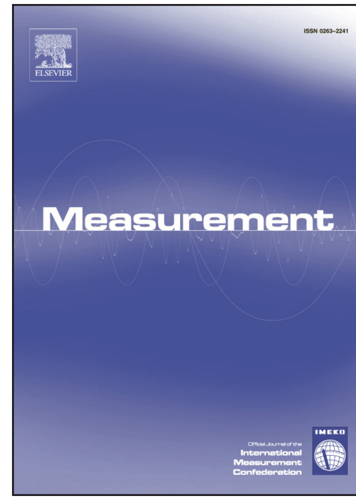

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PII: S0263-2241(13)00340-0
DOI: http://dx.doi.org/10.1016/j.measurement.2013.07.041
Reference: MEASUR 2421

To appear in: *Measurement*

Received Date: 31 May 2012
Revised Date: 24 July 2013
Accepted Date: 29 July 2013

Please cite this article as: H. Wang, D. Chen, G. Wang, Y. Long, J. Luo, L. Liu, Q. Yang, Measurement Technology for Material Emissivity under High Temperature Dynamic Heating Conditions, *Measurement* (2013), doi: http://dx.doi.org/10.1016/j.measurement.2013.07.041

Measurement Technology for Material Emissivity under High Temperature Dynamic Heating Conditions

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The thermal dissipation of radiation is main heat shield mechanism for non-ablative thermal protection materials on hypersonic vehicles withstanding high temperature dynamic heating cycle during endo-atmospheric ascent, cruise and reentry. Therefore, it is necessary to know the thermal radiative properties of the material under the simulated high temperature dynamic heating conditions on the ground. The emissivity depends on the surface state and its temperature. A new simultaneous measurement technology of emissivity and varying surface temperature is proposed under high temperature dynamic heating conditions. This new technology solved synchronous measurement problems by utilizing spectral signal of Fourier transform infrared (FTIR) spectroscopy. The calibration of different temperature ranges, the background disturbances, the influences on temperature measurement by wavelength range and its corresponding fluctuations of measurement signal, were thoroughly investigated. The measured results of steel and graphite as reference materials proved the effectiveness of this simultaneous measurement technology and showed great potential in engineering applications under high temperature dynamic heating conditions.

Keywords: Emissivity; Synchronous measurement; Dynamic heating; Fourier transform infrared spectroscopy

1. Introduction

Some components such as nose tip and sharp wing leading edge surfaces will undergo rigorous aerodynamic heating due to the compression effect of shock wave and intensive viscidity frication between the shell's surface of hypersonic vehicle and air during endoatmospheric ascent, cruise and reentry. The temperature of stagnation point area may exceed 2000K under extremely aerothermodynamics condition. Thus, thermal stability and good mechanical properties are extremely important for the safety of hypersonic flight. For these purposes, non-ablative heat shielding materials are developed and applied in slender vehicles in order to improve its lift-drag ratio, maneuverability and reusability. Outward thermal radiation is main thermal dissipation approach for non-ablative heat shielding materials. The normal emissivity is an important evaluating parameter for thermal radiation of heat shielding materials. Depending on the surface state and the temperature of thermal protection material, the emissivity may change. The temperature may rise rapidly when hypersonic vehicle is undergoing dynamic heating process during reentry period. The high emissivity will reduce surface temperature, and possibly avoid obvious ablation phenomena due to hyperthermal oxidation. Therefore, the measurement results of emissivity under ground dynamic heating test are important parameters during numerical calculation of heat transfer or development and optimization of thermal shielding material and its structure. In addition, spectral emissivity is also one of the important radiation characteristic parameters, based on which spectral selectivity of material is analyzed and the emissivity can be obtained indirectly by numeric integral in this paper.

In order to obtain spectral emissivity and normal emissivity, Fourier transform infrared (FTIR) spectroscopy was employed for spectral radiance measurement with high resolution, high signal-noise ratio and accuracy. Some applications of FTIR spectrometer to spectral emissivity measurement of material have been reported [1-6] and these measurement methods of emissivity were only available on static heating conditions. Direct and indirect methods are two basic methods for obtaining emissivity. For direct measurement method, emissivity is measured from the radiances ratio between heated sample and blackbody source with the same temperatures and optical paths, which means that the surface temperature of sample should be known firstly. For indirect measurement method, emissivity is obtained from reflectivity and transmittance; then, the corresponding surface temperature is then calculated from emissivity and radiance by Planck's law.

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Nomenclature		Greek symbol	
L_b	directional spectral radiance of blackbody, W/(m^2·μm·sr)	ε_n	normal emissivity
L_n	normal spectral radiance, W/(m^2·μm·sr)	λ	wavelength, μm
$L_{n,b}$	normal spectral radiance of blackbody, W/(m^2·μm·sr)	χ	least squares error
L_0	sum of directional spectral radiance from the collection optical system, detector, W/(m^2·μm·sr)	*Subscripts*	
		n	normal direction
		b	blackbody
R'	ratio between radiances of two different wavelengths	i or j	the ith or jth …
c_1	first constant of Planck function, 0.59544×10^{-16}W·m^2	meas	measured
c_2	second constant of Planck function, 14,388μm·K	sur	surrounding
N	the number of wavelengths	ref	reflected
LN	spectral response linearity of detector		

Therefore, surface temperature of heated sample must be measured or calculated first in direct method of emissivity based FTIR measurement system. Some direct or indirect measurement methods of surface temperature have been explored. One of the indirect temperature measuring methods is that thermocouple is embedded in lateral drilled hole adjacent to the center area of sample surface [7]. Jinmin Dai *et al.* [1] indirectly obtain surface temperature of sample from radiation temperature of blackbody cavity in heating body backside only when the temperature gradient between the heating body and its sample is almost negligible. In addition to that, the temperature of heating plate measured by thermocouple is also assumed as the temperature of heated sample when the heating process reached on steady-state [8]. Because isothermal condition must be approximated as much as possible in order to reduce difference of temperature between sample's surface and measurement location, these indirect approaches are difficult to measure the sample surface temperature under the dynamic heating condition. Surface temperature can also be directly measured by thermocouple [9]. But, the thermocouple cannot be welded on the surface of non-metallic type thermal protection material. Even if thermocouple can be welded on the surface of metallic type thermal protection material, it is not easy to survive because the strong scouring effect of high temperature flow field of plasma wind tunnel under dynamic heating condition. Contactless direct radiation thermometry methods are also adopted based on some special spectral characteristic. For example, radiation thermometry is adopted based Christiansen [10] approach, i.e. spectral emissivity is always one in Christiansen's wavelength; two color thermometry [11] is usually adopted under high temperature condition. But, the one-to-one correspondence can also hardly be kept in real time between spectral radiance signals by FTIR spectrometer and temperature values obtained by above discussed contactless direct methods under the dynamic heating condition.

In order to avoid measurement of surface temperature, emissivity can be indirectly obtained from reflectivity and transmittance based on Kirchhoff's law [12]. Reflectivity of the heated sample at the temperature of interest is measured by comparing the reflected light off the sample to that reflected off of a calibrated reflectivity reference at room temperature, which means that an external mirror in the interface optics is used to alternate viewing the sample and the reference and these corresponding reflectance signals are sampled respectively. Consequently, the indirect emissivity measurement method from reflectivity also can't be suitable for the measurement requirement under dynamic heating condition with temperature varying. Under certain spectral and directional conditions, a one-to-one correspondence between the emissivity and the p- and s-polarized radiance ratios for certain metals occurs during heating. Although emissivity is indirectly obtained from the correspondence relationship [13], many materials can't possess with these special characteristic bands.

In this work, the measurement technology under dynamic high temperature heating process was explored in order to obtain time-resolved temperature and its corresponding normal emissivity. Normal spectral signal from FTIR spectrometer measurement system is calibrated by blackbody source; the corresponding surface temperatures are calculated based on normal spectral radiance distribution calibrated in time history by multi-spectral measurement method with added smoothing technique.

Then, normal spectral emissivity history is obtained based on these calculated temperature points and these corresponding spectral radiance values. Finally, the normal emissivity history under dynamic heating condition is indirectly approximated from time-resolved normal spectral emissivity by numeric integral approach.

In the next section, the measurement principle and methodology of material thermal radiation characteristic parameters based on FTIR spectrometer are thoroughly described in dynamic heating condition. The dynamic heating test apparatus and measurement equipment, as well as optical path of measurement system are proposed in Sec. 3. Finally, surface temperature history and its corresponding emissivity results of steel and graphite materials that validate the dynamic measurement technology are presented and the results were compared with those of other researchers in Sec. 4.

2. Measurement Methods

Thermal radiation characteristics of materials generally are affected by composition, surface state, temperature, spectral selectivity and other factors, which are different from those of ideal blackbody [14-18]. In order to evaluate thermal dissipation capability of material radiation uniformly and with view to measurement direction limited of optical path, normal spectral emissivity and normal emissivity are selected as main evaluating parameters of radiation characteristic.

2.1. Measurement method of emissivity

Spectral emissivity, a surface radiative property is defined as the ratio of spectral radiance emitted by sample surface to that emitted by a blackbody at the same temperature. Because measurement direction is normal to sample surface in this paper, normal spectral emissivity is needed and can be expressed as

$$\varepsilon_{\mathrm{n}}(\lambda,T)=\frac{L_{\mathrm{n}}(\lambda,T)}{L_{\mathrm{n,b}}(\lambda,T)} \tag{1}$$

where $L_{\mathrm{n}}(\lambda,T)$ is the normal spectral radiance of sample and $L_{\mathrm{n,b}}(\lambda,T)$ is the normal spectral radiance of blackbody at the same temperature and wavelength λ. These suffix, n and b are denoted as the normal direction and blackbody respectively.

