3.74177118 \times 10^{-16}\,\mathrm{W \cdot m^2}$ and $c_2 = 1.4387752 \times 10^4\,\mathrm{\mu m \cdot K}$. The blackbody spectral distribution is characterized by a maximum, and the wavelength associated with this maximum, λ_{max}, depends on temperature. The nature of this dependence may be obtained by differentiating the spectral radiance, Eq. 1, with respect to λ and setting the result equal to zero. In so doing, we obtain

$$\lambda_{max} T = c_3 \tag{2}$$

Equation 2 is known as Wien's displacement law, and the Wien wavelength displacement law constant is $c_3 = 2897.7685\,\mathrm{\mu m \cdot K}$.

The spectral distribution from a blackbody surface at an unknown temperature T can be measured by an instrument and λ_{max} can be easily found. Moreover, the temperature T of the blackbody surface may be computed according to Eq. 2. We call this method the peak-wavelength method (PWM).

3 Resolution Analyses

By rewriting Eq. 2 as

$$T = c_3/\lambda_{max} \tag{3}$$

and differentiating Eq. 3 with respect to λ_{max}, the following equation can be easily obtained:

$$dT/d\lambda_{max} = -c_3/\lambda_{max}^2 \tag{4}$$

Equation 4 can be used to evaluate the uncertainty of the proposed method as a function of the uncertainty in determining λ_{max}. The sensitivities of temperature with respect to the maximum wavelength have been computed and listed in Table 1. Table 1 shows that, even at 3,000 K, the resolution of temperature is better than 3 K for a 1-nm measurement uncertainty in the maximum wavelength. For most cases, a 1-nm measurement uncertainty in the maximum wavelength can be easily obtained.

Table 2 shows the accuracy required in determining the maximum wavelength to achieve various uncertainties in temperature. It is obvious that a 50-K uncertainty in temperature only needs 1.6-μm and 16-nm uncertainties in maximum wavelength

Table 1 Sensitivities of temperature with respect to wavelength

T (K)	λ_{max} (μm)	$dT/d\lambda_{max}$ (K · nm^{-1})	T (K)	λ_{max} (μm)	$dT/d\lambda_{max}$ (K · nm^{-1})
300	9.65923	0.031	1,600	1.81111	0.884
500	5.79554	0.086	2,000	1.44888	1.381
800	3.62221	0.221	2,500	1.15911	2.170
1,200	2.41481	0.497	3,000	0.96592	3.108

Table 2 Measurement uncertainty of maximum wavelength needed for the desired temperature uncertainties

T (K)	λ_{max} (μm)	$u(T)$ (K)	$u(\lambda_{max})$ (nm)
300	9.65923	0.1	3.21
		1.0	32.18
		50.0	1609.44
500	5.79554	0.1	1.16
		1.0	11.58
		50.0	579.40
800	3.62221	0.1	0.45
		1.0	4.53
		50.0	226.37
1,200	2.41481	0.1	0.20
		1.0	2.01
		50.0	100.59
1,600	1.81111	0.1	0.11
		1.0	1.13
		50.0	56.58
2,000	1.44888	0.1	0.07
		1.0	0.72
		50.0	36.21
2,500	1.15911	0.1	0.05
		1.0	0.46
		50.0	23.17
3,000	0.96592	0.1	0.03
		1.0	0.32
		50.0	16.09

