Int J Thermophys (2009) 30:249–256
DOI 10.1007/s10765-008-0448-3

Research on the Temperature and Emissivity Measurement of the Metallic Thermal Protection Blanket

Xiaogang Sun · Peng Xiao · Guibin Yuan · Jingmin Dai

Published online: 5 June 2008

Abstract The temperatures and emissivities of the metallic thermal protection blanket at (900–1,300) °C are investigated experimentally by using a multi-wavelength pyrometer. A linear relation between the emissivity and true temperature at different wavelengths is assumed. Based on this assumption, the true temperatures and spectral emissivities of the metallic thermal protection blanket at the two temperature measurement points can be calculated simultaneously. Some experimental results for the practical data processing of measurements performed on the metallic thermal protection blanket show that the difference between the calculated temperature and the temperature measured by a standard thermocouple is within ±10 °C.

Keywords Emissivity · Metallic thermal protection blanket · Multi-wavelength pyrometer · True temperature

1 Introduction

The metallic thermal protection system (TPS) is an important part of the reusable launch vehicle (RLV). The TPS can protect the RLV from serious aerodynamic-heating when the latter enters the aerosphere [1]. The metallic TPS requires enhanced emittance, reduced catalytic activity, and high oxidation resistance. The choice of material is the key in designing a passive, reusable metallic thermal protection system for aerospace crafts [2]. The emissivity is an important material thermophysical property. It is not only the quantitative criterion that determines whether the material can satisfy the demands of the thermodynamic process, but also the key parameter of basic research, analysis calculations, and engineering design. The research into emissivity

X. Sun (✉) · P. Xiao · G. Yuan · J. Dai
Harbin Institute of Technology, P. O. Box 308, Harbin 150001, People's Republic of China
e-mail: sxg@hit.edu.cn

measurement, as a basic method to obtain the material emissivity, has a special significance.

In order to obtain the true temperature and emissivity of metallic thermal protection blanket materials, the technique of multi-wavelength pyrometry is mainly used. Details about the processing of multi-wavelength pyrometry data were given in earlier publications [3]. The true temperatures and emissivities of a certain metallic thermal protection blanket material at 900 °C to 1,300 °C are measured with this method. In this paper, we describe the construction of a compact measurement system. The results of initial experiments, which were performed on specimens, are also presented.

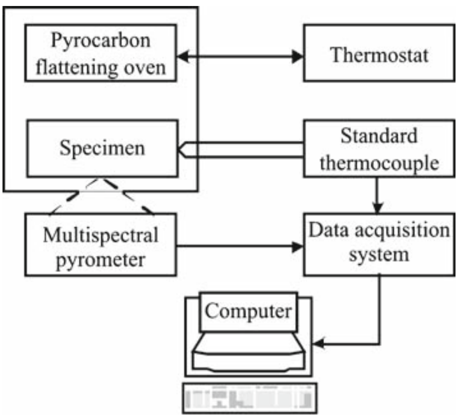
2 Measurement System

The measurement system is constructed as two separate units: (1) a compact heating system, which consists of the pyrocarbon flattening oven and the experimental chamber, and (2) the measuring and recording instruments. A schematic diagram of the measurement system is presented in Fig. 1.

The chamber wall and pyrocarbon flattening oven are water cooled, and the chamber is designed for use either in high vacuum (better than 10^{-3} Pa) or in a controlled atmosphere of flowing argon. The experimental method is based on rapid heating of the specimen from room temperature to high temperature (up to 1, 600 °C) by a pyrocarbon flattening oven.

The radiance temperature of the specimen is measured with a high-speed pyrometer that is designed and constructed specifically for this apparatus and based on the multi-wavelength pyrometer of the Harbin Institute of Technology of China (HIT) [4,5]. Figure 2 is the optical layout of the multi-wavelength pyrometer designed by the author. In the measurement, the multi-wavelength pyrometer is operated at a fixed distance from the target (300 mm). The response time of the pyrometer is less than 5 μs, and the pyrometer covers the temperature range from 1,000 K to 4,000 K with an auto-ranging feature. Pyrometer auto-ranging is accomplished by inserting three amplifiers (connected in series) between the pyrometer signal output and the data