In fact, normal spectral radiance, $L_{\mathrm{n,\,meas}}(\lambda,T)$ measured by FTIR spectroscopy can be written as:

$$L_{\mathrm{n,\,meas}}(\lambda,T)=L_{\mathrm{n}}(\lambda,T)+L_{\mathrm{sur,\,ref}}(\lambda,T_{\mathrm{sur}})+L_0(\lambda) \tag{2}$$

where the subscripts n and sur are referring to the normal direction and the surroundings, $L_n(\lambda,T)$ is the self-emitted normal spectral radiance from sample, $L_{\mathrm{sur,\,ref}}(\lambda,T_{\mathrm{sur}})$ is the spectral radiance from the surrounding irradiation at temperature, T_{sur} reflected by the sample[19], $L_0(\lambda)$ is the total spectral radiance from the collecting optical system, detector itself[20] and atmospheric scattering and absorption (H_2O, CO_2, dust particles, etc). Because this surrounding radiation is considered to be blackbody, eq. (2) can be rewritten as

$$L_{\mathrm{n,\,meas}}(\lambda,T)=\varepsilon_{\mathrm{n}}(\lambda,T)L_{\mathrm{b}}(\lambda,T)+\left(1-\varepsilon_{\mathrm{n}}(\lambda,T)\right)L_{\mathrm{b}}(\lambda,T_{\mathrm{sur}})+L_0(\lambda) \tag{3}$$

Because the temperature of sample is much hotter than the environmental temperature (usually room temperature), which means $L_{\mathrm{b}}(\lambda,T)\gg L_{\mathrm{b}}(\lambda,T_{\mathrm{sur}})$, then the second term on the right-hand-side of Eq. (3) can be neglected without compromising measurement accuracy [21]. Therefore, the second term is approximately regarded as a constant without considering the variability of spectral emissivity. Consequently, eq. (3) can be simplified as

$$L_{\mathrm{n,\,meas}}(\lambda,T)\cong\varepsilon_{\mathrm{n}}(\lambda,T)L_{\mathrm{b}}(\lambda,T)+B(\lambda) \tag{4}$$

Where, $B(\lambda)=\left(1-\varepsilon_{\mathrm{n}}(\lambda,T_{\mathrm{sur}})\right)L_{\mathrm{b}}(\lambda,T_{\mathrm{sur}})+L_0(\lambda)$ is defined as background spectral radiance, which can be measured before sample is heated.

The spectral electrical signal, $S(\lambda,T)$ measured by detector can be related with spectral radiance measured, $L_{\mathrm{n,\,meas}}(\lambda,T)$ by means of spectral photoelectric response, $R(\lambda,T)$ of FTIR spectrometer, i.e.

$$S(\lambda,T)=\varepsilon_{\mathrm{n}}(\lambda,T)R(\lambda,T)L_{\mathrm{b}}(\lambda,T)+R(\lambda,T)B(\lambda) \tag{5}$$

Eq. (5) can also be written as

$$K(\lambda,T)\cdot S(\lambda,T)=\varepsilon_{\mathrm{n}}(\lambda,T)L_{\mathrm{b}}(\lambda,T)+B(\lambda) \tag{6}$$

where, spectral response, $K(\lambda,T)=1/R(\lambda,T)$. From eq. (6), spectral emissivity can be calculated as

$$\varepsilon_{\mathrm{n}}(\lambda,T)=\frac{K(\lambda,T)\cdot S(\lambda,T)-B(\lambda)}{L_{\mathrm{b}}(\lambda,T)} \tag{7}$$

Where, The detailed calibrations about $K(\lambda,T)$ and $B(\lambda)$ are described in the following subsection 2.2.

If this normal spectral emissivity is available in wavelength range $[\lambda_1,\ \lambda_2]$ due to constraints from measurement equipment and corresponding surface temperature are known, the normal emissivity can be approximated to some extent with view of practical application as

$$\varepsilon_{\mathrm{n}}(T) \cong \frac{\int_{\lambda_1}^{\lambda_2} \varepsilon_{\mathrm{n},\lambda}(T) L_{\mathrm{b}}(\lambda,T)\,d\lambda}{\int_{\lambda_1}^{\lambda_2} L_{\mathrm{b}}(\lambda,T)\,d\lambda} \qquad (8)$$

Where, L_{b} is the spectral radiance of blackbody. Because the signal sampled by computer is discrete value, the above Eq. (8) may be rewritten by numeric integral method as

$$\varepsilon_{\mathrm{n}}(T) \approx \sum_i \varepsilon_{\mathrm{n},\lambda_i} L_{\mathrm{b}}(\lambda_i,T) \Big/ \sum_i L_{\mathrm{b}}(\lambda_i,T) \qquad (9)$$

Before normal spectral emissivity is approximated based Eq. (8), surface temperature must be obtained. This will be discussed in the following subsection 2.3.

2.2. Calibration Method of Measurement System

Because the sample temperature range is wide, the spectral response of the FTIR is slightly variable, which is different from the Ref. [22]. Therefore, wide range of temperature is divided into many subintervals, which means that spectral response of detector and background radiance almost keep constant in each subinterval of temperature range. Spectral response values and background radiance are calibrated by two-temperature method [20] within each subinterval.

It is supposed that the spectral response, $K_{i,i+1}(\lambda)$ of spectrometer is constant within temperature range, [T_i, T_{i+1}]. Then, two spectral radiances of blackbody furnace at temperatures, T_i and T_{i+1}, are given respectively based Eq. (6) as

$$L_b(\lambda,T_i) = S_b(\lambda,T_i) K_{i,i+1}(\lambda) - B(\lambda), \qquad (10)$$

$$L_b(\lambda,T_{i+1}) = S_b(\lambda,T_{i+1}) K_{i,i+1}(\lambda) - B(\lambda). \qquad (11)$$

Combined with Eq.(10) and Eq.(11), the spectral response of FTIR spectrometer measurement system can be solved by

$$K_{i,i+1}(\lambda) = \frac{L_b(\lambda,T_{i+1}) - L_b(\lambda,T_i)}{S_b(\lambda,T_{i+1}) - S_b(\lambda,T_i)}. \qquad (12)$$

The background radiance is calculated from Eq. (11) and Eq. (12), i.e.,

$$B(\lambda) = K_{i,i+1}(\lambda) S_b(\lambda,T_{i+1}) - L_b(\lambda,T_{i+1}). \qquad (13)$$

Based on Eq. 12 and Eq.13, calibration parameters of spectral response and background radiance are determined by wavelength and static temperature points of blackbody. Then, the self-emitted normal spectral radiance from sample can be calibrated based on calibration parameters of measurement system and spectral signal of sample, as Eq. (6).

From these above discussion, wide temperature range needs to be divided into many subintervals. Therefore, the scan velocity of FTIR spectrometer must be enough high in order to obtain more spectral signals, $S(\lambda,T)$ in quickly varying temperature history of dynamic heating condition.

2.3. Contactless Measurement Methods of Temperature based on Infrared Spectrometer

2.3.1. Two color thermometry [11]

If $\exp\left(c_2/(\lambda T)\right) \gg 1$, then the Planck's law can be approximated by Wien's law, and the spectral radiance, $L(\lambda,T)$ of sample is given by

$$L(\lambda,T) = \varepsilon(\lambda,T) c_1 \exp\left(-c_2/(\lambda T)\right) \big/ \lambda^5, \qquad (14)$$

Where, c_1, c_2 are the constants for Planck function; $\varepsilon(\lambda,T)$ is spectral emissivity of sample. If spectral emissivities are same with each other at two adjacent wavelengths, λ_1 and λ_2, then the ratio between two spectral radiances is formulated based on Eq.(14), as

$$R' = \frac{L(\lambda_1)}{L(\lambda_1)} = \left(\frac{\lambda_2}{\lambda_1}\right)^5 \exp\left(\frac{c_2}{T}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\right) \qquad (15)$$

Solving for surface temperature, T from Eq. (15),

$$T = c_2(\lambda_1 - \lambda_2) \Big/ \left(\ln\left(L(\lambda_1)\lambda_1^5 \Big/ L(\lambda_2)\lambda_2^5 \right) \lambda_1 \lambda_2 \right) \qquad (16)$$

2.3.2. Multi-spectral measurement method of temperature

Similar to Eq. (14), the spectral radiances of sample at multi-wavelengths are formulated as

$$L(\lambda_i,T) = \varepsilon(\lambda_i,T) c_1 \exp\left(-c_2/(\lambda_i T)\right) \big/ \lambda_i^5, \quad i = 1, 2 \cdots N. \qquad (17)$$

Here, N is the number of wavelengths. The ratio between radiances of any two wavelengths among multi-spectral formulations in Eq. (17) is given,

$$R'_{i,j} = \frac{L(\lambda_i,T)}{L(\lambda_j,T)} = \frac{\varepsilon(\lambda_i,T)}{\varepsilon(\lambda_j,T)} \cdot \frac{\lambda_j^5}{\lambda_i^5} \exp\left(\frac{c_2}{T}\frac{\lambda_i - \lambda_j}{\lambda_i \lambda_j}\right),$$

$$(\ i = 1, 2 \cdots (N-1);\ j = i+1, \cdots, N\ ). \qquad (18)$$

In Eq. (17), measurements are made on N different wavelengths and the resulting set of equations for i =1 to N contains $(N+1)$

unknown variables, and hence cannot be solved. Therefore, the emissivity $\varepsilon(\lambda,T)$ may be expressed as an explicit function of wavelength containing not more than (N-1) variables in certain wavelength subinterval of temperature measurement, which is obtained by spectral emissivity measurement methods under static heating condition and function fitting. The exponential emissivity model [23] is taken here as

$$\varepsilon(\lambda,T)=\exp(a\lambda+b). \tag{19}$$

Substituting Eq. (19) into Eq. (18) yields the following relationship

$$\frac{\lambda_i^5}{\lambda_j^5}\cdot R_{i,j}=\exp\left(a\left(\lambda_i-\lambda_j\right)\right)\cdot\exp\left(\frac{c_2}{T}\frac{\lambda_i-\lambda_j}{\lambda_i\lambda_j}\right),$$

$$(\ i=1,2\cdots(N-1);\ j=i+1,\cdots,N\ ). \tag{20}$$

Then, carrying natural logarithm operation on two sides of Eq. (20) leads to

$$\ln\left(\frac{R'_{i,j}\lambda_i^5}{\lambda_j^5}\right)=a\left(\lambda_i-\lambda_j\right)+\frac{c_2}{T}\frac{\lambda_i-\lambda_j}{\lambda_i\lambda_j},$$

$$i=1,2\cdots(N-1);\ j=i+1,\cdots,N. \tag{21}$$

Then, the above Eq. (21) may be rewritten as

$$y_{i,j}=a_{i,j}x_1+b_{i,j}x_2,$$

$$(\ i=1,2\cdots(N-1);\ j=i+1,\cdots,N\ ). \tag{22}$$

Here $y_{i,j}=\ln\left(R'_{i,j}\cdot\lambda_i^5/\lambda_j^5\right)$, $a_{i,j}=\lambda_i-\lambda_j$, $b_{i,j}=c_2\left(\lambda_i-\lambda_j\right)/\left(\lambda_i\lambda_j\right)$, $x_1=a$, $x_2=1/T$.