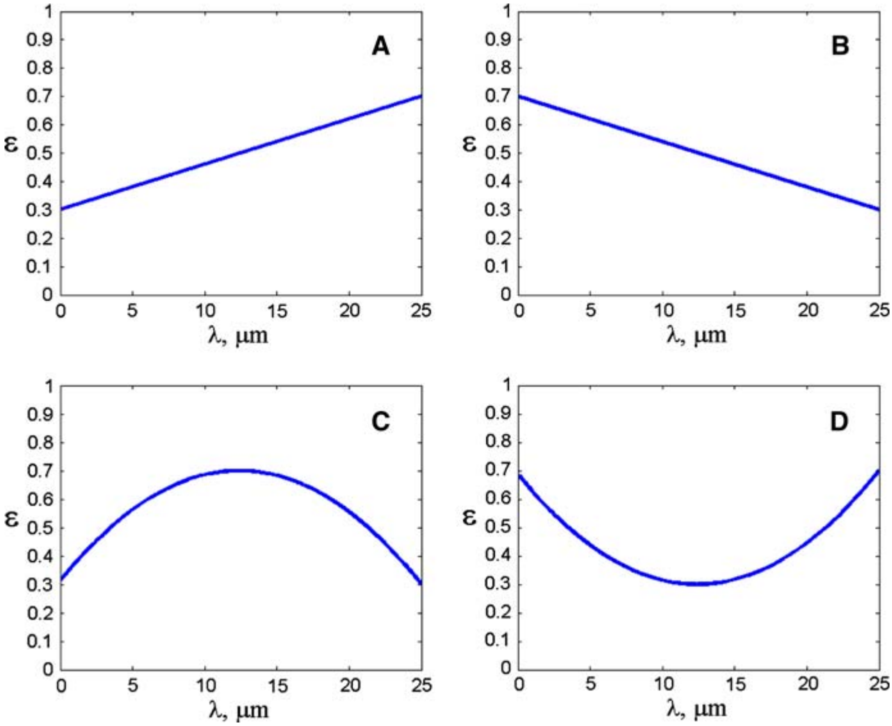

Fig. 1 Emissivity functions

determination for targets of 300 K and 3,000 K, respectively. So, in theory, the peak-wavelength method (PWM) for temperature measurement can easily achieve good accuracy in application.

4 Uncertainty Analyses for Non-blackbody Surfaces

It must be pointed out that all the favorable results above assume a blackbody target. However, what will the situation be for a real surface (non-blackbody)? Here we will investigate it theoretically. First, we selected four typical emissivity functions as shown in Fig. 1.

By using the following equation, we can obtain several spectral distribution curves for real surfaces with known temperature and different emissivity functions (A-D):

$$L_{\text{real}}(\lambda, T) = \varepsilon(\lambda) L_{\text{b}}(\lambda, T) \tag{5}$$

In Eq. 4, $L_{\text{real}}(\lambda, T)$ and $L_{\text{b}}(\lambda, T)$ are the spectral radiances of the real surface and a blackbody at the same temperature, T, respectively.

With these spectral curves, the maximum wavelength $\lambda_{\max}$ can be easily found for each surface. The temperatures related to the maximum wavelength $\lambda_{\max}$ were computed using Eq. 3 and are listed in Table 3. Here, T_{b} and T_{r} are the temperatures of the

Table 3 Temperature errors for a real surface (non-blackbody)

ε	T_b (K)	$\lambda_{b\ max}$ (μm)	T_r (K)	$\lambda_{r\ max}$ (μm)	$\Delta\lambda$ (μm)	ΔT (K)
A	300	9.65923	277.67	10.43598	−0.77675	22.33
	500	5.79554	474.47	6.10742	−0.31189	25.53
	800	3.62221	772.30	3.75211	−0.12990	27.70
	1,200	2.41481	1170.96	2.47469	−0.05988	29.04
	1,600	1.81111	1570.26	1.84541	−0.03430	29.74
	2,000	1.44888	1969.81	1.47109	−0.02220	30.19
	2,500	1.15911	2469.46	1.17344	−0.01433	30.54
	3,000	0.96592	2969.20	0.97594	0.01002	30.80
B	300	9.65923	316.41	9.15819	0.50104	−16.41
	500	5.79554	515.26	5.62390	0.17164	−15.26
	800	3.62221	814.66	3.55704	0.06517	−14.66
	1,200	2.41481	1214.34	2.38630	0.02851	−14.34
	1,600	1.81111	1614.18	1.79519	0.01591	−14.18
	2,000	1.44888	2014.08	1.43876	0.01013	−14.08
	2,500	1.15911	2514.00	1.15265	0.00645	−14.00
	3,000	0.96592	3013.96	0.96145	0.00447	−13.96
C	300	9.65923	289.10	10.02356	−0.36433	10.90
	500	5.79554	466.61	6.21026	−0.41472	33.39
	800	3.62221	746.37	3.88247	−0.26026	53.63
	1,200	2.41481	1130.51	2.56325	−0.14844	69.49
	1,600	1.81111	1520.70	1.90556	−0.09445	79.30
	2,000	1.44888	1914.05	1.51395	−0.06506	85.95
	2,500	1.15911	2408.24	1.20327	−0.04417	91.76
	3,000	0.96592	2904.13	0.99781	−0.03189	95.87
D	300	9.65923	329.73	8.78837	0.87086	−29.73
	500	5.79554	545.86	5.30866	0.48687	−45.86
	800	3.62221	850.64	3.40658	0.21563	−50.64
	1,200	2.41481	1252.45	2.31369	0.10112	−52.45
	1,600	1.81111	1653.16	1.75287	0.05824	−53.16
	2,000	1.44888	2053.51	1.41113	0.03776	−53.51
	2,500	1.15911	2553.79	1.13469	0.02442	−53.79
	3,000	0.96592	3053.95	0.94886	0.01706	−53.95

