Spectral pyrometry of surface and flame

V E Mosharov, V N Radchenko, I V Senyuev
Central Aerohydrodynamic Institute, 1 Zhukovsky Street, Zhukovsky, Moscow Region, 140180, Russian Federation
E-mail: ivan.senyuev@tsagi.ru

Abstract. The development of high-speed aircraft requires the study of high-temperature materials and of combustion processes in engine combustion chambers. One of the main parameters in these studies is the temperature, which must be measured up to 3000K. Such high temperatures can be measured only by non-contact methods. One of these methods is spectral pyrometry, which is based on temperature measurement from the energy distribution in thermal radiation spectrum of investigated object. This paper presents the results of spectral pyrometry application to measure the surface temperatures and hydrocarbon flame temperatures.

1. Introduction

High-temperature material testing requires the measurement of surface temperature of material samples in thermal wind tunnels. Their temperature can reach 3000 K. Such high temperature can be measured only by pyrometry methods. Until recently, the main method of temperature measurement was brightness pyrometry, which allows to obtain the distribution of brightness temperature over the studied surface. In order to recalculate brightness temperature into thermodynamic temperature information about the emissivity of the studied object is needed. The method of spectral pyrometry does not require information about the emissivity, but it is necessary for the investigated surface to be a gray body in some spectral range, in which the temperature is measured [1, 2].

Another application area of spectral pyrometry is the measurement of flame temperature from the intrinsic thermal radiation of soot particles. There are analytical expressions of the soot particles emissivity for the case when their size is much smaller than the measurement wavelength, which were obtained on the basis of the theory of light propagation in a turbid medium [3].

2. Physical aspects of spectral pyrometry

Thermal radiation is described by two fundamental laws: the Kirchhoff law, which establishes a relation between the thermal radiation spectrum of a real body and that of a blackbody, and Planck's law, which describes thermal radiation of a blackbody. In practice, the Wien law is often used instead of the Planck law for the simplification of mathematical manipulations. The following expression of the thermal radiation law is convenient for spectral pyrometry, taking into account the laws of Wien and Kirchhoff:

$$\ln \left( I(\lambda, T) \right) = -\frac{c_2}{T} \frac{1}{\lambda} + \ln \left( \varepsilon \varepsilon (\lambda, T) \right),$$

(1)

where $I(\lambda, T)$ is the radiation intensity of the studied object at a wavelength $\lambda$ and at temperature $T$; $c_1$ and $c_2$ are Planck's law constants; $\varepsilon$ is the emissivity. Equation (1) shows that the thermal radiation
The nose of the sample. The temperature \( T_c \) of the sample, and as a result, the nose becomes “white” due to a further heating of the surface. The emissivity of white material is 0.03, which is consistent with the results obtained from laboratory measurements.

Spectral pyrometry of a flame is based on the fact that the flame’s radiation is the thermal radiation of incandescent soot particles. If the flame is considered as a cloud of small particles, then the emissivity dependence on the wavelength \( \lambda \) can be described as [4,5,6]:

\[
e(\lambda) = \frac{36\pi N
\lambda}{(n^2 - \chi^2 + 2)^2 + 4n^2 \chi^2},
\]

where \( n \) is the real part of the complex refractive index; \( \chi \) is the imaginary part of the complex refractive index; \( N \) is the concentration of soot particles; \( v \) is the volume of a soot particle; \( I \) is the optical path in the medium. From the expression (3) it can be seen that the emissivity of the flame is inversely proportional to the wavelength:

\[
e(\lambda) = \frac{K}{\lambda},
\]

where \( K \) is a coefficient weakly dependent on the wavelength. If expression (4) is substituted into equation (1), the relation corresponding to the spectral pyrometry of the flame is obtained:

\[
\ln \left( \frac{I(\lambda, T)}{I(\lambda, T_0)} \right) = -\frac{c_2}{T} \frac{1}{\lambda} + \ln (\varepsilon K),
\]

i.e. the thermal radiation spectrum of the flame becomes a straight line in the coordinates \((\ln(I), 1/\lambda)\). It should be noted that in the flame temperature measurements the thermal spectra are acquired from the entire thickness of the flame; therefore, the temperature measured by spectral pyrometry will be averaged along the observation line.

Using the results of measurements of soot particles refractive index from [4,5,6] and using expressions (2) and (3), the soot volume fraction in the flame \( N_0 \) along the observation line can be determined.

3. Measurement results

Within the framework of this study, surface temperature was measured during high-temperature materials testing in thermal wind tunnels VAT-104 and T-122M of TsAGI and flame temperature was measured in a model combustion chamber in T-131 wind tunnel of TsAGI.