In order to improve measurement uncertainty, the unknown x_1 and x_2 are determined by the least linear squares algorithm [23] i.e. minimizing the summed square of residuals, (χ) given by

$$\chi=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left(y_{i,j}-\hat{y}_{i,j}\right)^2 \tag{23}$$

Where $y_{i,j}$ is calculated based on Eq.(22) and $\hat{y}_{i,j}$ is obtained by the measured values, i.e.

$$\hat{y}_{i,j}=\ln\left(\hat{R}_{i,j}\lambda_i^5/\lambda_j^5\right),\quad \hat{R}_{i,j}=\frac{\hat{L}(\lambda_i,T)}{\hat{L}(\lambda_j,T)}$$

Where, $\hat{L}(\lambda_i,T)$ is the measured spectral radiance of sample; the measuring wavelengths, λ_i and λ_j are also known. Then, the surface temperature reduces to

$$T=1/x_2 \tag{24}$$

3. Experimental

The experimental setup (Fig. 1) has four main components: dynamic heating facility, an optical entrance path, calibration resource of blackbody furnace, and FTIR spectrometer. In this experimental configuration, sample is dynamically heated by high frequency induction heater, whose maximum power is 25KW with frequency up to 30 KHz. Heating efficiency of heater is high and its supply power is adjusted according to the elevating rate of temperature. The background thermal radiation of heating resource may be neglected because the induction heating coil is cooled by pressured following water. With a view to these materials without electromagnetic induction effect, these samples may be heated through heat conduction from outside heating body of graphite. In order to simulate the heating condition of high frequency plasma wind tunnel, the window with ZnSe lens is fixed at the corresponding location on the optical path of measurement system. The optical entrance path consists of aperture diaphragm, flat gilded mirror and concave mirror for focus function, which guides the thermal radiation into spectrometer. The emission spectrum of radiation source is obtained by interferometer and measured by Liquid Nitrogen cooled HgCdTe (MCT) Infrared detectors. The high temperature blackbody furnace is adopted to calibrate the measurement system based on spectrometer.

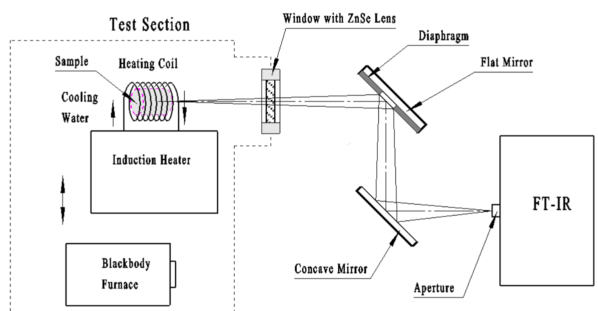

Fig. 1. Schematic view of the emissivity measurement experimental setup with high temperature dynamical heating

4. Results and Discussion

4.1 Surface temperature measurement technology study based on Infrared Spectroscopy

4.1.1. Contactless measurement methods

Because the proposed emissivity models and calculation processes are different from each other, the calculated errors from two color thermometry and multi-spectral thermometry are respectively compared and analyzed at different wavelength locations.

These predicted temperatures are obtained by above methods based on spectral radiance of ideal blackbody with known temperatures at two wavelength ranges. Figure 2 and 3 shows relative percent difference , $\Delta T/T$ between these calculated temperatures and those of actual blackbody. The relative percent differences are smaller in short wavelength range than that in long wavelength range for two methods. But the error trend at two wavelength ranges will both increase along with the elevation of temperature. These measurement results of two colors method are better than that of multi-wavelength method at relatively high temperature range. But at relatively long wavelength range and higher temperature, the temperature differences of multi-wavelength method are lower than that of two colors method instead. As a whole, these calculation errors of these two methods are small based on ideal spectral radiance of blackbody at short wavelength range.

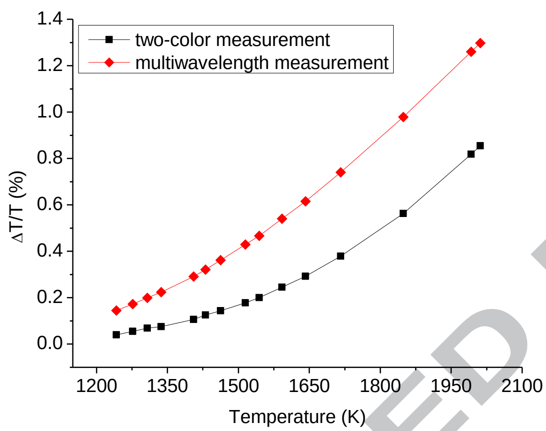

Fig. 2. Error results from two measurement methods (wavelength range: 1.5μm to 1.56μm)

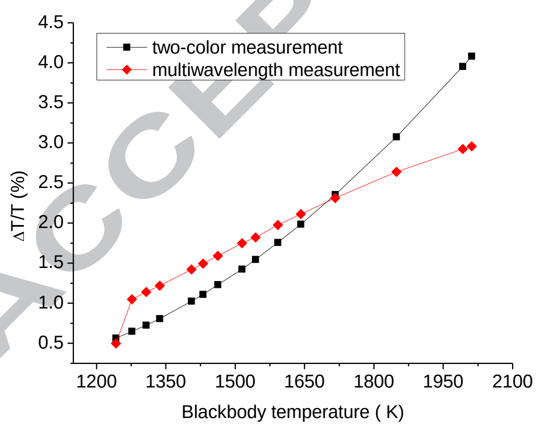

Fig. 3. Error results from two measurement methods (wavelength range: 2.23μm to2.29μm)

4.1.2. Processing technique of contactless measurement temperature based FTIR spectrometer

The above calculation error results of two methods are obtained based on the ideal spectral blackbody radiance. Practically, the measured signal curve from spectrometer is not smooth and contains some slightly fluctuations. The slightly fluctuation phenomena may come from high spectral resolution, high sensitivity and the measurement noise of detector. Therefore, these small fluctuations in output signal still exist even if the measurement process is carried out under static heating condition. In order to evaluate the effect of these small fluctuations on above methods of temperature measurement, these small fluctuation information extracted from in-situ measurement signal are added to ideal spectral blackbody radiance curves with known temperature of 1750K (shown as Fig.4 and Fig.5). Then, the temperature is calculated respectively by these above discussed methods at two wavelength ranges, which is summarized in Table 1.

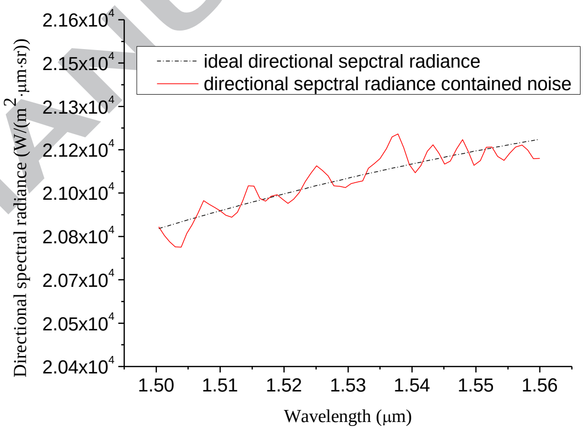

Fig. 4. Directional spectral radiance of blackbody contained noise (wavelength range: 1.5μm ~1.56μm)

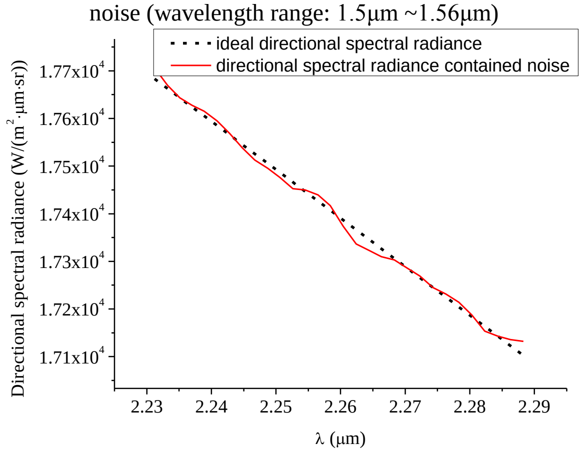

Fig. 5. Directional spectral radiance of blackbody contained noise (wavelength range: 2.23μm ~2.29μ)

The calculation results of two methods are obviously different from the set temperature value when spectral radiance curve contained small fluctuation noise. The multi-wavelength method is more sensitive and its calculation results are false even included with a negative absolute temperature. Therefore, this formidable problem needs to be resolved in order to accomplish the dynamic measuring based on FTIR spectrometer. Two smooth approaches are proposed in this work, among which linearity and exponential function nonlinearity smoothing approaches are respectively adopted in two-colors and multi-wavelength measurement methods. These approximation results by the least mean square algorithm (LMS) are given in Fig. 6 and 7 at wavelength range of 1.5μm to 1.56μm.

Table 1. Calculation results of temperature based on spectral blackbody radiance with and without noise

Wavelength / Measurement methods	1.5μm~1.56μm (contained noise)	2.23μm~2.29μm (contained noise)	1.5μm~1.56μm	2.23μm~2.29μm
Two-color thermometry	2081.3K	1784.5K	1705.7K	1742.6K
Multi-wavelength thermometry	666.1K	-1099K	1792K	1764K
Two-color thermometry with linearity smooth	1774.9K	1707.2K	--	--
Multi-wavelength thermometry with nonlinearity smooth	1741.7K	1703.2K	--	--

The comparison results in table 1 show that calculation sensitivity on small fluctuation of two methods is greatly reduced by the proposed linear or nonlinear smooth approach and the calculation accuracy of multi-wavelength method is improved.

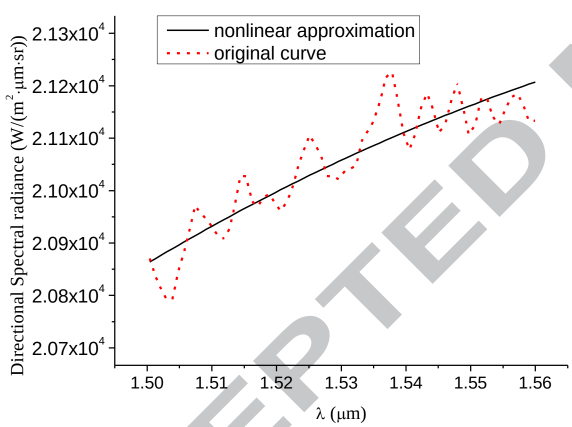

Fig. 6. Nonlinearity approximation (Wavelength range: 1.5μm to 1.56μm)

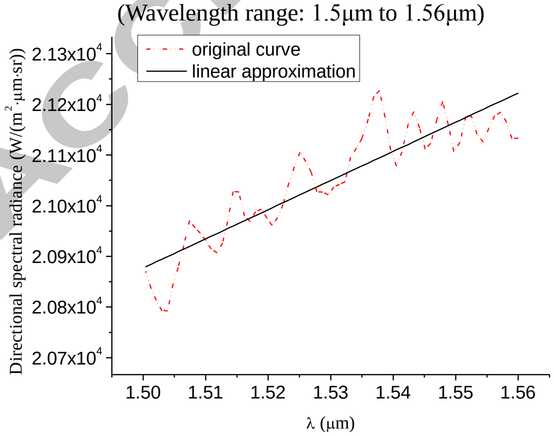

Fig. 7. Linear approximation (Wavelength range: 1.5μm to 1.56μm)

In order to demonstrate the validity of the above contactless temperature calculation method with nonlinear smoothing technique, the calculated temperature values are simultaneously compared with those measured by two-colors pyrometer when the graphite sample as reference emissivity material reach different heat balances by adjusting heating power. Wavelength range for temperature measurement is 1.6μm to 1.8μm.