blackbody surface and the real surface, respectively. $\lambda_{b\ max}$ and $\lambda_{r\ max}$ were calculated using Eqs. 3 and 5, respectively. $\Delta\lambda = \lambda_{b\ max} - \lambda_{r\ max}$ and $\Delta T = T_b - T_r$.

In Table 3, it is shown that accurate measurements of real surfaces can also be made. Here, the sample increment of λ is 1.56188×10^{-5} μm. If the emissivity of an object is equal to one or is wavelength-independent, PWM can measure the temperature of the blackbody. In fact, the emissivity function of an object is not constant. Thereby, the error of this method depends mainly on the emissivity function. For the above-mentioned emissivity functions, the largest error was 95.87 K at 3,000 K. We conclude that this method offers good accuracy and practical potential.

5 Experimental Setup

An experimental setup was constructed in our lab as shown in Fig. 2. A simple heating apparatus was employed to heat the sample and measure its temperature. A Fourier transform infrared (FTIR) spectrometer was used to record the spectral radiance of

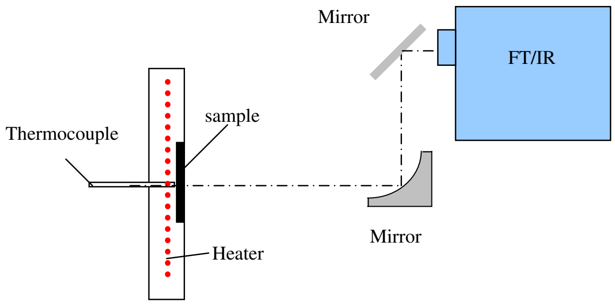

Fig. 2 Experimental setup

Table 4 Measurement results

Sample	T (K)	λ_{max} (μm)	T_r (K)	ΔT (K)
S1 (Graphite)	300	9.733	297	3
	500	5.975	484	16
	800	3.635	796	4
	1,200	2.414	1,186	14
S2 (Copper)	300	10.333	280	20
	500	6.245	463	36
	800	3.715	779	21

the samples. The thermocouple is used to obtain the true temperature of the sample during the experiment. Two samples were measured at different temperatures, and the computed temperatures were calculated from the maximum wavelength, λ_{max}. The results are listed in Table 4. It is shown that reasonable accuracy can be obtained for both samples.

Here, the values of ΔT are small and positive. We suspect that the absorption from non-sample material in the experimental environment, such as water and carbon dioxide, leads to the shift of the maximum wavelength, λ_{max}. The absorption curve of water and carbon dioxide can be obtained from other experiments prior to measuring the target's temperature. Then, the absorption curve can be introduced to smooth data when processing the spectra. We are currently exploring how to reduce the error associated with the emissivity function.

6 Conclusion

It has been theoretically and experimentally demonstrated that the peak-wavelength method (PWM) may be an accurate and practical method for temperature measurement by employing a spectrometer. With this method, it is not necessary to calibrate the instrument in advance and the estimated temperature is less influenced by the environment than that obtained using some other methods.

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