Fig. 1 Functional diagram of the complete system



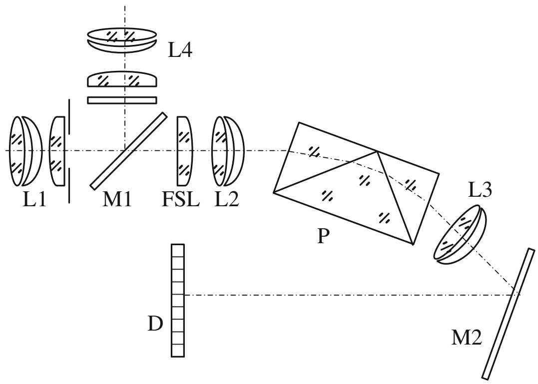


Fig. 2 Optical diagram of the high-speed multi-wavelength pyrometer. *Note*: L1: main object lens; L2: collimating lens; M1: mirror; FSL: field stop lens; P: prism; L3: dark box lens; M2: mirror; L4: eyepiece; D: photodetectors

acquisition system, with each amplifier output signal recorded by the data acquisition system. One output is selected and analyzed by appropriate software following the experiment.

Data corresponding to the electrical signals from the pyrometer and the thermocouple are recorded with a high-speed data acquisition system, which consists of a multiplexer, analog-to-digital converter, and memory, together with control and interfacing equipment. All signals are brought to the multiplexer through differential amplifiers in order to avoid the inaccuracy arising from common ground points. The multiplexed signals go to the analog-to-digital converter, which has a full-scale reading of ±10 V and a full-scale resolution of one part in 10^5. The digital output from the converter consists of 12 binary bits plus a sign bit. The data acquisition system is capable of recording a set of signals every 0.4 ms, approximately. At the end of the experiment, data stored in the memory are transferred to a computer for processing.

3 Method and Calibrations

In order to measure the temperature and spectral emissivity of the material, the data processing method for the multi-wavelength pyrometer as given in an earlier publication [3] is applied. The main technical characteristics of the experiment and the specimen data are introduced as follows:

(1) The temperature range of (900–1,300) °C is covered in the experiment; (2) the reference temperature of the blackbody is 900 °C; (3) the effective spectral bands of the multi-wavelength pyrometer are (0.768, 0.854, 0.890, and 0.960) μm; (4) the search range for the spectral emissivity is set to 0.1 to 0.99; (5) in order to verify the above-mentioned algorithm, a standard thermocouple is put on the surface of the test sample (Fig. 1). The experimental results are presented in Table 1 and Figs. 3 and 4.

All temperatures reported in this paper are based on the International Temperature Scale of 1990 (ITS-90) [6]. The individual sources of uncertainty in the measurement of spectral radiance temperature with the four-wavelength pyrometer are discussed in the following subsections, and estimates of their magnitudes are summarized in Table 2.

Table 1 Results of the metallic thermal protection blanket specimen

Experiment number	Temperature of thermocouple (°C)	Measured temperature (°C)	Measured emissivity
1	950.0	949.1	0.782
2	951.0	949.9	0.775
3	955.0	951.3	0.778
4	995.0	986.4	0.783
5	955.0	951.0	0.779
6	953.0	950.8	0.779
7	980.0	971.6	0.780
8	1340.0	1330.3	0.754
9	1190.0	1182.2	0.743
10	1320.0	1310.9	0.798
11	1235.0	1225.0	0.771
12	1130.0	1123.0	0.697
13	1285.0	1278.1	0.791
14	1280.0	1274.6	0.786

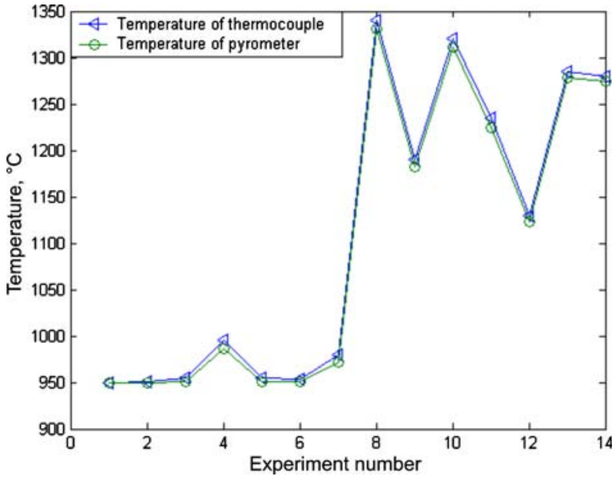


Fig. 3 Temperature of thermocouple and pyrometer as a function of experiment number

The calibration of the four-wavelength pyrometer is performed under steady-state conditions in two steps. First, the 0.890 μm channel is calibrated with a tungsten-filament standard lamp. Then, the temperature of the calibration graphite-tube blackbody furnace at 900 °C is used as a reference temperature. The effective emissivity of the blackbody source is larger than 0.99, and the temperature uncertainty is within ±1 K. The calibration certificates for the tungsten-filament lamps used as secondary standards state that the estimated uncertainty in radiance temperature is approximately