Fig. 8 and 9 show the comparison results of time-wise steady state temperatures obtained by multi-wavelength calculation based on FTIR spectrometer and two-color pyrometer. These calculation values are consistent with these measured values and the relative percent difference is within 1%. Therefore, the proposed calculation method of sample surface temperature is adopted in this work with view of direct emissivity measurement under dynamic heating conditions.

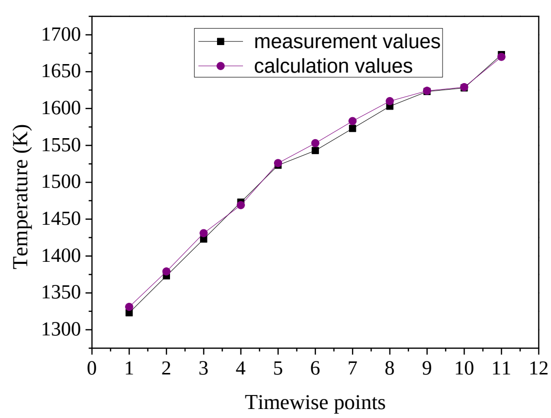

Fig. 8. Comparison of the temperatures obtained by the proposed calculation method and two-color pyrometer

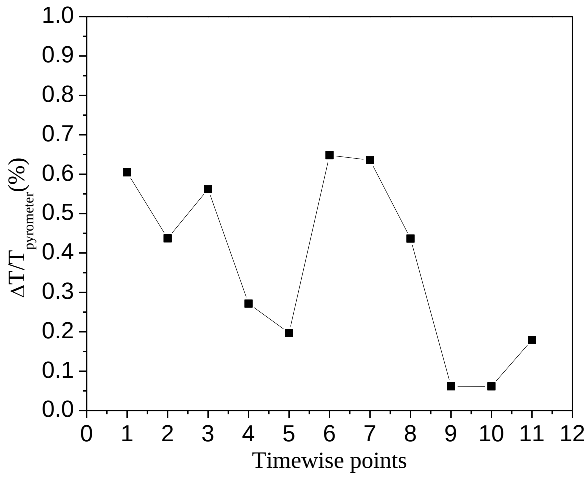

Fig. 9. Relative measurement difference of temperature between the proposed calculation and two-color pyrometer

4.2. Spectral response linearity of FTIR spectroscopy

Although shorter wavelength is preferred for better accuracy of temperature measurement as described in Fig.2, Fig. 3 and Table 1, it's also important to choice appropriate position and width of wavelength for contactless measurement temperature based on spectral response characteristic of FTIR spectrometer [24]. Good spectral response linearity contributes to improve robustness of measurement, which means the spectral response of FTIR is slightly varied with radiation resource at different temperature. Therefore, the spectral response of spectral radiation measurement equipment should be analyzed. The response linearity of infrared detectors has been studied [25-27]. Similar analysis about detector in FTIR spectroscopy is carried out in order to fix appropriate wavelength range in contactless measurement temperature. The spectral response linearity between different temperature subintervals is defined based on Eq. (12), as

$$LN\left(\left[T_i,T_{i+1}\right],\left[T_j,T_{j+1}\right],\lambda\right)=\frac{K_{i,i+1}(\lambda)}{K_{j,j+1}(\lambda)} \quad (25)$$
$$=\frac{L_b(\lambda,T_{i+1})-L_b(\lambda,T_i)}{S_b(\lambda,T_{i+1})-S_b(\lambda,T_i)}\cdot\frac{S_b(\lambda,T_{j+1})-S_b(\lambda,T_j)}{L_b(\lambda,T_{j+1})-L_b(\lambda,T_j)}$$

where $T_{i+1}=T_i+\Delta T$; $T_{j+1}=T_j+\Delta T$.

The spectral response linearity between the temperature subintervals of [1573K, 1623K] to [1623K, 1673K] is only given in this paper, shown in Fig.10 (with local zoom).

Fig. 10 shows the there is existing different spectral response characteristic of FTIR spectrometer with wavelength. Good spectral response linearity is located in wavelength range of 1.6μm to 2.5μm, which means linearity is close to one. Therefore, wavelengths of temperature calculation described in section 2.3 are limited to the range of 1.6μm to 2.5μm.

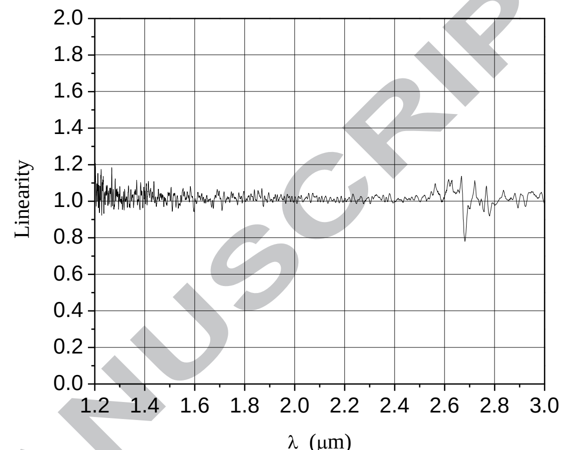

Fig. 10. Spectral response linearity distribution of measurement system (with local zoom)

4.3. Measurement Results of Emissivity

In order to validate the proposed measurement technology of material emissivity under high temperature dynamic heating condition, normal emissivities of steel and graphite as thermal radiation reference materials are measured.

Normal emissivity distribution of steel during dynamically heating process is given in Fig.11. The average value of emissivity for oxidized steel is about 0.76, which is close to emissivity of 0.78 as reported [28].

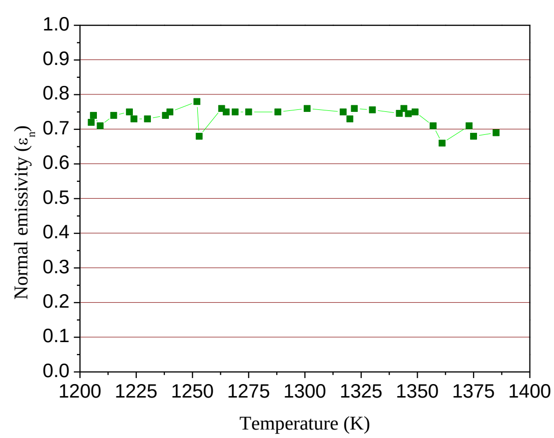

Fig.11. Normal emissivity of oxidized steel with temperature

Fig.12 and 13 show normal spectral emissivity and normal emissivity of graphite sample with corresponding temperature values under dynamic heating condition. The average normal emissivity is ~0.91 and emissivity distribution varies insignificantly with elevation process of surface temperature. Normal spectral emissivity varies slightly with different wavelength shown in Fig 12, which confirmed the gray body assumption of graphite. Because of atmospheric absorption affection from vapor and carbon dioxide in optical path, there are local abnormal phenomena at two wavelength positions in Fig. 12, which may be neglected during normal emissivity calculation. The experimental results of graphite sample are consistent with reported value [29].

For these materials with strong wavelength dependence, it is also possible to achieve reasonable accuracy of emissivity measurement because wavelength range and its width for temperature measurement can be adjusted based on local similarity degree of spectral radiances between sample and blackbody.

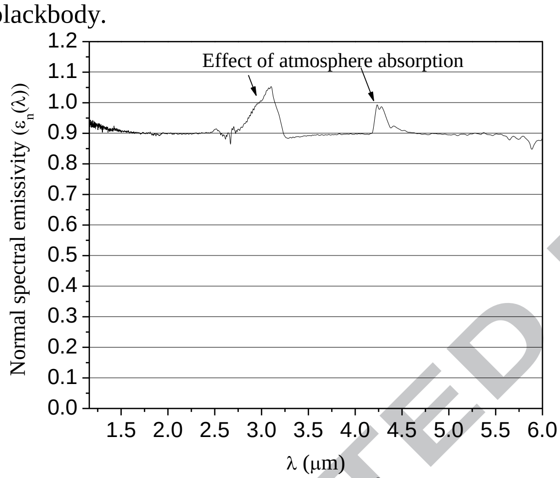

Fig. 12. Normal spectral emissivity of graphite at 1623K

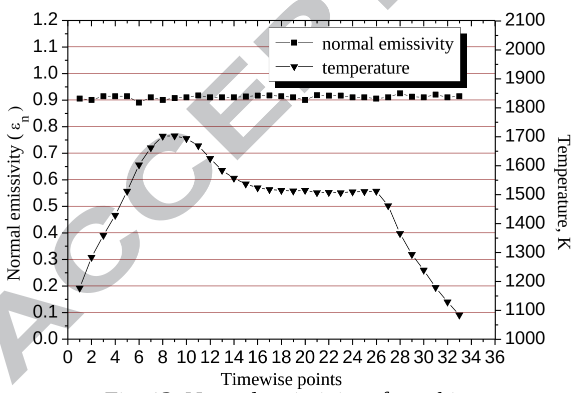

Fig. 13. Normal emissivity of graphite under dynamic heating condition

5. Conclusion

In this paper, a new simultaneous measurement technology has been employed under high temperature dynamic heating conditions. Surface temperature of sample is initially calculated by multi-wavelength method based on the time sequence calibrated spectral radiance of Fourier transform infrared (FTIR) spectroscopy under dynamic heating conditions. Taking into account of small noises in the time sequence spectral radiance calibrated from FTIR measurement system, a novel contactless temperature measurement method based on nonlinear smooth technology is given. In addition, a new effective identification method about spectral range of temperature measurement is adopted based on spectral response linearity analysis. Then, the sensitivity to noise about multi-wavelength method of measurement temperature is greatly decreased. The derived surface temperatures are consistent with measurements of two-color pyrometer with relative percent difference less than 1%. At the same time, spectral and normal emissivities are obtained from the measured temperature and the corresponding time sequence spectral radiance. In order to validate the proposed measurement technology of material emissivity under high temperature dynamic heating condition, normal emissivities of steel and graphite as thermal radiation reference materials were measured. The results are consistent with those reported by other researchers. One of the perspectives of the current work is then to extend the measurement technology to dynamic heating condition of high frequency plasma wind tunnel.