A series of experiments of cone-shaped samples was carried out in T-122M wind tunnel, the samples were made of white material. Temperature was measured on the nose of the sample. The results of brightness and spectral temperatures measurements of the sample are shown in Fig. 1. The emissivity was determined from the values of measured spectral and brightness temperatures, Fig. 2.

At the start of the experiment the white model surface reflects the light of the electric arc heater penetrating from the plenum chamber, and the spectral temperature is too high. As the model warms up, the intensity of the model’s own radiation increases, becomes greater than the intensity of the background illumination, and the spectral temperature begins to correspond to the thermodynamic temperature of investigated surface. During the experiment the copper compounds appearing in the flow as a result of the electric arc heater electrodes erosion are deposited on the model surface, which leads to an increase in its spectral emissivity. With a further temperature increase, the material of the model nose begins to swell and entrain, and, as a result, the nose becomes “white” again. White surface occurs in the measurement volume, which leads to a decrease in emissivity. The obtained emissivity of white material is 0.03-0.04, which is consistent with the results obtained from laboratory measurements.
measurements of the materials’ spectral emissivity using a spectrophotometer SPECORD M40 (CarlZeissJena, GDR). Model images before and after experiment are shown in Fig. 3.

![Figure 1. Results of spectral and brightness temperature measurements](image1)

![Figure 2. The change of emissivity during the experiment](image2)

![Figure 3. Model images: a - before the test, b - after the test](image3)
Fig. 4 presents the results of the measurement of flame spectral temperature in a model combustion chamber in T-131 wind tunnel. Brightness temperature was measured together with spectral temperature, which made it possible to determine the soot volume fraction in the flame (Fig. 5).

4. **Verification of the spectral pyrometry method with the CARS method**

Within the framework of this study, in order to verify the spectral pyrometry, an experiment was conducted in CIAM facility to compare the results of temperature measurement by spectral pyrometry with the results of temperature measurement using the CARS (Coherent Anti-Stokes Raman Spectroscopy) method. A Wolfhard-Parker slot burner with a laminar diffusion flame was chosen as an object for comparative temperature measurements [7]. This burner is small in size and provides a stable flame and high repeatability of temperature distribution.
The CARS method, in contrast to pyrometry, is a local method. The measurement volume from which the temperature value is acquired is determined by the diameter and length of the laser waist and is approximately 0.05×0.05×2 mm³.

Using the CARS method, CIAM employees (Kobtsev V.D., Kostritsa S.A.) measured temperature distribution in the flame along the line of thermal spectra registration at several points. As expected, the temperature measured by spectral pyrometry was lower than maximal temperature measured by the CARS method by about 10%, Fig. 6.

Figure 6. Flame temperatures measured by spectral pyrometry and maximum temperature measured by CARS

It should be noted that the CARS method cannot provide the measurement of flame temperature at high soot volume fraction, where the pyrometry method works well. The measurements were made in compromising range of soot content suitable for both methods.

5. Conclusion
Spectral pyrometry provides the measurement of surface temperature of grey bodies with unknown or changing emissivity when testing high temperature materials in thermal wind tunnels. Combined measurements of brightness and spectral temperatures allow to determine the emissivity, which can be used to recalculate the distribution of brightness temperature into a thermodynamic one.

Spectral pyrometry allows to measure the temperature of a hydrocarbon flame if the soot is presented in the flame. In this case the method is integral, i.e. temperature is averaged along the observation line. Measured temperature is lower than maximal value. Measuring flame spectral and brightness temperatures simultaneously allows to determine the soot volume fraction.

References
[1] Mosharov V E, Radchenko V N and Senyuev I V 2013 J. Instrum Exp Tech 56, pp. 491–496.
[2] Kazakov V A, Senyuev I V 2017 Measurement of temperature distribution on the sample surface in thermal wind tunnel tests J. Trudy MAI, №94. (in Russian)
[3] Senyuev I V 2017 TsAGI Science Journal V 48, №2, pp. 173-185.
[4] Dalzell W H, Sarofim A F 1969 Journal of Heat Transfer, Vol. 91, No. 1, pp. 100-104.
[5] Lee S C, Tien C L 1981 Eighteenth Symposium (International) on Combustion. pp. 1159-1166.
[6] Chang H C, Charalampopoulos T T 1990 Proceedings of the Royal Society A, Vol. 430, pp. 577-591.
[7] Datta A, Beyrau F, Seeger T 2004 J. Combustion Science and Technology, No. 176, pp. 1965-1984.