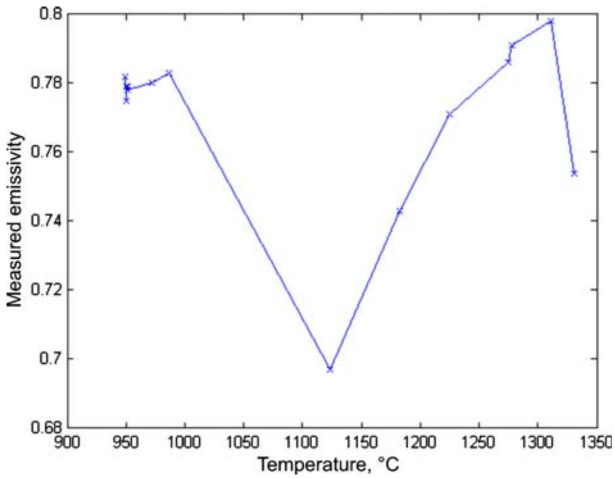


Fig. 4 Normal spectral emissivity at 0.890 μm as a function of temperature

Table 2 Sources and magnitudes of uncertainties in the measurement of radiance temperatures near 1,200 K with the four-wavelength pyrometer

Source	Uncertainty (K) at nominal wavelength (μm)			
	0.768	0.854	0.890	0.960
Secondary standard	2	2	2	2
Geometry differences	0.5	0.5	0.5	0.5
Effective wavelength	2	2	0.5	2
Nonlinearity	0.5	0.5	0.5	0.5
Calibration transfer	2	2	1	2
Radiance source align	2	2	2	2
Noise and digitization	0.5	0.5	0.5	0.5
Total uncertainty	5	5	4	5

1.5 K at 1,000 K and 2 K at 2,000 K. A comparison of periodic recalibrations of the "working standard" lamp and another lamp reserved for checking the working standard indicates that the uncertainty due to drift of the working standard is within 1 K.

During the calibration of the 0.890 μm channel with the standard lamp, the four-wavelength pyrometer accepts light from a circular cone with a vertex angle of 8.25 °. Since the spectral emissivity of the tungsten filament varies with angle from the normal, the radiance temperature as seen by the four-wavelength pyrometer may differ somewhat from the certified radiance temperature due to the differences in acceptance angle. Earlier measurements [7] of the calibrated tungsten-strip lamps showed that the spectral radiance increased slightly when measurements were made at small angles off the normal to the strip. The average increase in measured radiance is 0.25 % when the strip is turned at an angle of 7 ° from the normal.

The excess solid angle accepted by the four-wavelength pyrometer above that accepted by the calibration pyrometer forms an annulus that is centered near a vertex angle of 7 ° and corresponds to approximately 50 % of the total solid acceptance angle of the four-wavelength pyrometer. Thus, the spectral radiance of the lamp as viewed by the four-wavelength pyrometer is estimated to be approximately 0.13 % greater than the radiance measured by the calibration pyrometer. This excess radiance will correspond to an error in temperature of less than 0.5 K at 2,000 K.

Long-standing primary calibrations of the effective wavelength and of the linearity of the detector for the pyrometer are used in these experiments. The wavelength uncertainty depends on a possible mismatch at the pyrometer wavelength (center wavelength: (768, 854, 890, and 960) nm; bandwidth: (78, 56, 53, and 41) nm), and the concept of effective wavelength is valuable in assigning a particular wavelength within the spectral band of each pyrometer channel to a given measurement of radiance temperature. The variation of effective wavelength with temperature does not affect the accuracy of temperature measurement since it is taken into account by numerical integration over the given spectral band. However, uncertainties in the spectral response of a given channel, arising from sources such as error in spectral transmission measurement and drift of the interference filters, may give rise to an uncertainty in effective wavelength estimated to be not greater than 2 nm for the four channels. The corresponding uncertainty in temperature will depend upon the wavelength dependence of radiance temperature for the particular target surface. For many high-melting-point metals, the wavelength coefficient for radiance temperature is of the order of $1\,\mathrm{K}\cdot\mathrm{nm}^{-1}$ [7], in which case the temperature uncertainty due to uncertainty in effective wavelength will be not greater than 2 K.