Acknowledgments

The authors gratefully acknowledge the financial support from National Natural Science Foundation of China under grant No. 90716018.

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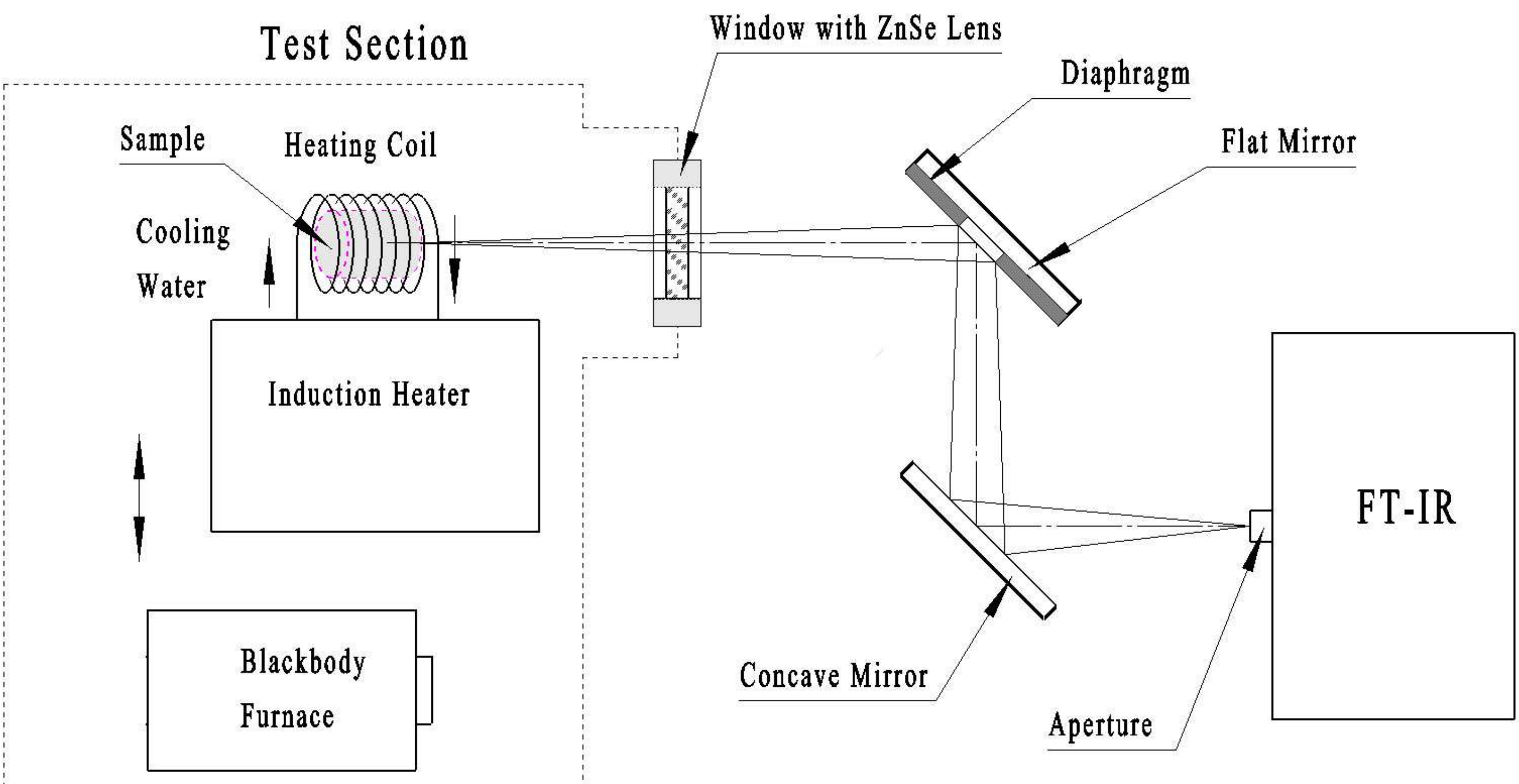
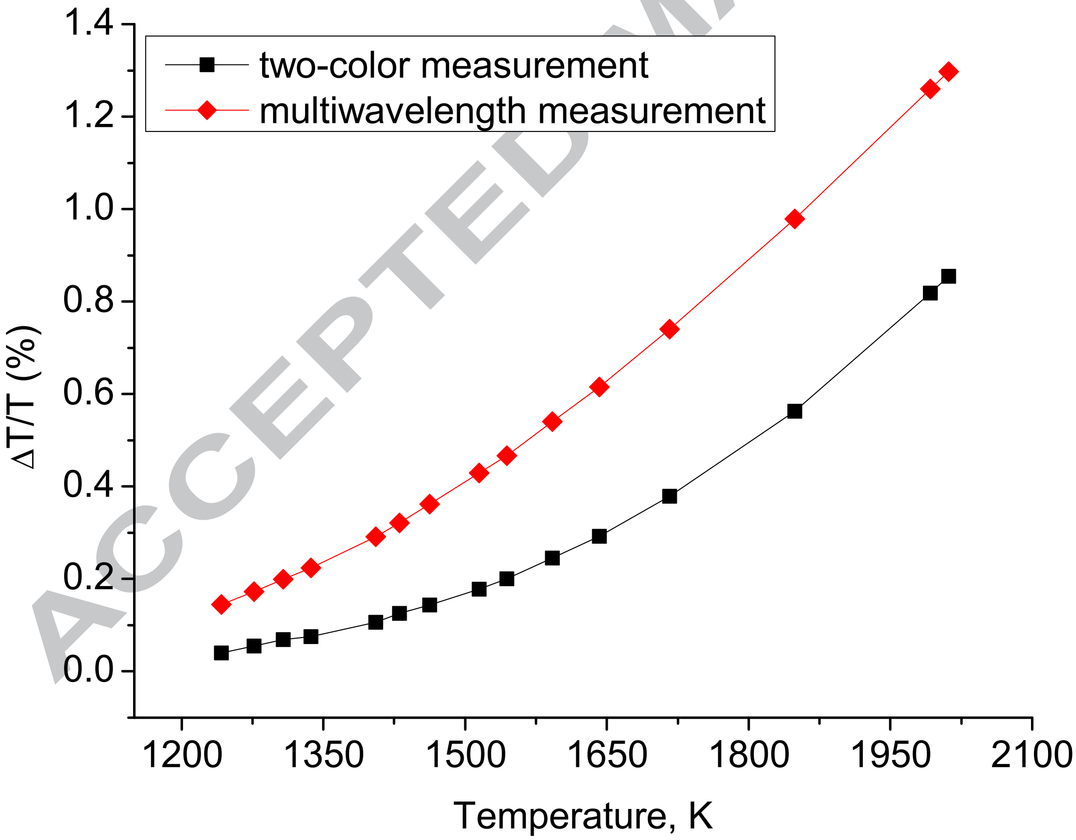
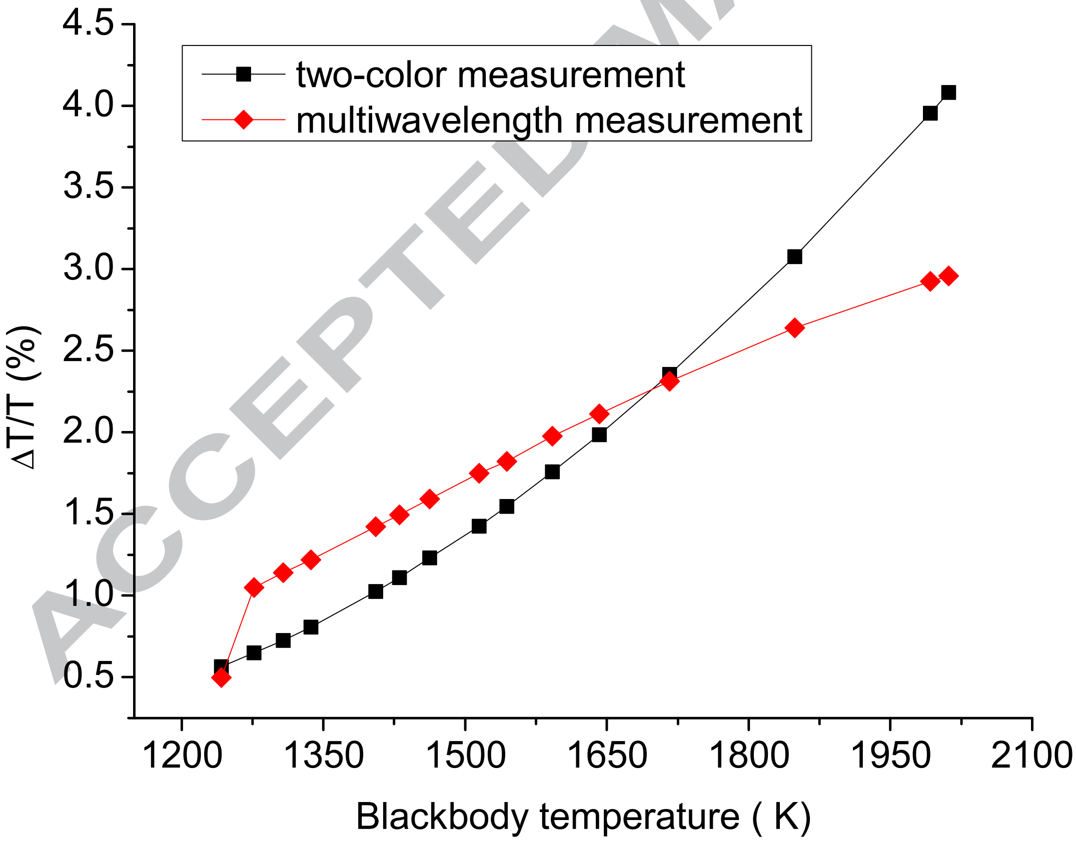


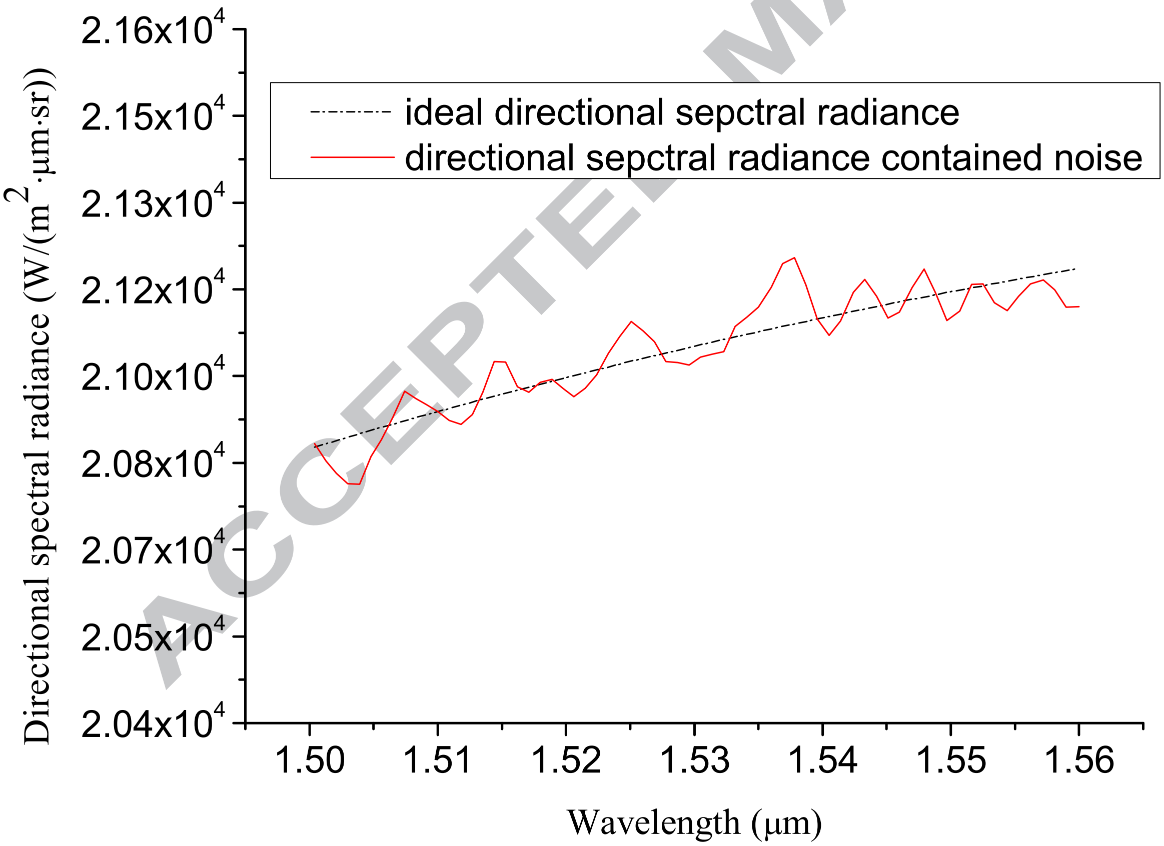
Test Section
Window with ZnSe Lens
Diaphragm
Flat Mirror
Sample
Heating Coil
Cooling
Water
Induction Heater
FT-IR
Blackbody
Furnace
Concave Mirror
Aperture



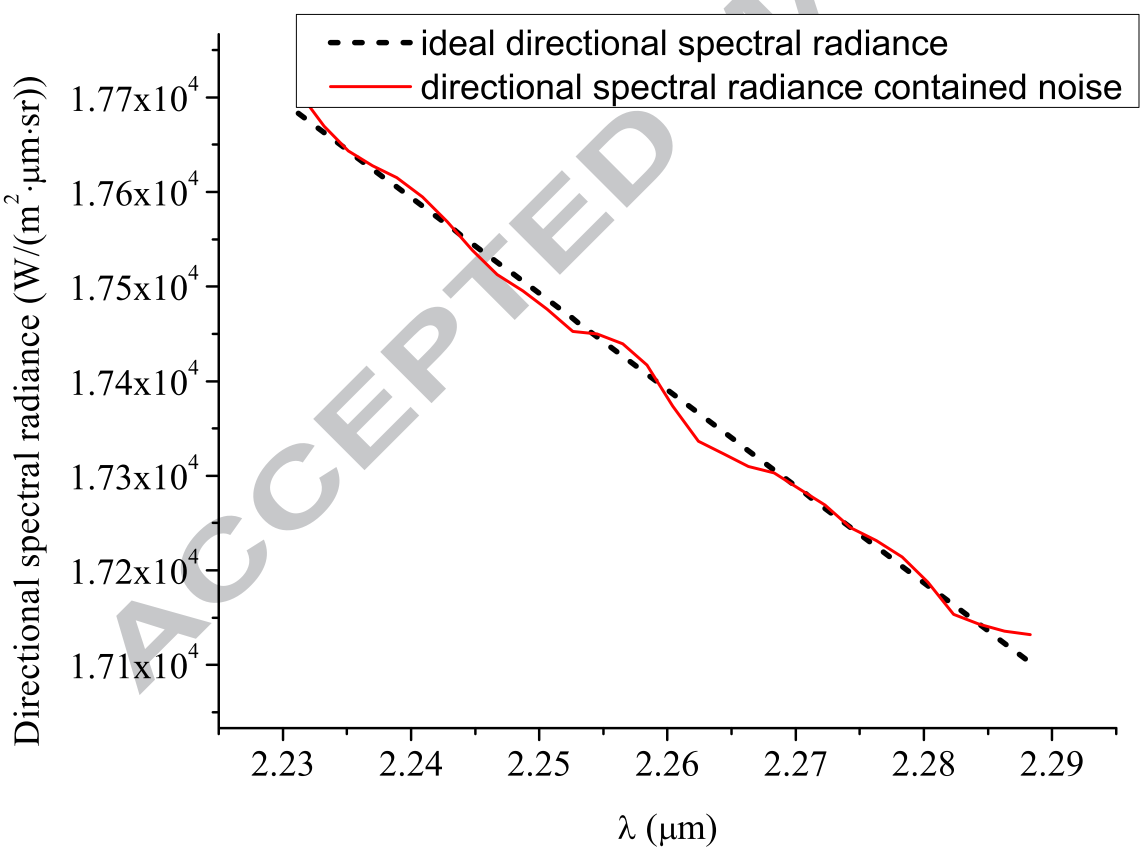
two-color measurement
multiwavelength measurement
ΔT/T (%)
Temperature, K
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1200
1350
1500
1650
1800
1950
2100



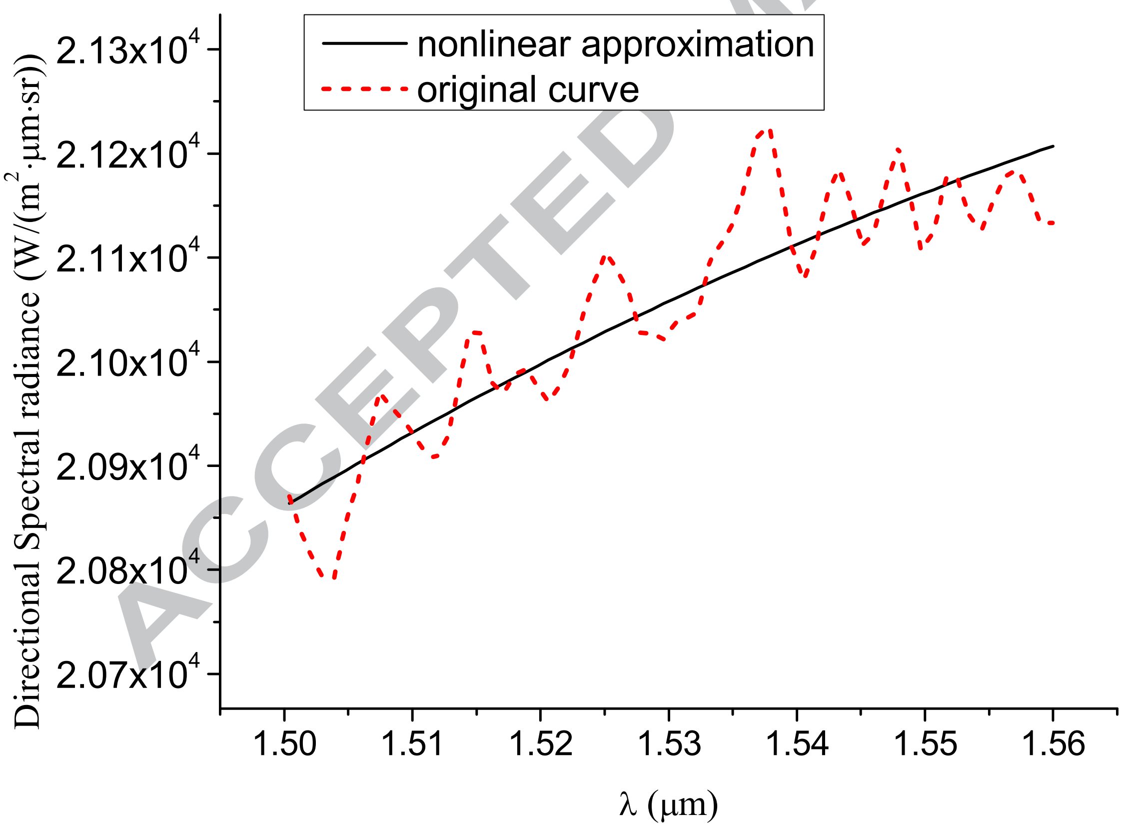
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ΔT/T (%)
1200
1350
1500
1650
1800
1950
2100
Blackbody temperature (K)
two-color measurement
multiwavelength measurement