The one-point calibration technique of pyrometry based on measurement of the pyrometer wavelength function (PWF) by using only one output signal of the pyrometer at a reference temperature is described in a previous paper [7]. The main error sources were identified and estimated by a Monte Carlo method, and some important conclusions were drawn. Moreover, a multi-wavelength pyrometer was employed to do a one-point calibration after the calibration using a high-temperature blackbody cavity. A higher accuracy was obtained.

As described earlier, repeated measurements have shown that drifts of the amplifier zero and gain and drifts of the detector sensitivity are completely negligible when compared with other sources of error. However, measurable drifts in the interference filters, both in optical transmission and in spectral response, have been observed. The changes in optical transmission are sufficiently slow that significant errors can be prevented by periodic calibrations. Changes in optical spectral response, even though much slower, are more serious because they affect the calculation of temperature in a non-linear manner, unlike simple changes in transmission. It has been found that a measurement of spectral transmission of the pyrometer once every year is sufficient to prevent significant error.

The optical and electronic components of the four-wavelength pyrometer that could affect the linearity are substantially similar to those of a microsecond-resolution pyrometer described in an earlier publication [4]. The previous paper [4] described a multi-wavelength pyrometer for true temperature and spectral emissivity measurements of ablative material. Therefore, the results of tests on the earlier pyrometer should apply equally to the present instrument. It is estimated that nonlinearity of the present pyrometer may contribute an uncertainty in measured radiance of less than

0.2 % at 2,500 K, which corresponds to an uncertainty in temperature of less than 0.5 K. The effect of nonlinearity on temperature measurements at 2,000 K may be neglected.

The uncertainty caused by the combined effect of calibration source alignment and noise (from the electronics and from digitization by the analog-to-digital converter) is estimated for a given channel from the standard deviation of an individual value from the weighted mean of the values determined at different radiance source levels. This uncertainty affects the calibration of the 0.890 μm channel once and the calibration of the other three channels twice, once when the 0.890 μm channel is calibrated with the standard lamp and once when the calibration of the principal channel is used to calibrate the other channels via the graphite-tube blackbody furnace. An additional uncertainty in the calibration of the other three channels arises from the uncertainty in furnace blackbody quality, which is believed to be accurate to within 0.5 %. The root sum square of these uncertainties is given in Table 2 for measurements at 900 °C.

In the actual use of the pyrometer, an uncertainty arises from aligning the pyrometer with the radiance source whose temperature is to be measured. This uncertainty is determined by measuring the temperature of a steady source (tungsten-filament lamp) after each of several realignments of the pyrometer. Differences in the mean of a hundred sample temperatures for each realignment indicate that the uncertainty due to radiance source alignment is not greater than 1 K at 1,000 K and not greater than 2 K at 2,000 K for each pyrometer channel.

In measuring temperature, there is an additional uncertainty due to the combined effect of noise from the electronics and digitization by the analog-to-digital converter. This uncertainty is determined by calculating the standard deviation of individual digitized samples from the mean of a hundred samples when the pyrometer is focused on a steady radiance source (a tungsten-filament lamp). The standard deviation is found to be independent of radiance, which indicates that the uncertainty in temperature due to noise and digitization increases rapidly with decreasing temperature. At 2,000 K, the uncertainty is less than 0.5 K for all the pyrometer channels, whereas at 1,200 K the uncertainty is nearly 3 K for the worst case (the channel centered at 0.768 μm).

Table 2 summarizes the estimated uncertainties from various sources for each channel. The root sum square of the various individual uncertainties (rounded upward) is taken as the total uncertainty in the measurement of radiance temperature by each channel, and the uncertainty of the thermocouple measurement is 10 K at 1,200 K.

4 Conclusions

(1) The difference between the calculated true temperature of the specimen and the temperature measured by the thermocouple is within ± 10 K.

(2) The data processing method of the multi-wavelength pyrometer mentioned above cannot be applied to on-line data processing.

Acknowledgments The project is supported by the National Natural Science Foundation of China (No. 60377037).

References

1. M.L. Blosser, R. Chen, in *Proceedings of the 40th Aerospace Sciences Meeting & Exhibit* (Reno, Nevada, 2002), p. 20
2. M.L. Blosser, J. Phys. E **13**, 306 (2000)
3. X.G. Sun, Int. J. Thermophys. **26**, 1255 (2005)
4. J.M. Dai, J. Infrared Millim. Waves **14**, 461 (1995)
5. P. Coppa, High Temps.-High Press. **22**, 479 (1988)
6. H. Preston-Thomas, Metrologia **27**, 3 (1990)
7. J.M. Dai, Acta Metrologica Sinica **20**, 53 (1999)