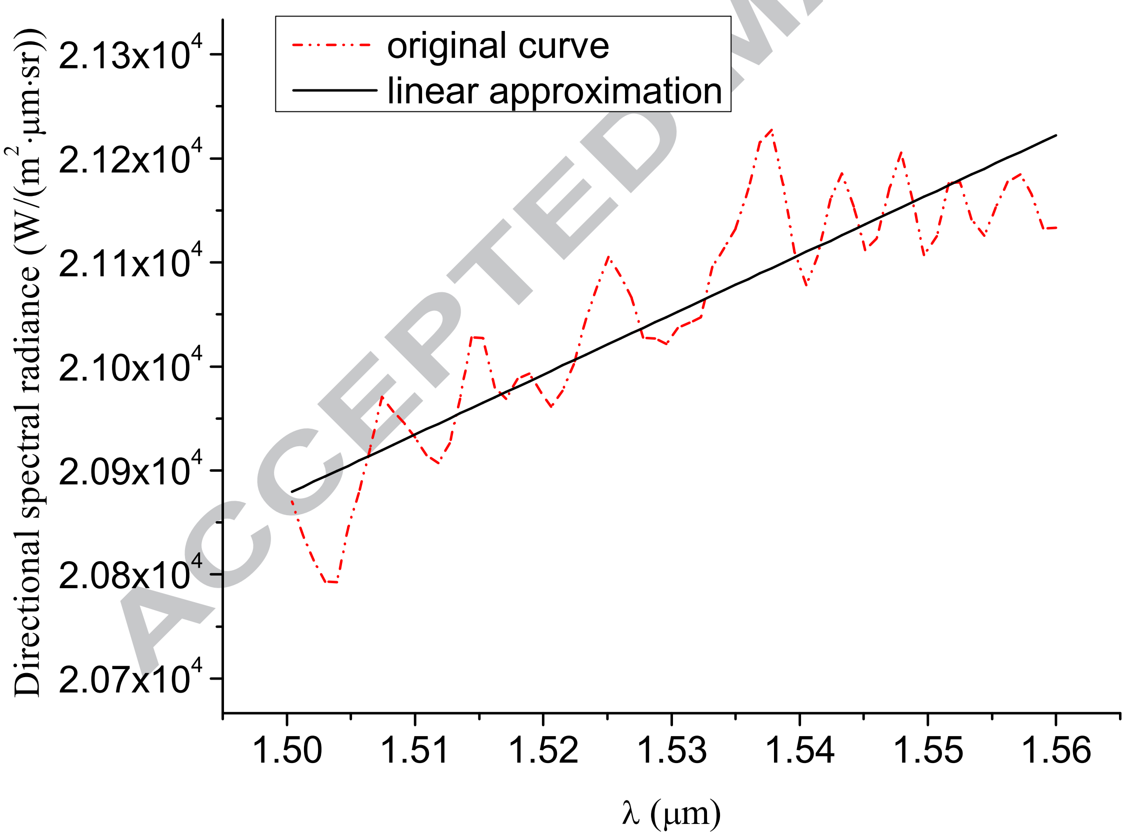
2.16x10^4
2.15x10^4
2.13x10^4
2.12x10^4
2.10x10^4
2.08x10^4
2.07x10^4
2.05x10^4
2.04x10^4
Directional spectral radiance (W/(m^2·μm·sr))
ideal directional sepctral radiance
directional sepctral radiance contained noise
1.50
1.51
1.52
1.53
1.54
1.55
1.56
Wavelength (μm)



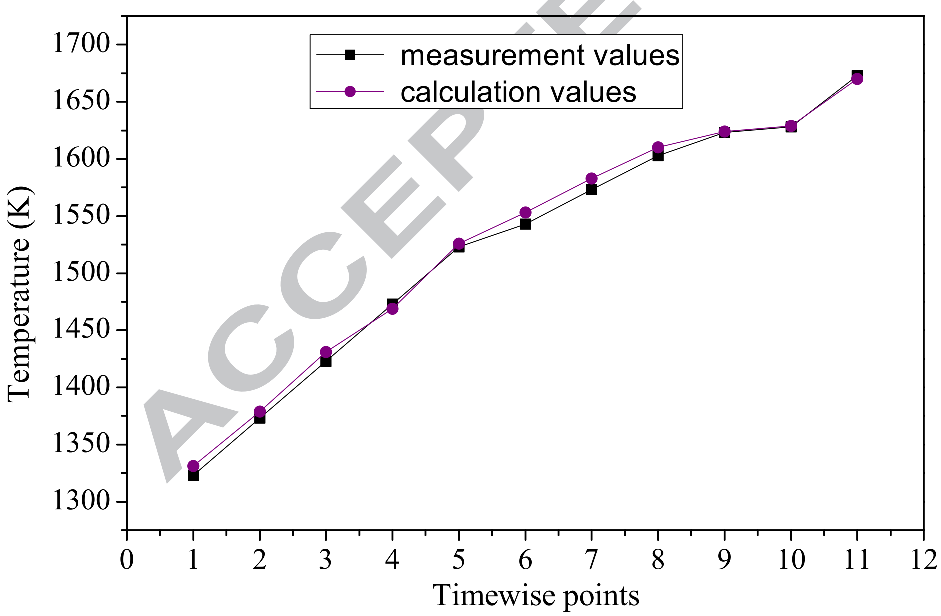
ideal directional spectral radiance
directional spectral radiance contained noise
Directional spectral radiance (W/(m²·μm·sr))
1.77x10⁴
1.76x10⁴
1.75x10⁴
1.74x10⁴
1.73x10⁴
1.72x10⁴
1.71x10⁴
2.23
2.24
2.25
2.26
2.27
2.28
2.29
λ (μm)



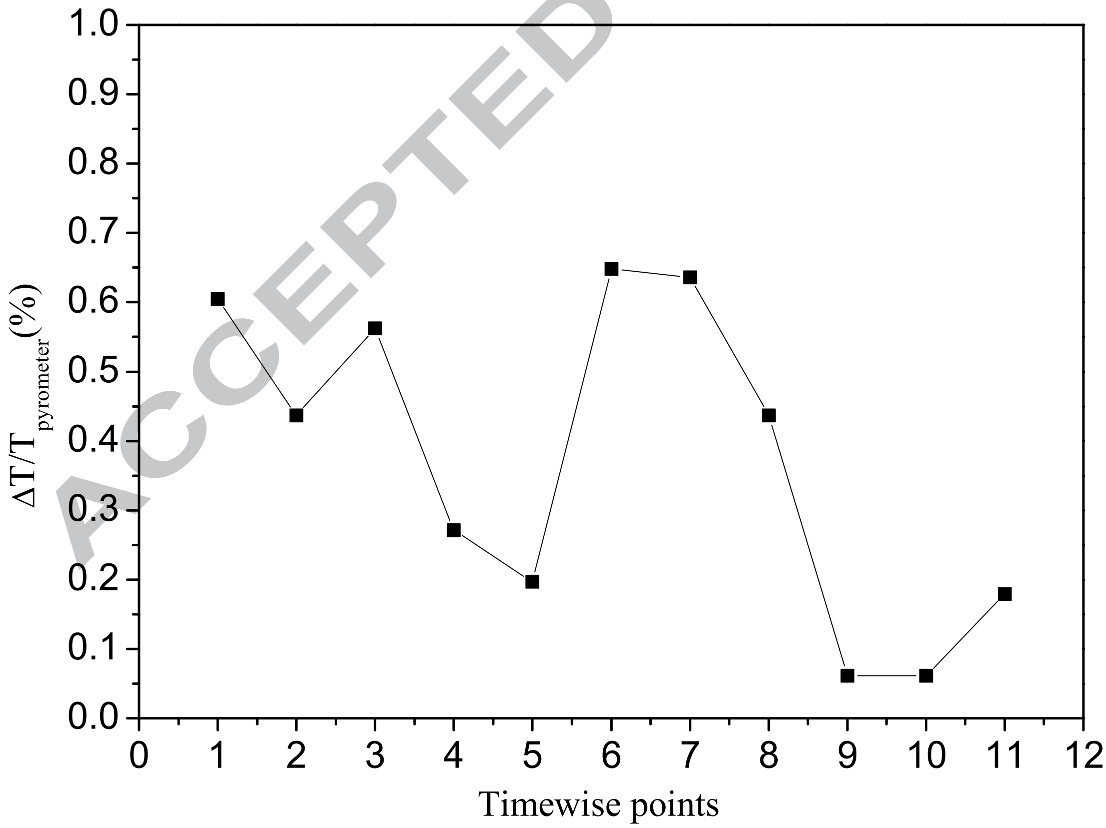
nonlinear approximation
original curve
Directional Spectral radiance (W/(m^2·μm·sr))
2.13x10^4
2.12x10^4
2.11x10^4
2.10x10^4
2.09x10^4
2.08x10^4
2.07x10^4
1.50
1.51
1.52
1.53
1.54
1.55
1.56
λ (μm)



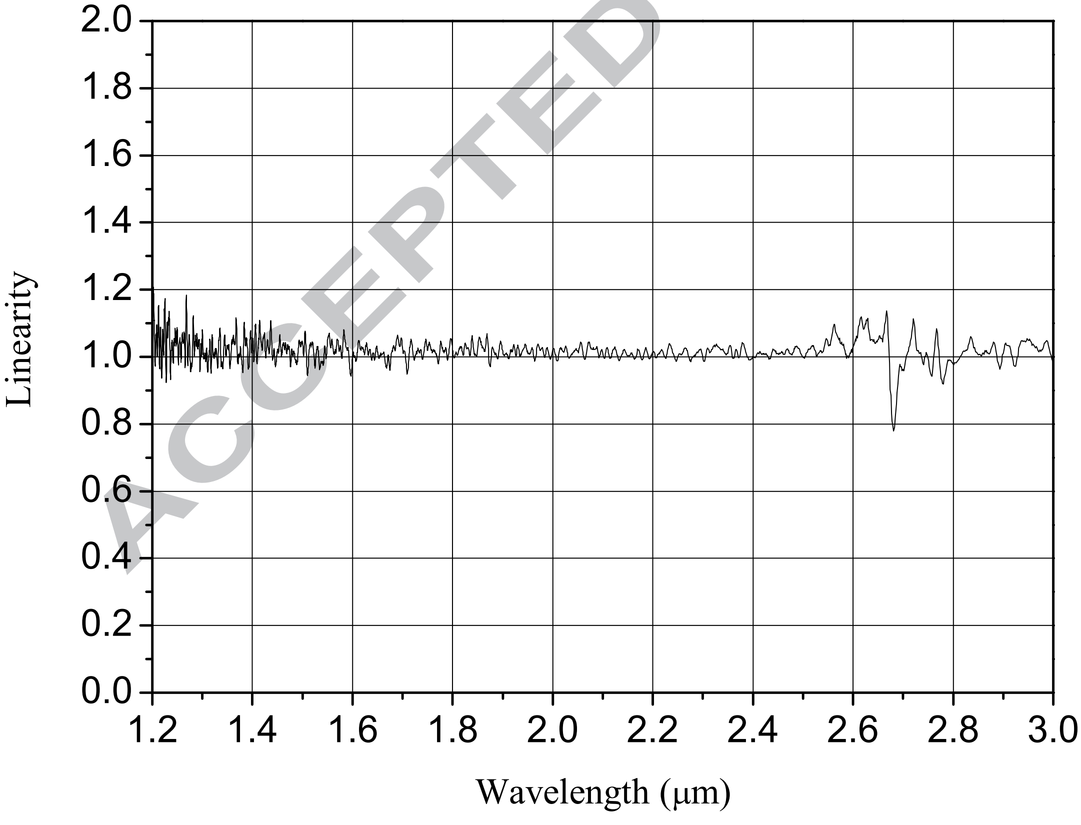
original curve
linear approximation
Directional spectral radiance (W/(m2·μm·sr))
2.13x10^4
2.12x10^4
2.11x10^4
2.10x10^4
2.09x10^4
2.08x10^4
2.07x10^4
1.50
1.51
1.52
1.53
1.54
1.55
1.56
λ (μm)



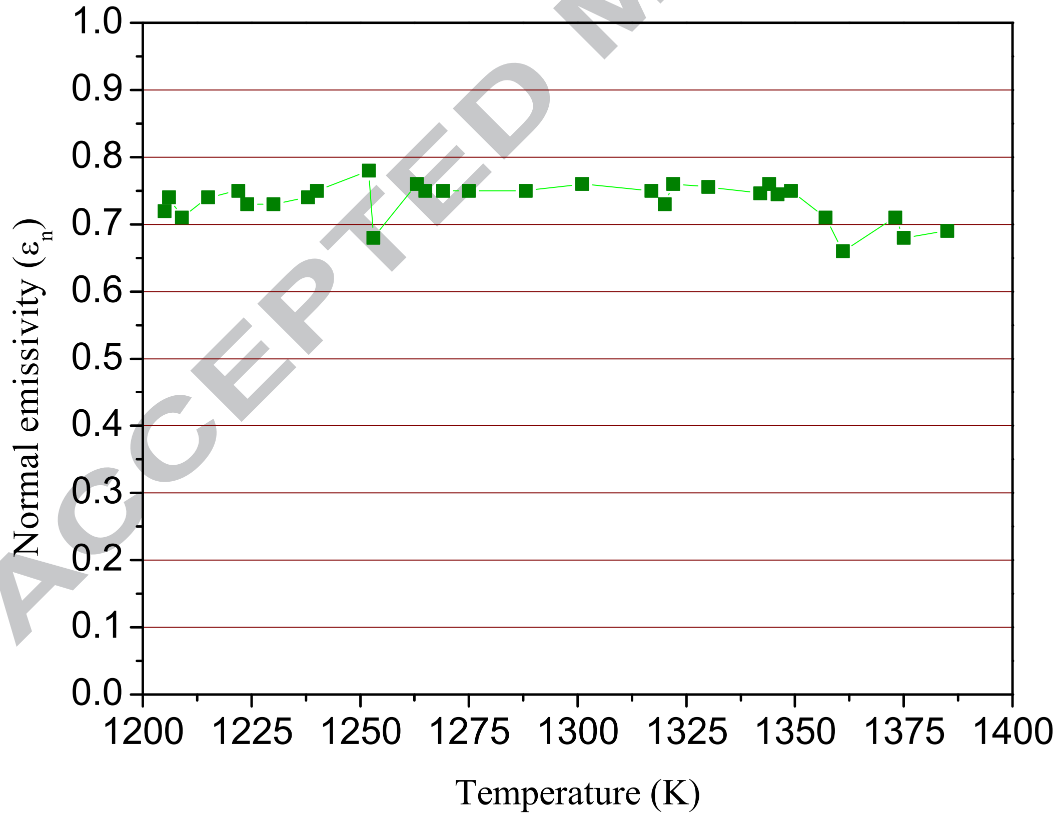
measurement values
calculation values
Temperature (K)
Timewise points
1300
1350
1400
1450
1500
1550
1600
1650
1700
0
1
2
3
4
5
6
7
8
9
10
11
12



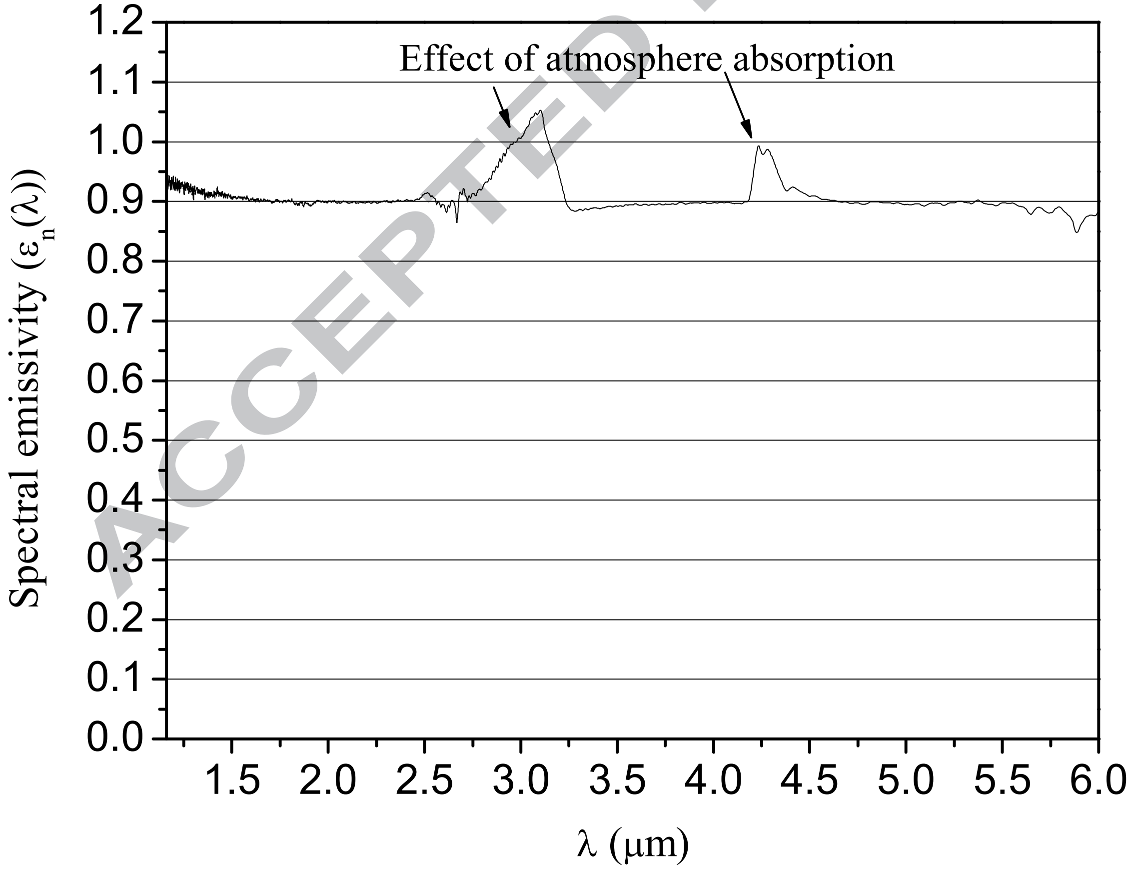
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$\Delta T/T_{pyrometer}$(%)
0
1
2
3
4
5
6
7
8
9
10
11
12
Timewise points

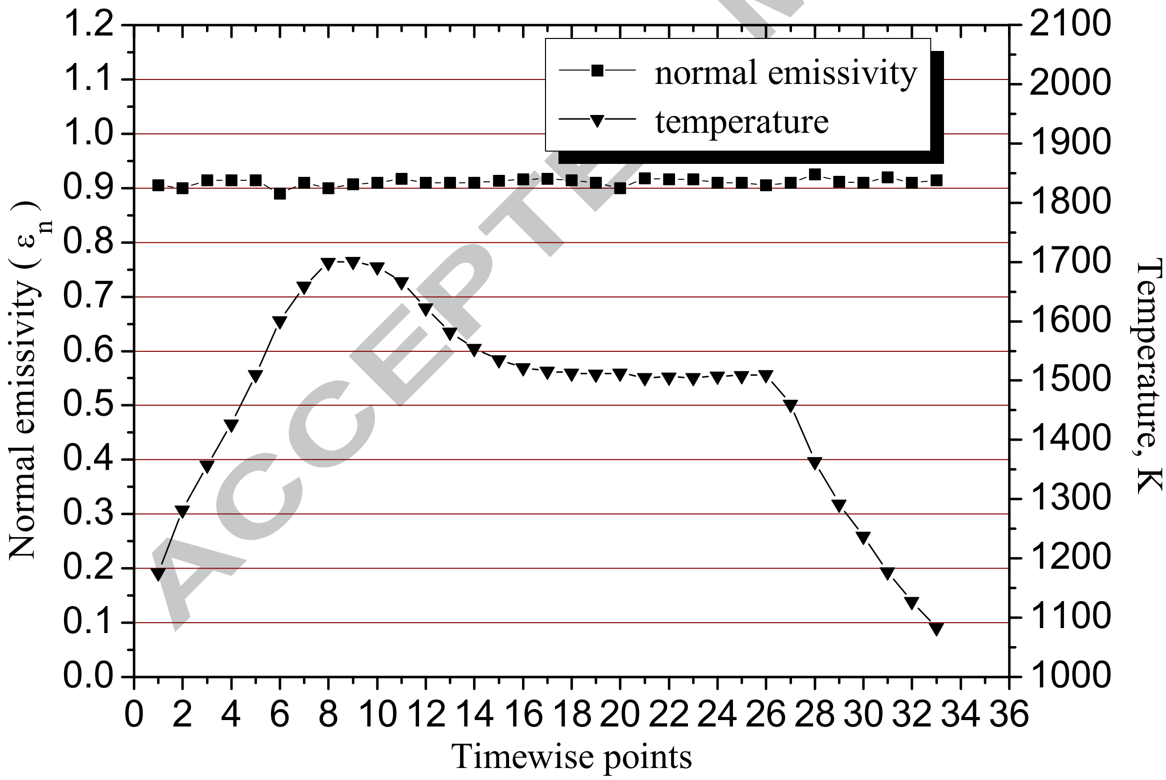


2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Linearity
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
Wavelength (μm)



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Normal emissivity (ε_n)
1200
1225
1250
1275
1300
1325
1350
1375
1400
Temperature (K)


Effect of atmosphere absorption
Spectral emissivity ($\varepsilon_n(\lambda)$)
λ (μm)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0


normal emissivity
temperature
Normal emissivity (ε_n)
Temperature, K
Timewise points
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36

Highlights：

1. Emissivity and temperature can be measured under dynamic heating condition.
2. New calibration method of system based on different temperature range is given.
3. Spectral range for temperature is determined based on response linearity of system.
4. Smooth technology is used to reduce effect on measurement from signal fluctuation.