Spectroscopic and pyrometric temperature measurements of heated type B and S thermocouples

Yuan Yao[1], Aidin Panahi[1,2], and Yiannis A. Levendis[1]*

[1]Mechanical and Industrial Engineering Department, Northeastern University, Boston, MA, USA

[2]Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA, USA

[*]Corresponding Author Email: y.levendis@northeastern.edu

Abstract
This research experimented with two different non-contact methods for determining the surface temperature of a hot object (in this case heated type-B and type-S thermocouples): multi-wavelength spectrometry and three-wavelength pyrometry. A spectrometer was first used to obtain the spectral emissivities and temperatures of the object at a large number of wavelengths (in the range of 600-1000 nm). A three-wavelength pyrometer was then used to measure the radiation intensity of the object at three distinct wavelength bands (centered at 640, 810 and 998 nm); temperatures were determined either with the gray-body assumption (i.e., constant emissivities in wavelength pairs) or with the spectral emissivities obtained with the spectrometer. If the spectrometry-derived emissivities of the object at the aforementioned wavelengths of the pyrometer were used in the pyrometric calculations, then the temperatures of the two instruments should agree. To test this hypothesis, the temperature of the B-type and S-type thermocouples were also acquired from their generated voltages, and they were contrasted with those obtained with both the spectrometric and pyrometric measurements. The spectral emissivity values of the S-type thermocouple were compared with relevant values published in the literature. The emissivity and temperatures for a B-type thermocouple are new additions to the literature.

Introduction
For certain small objects, such as burning fuels, their surface temperature and spectral emissivity must be acquired with non-contact measurements. Pyrometric/spectroscopic techniques can be used to measure their temperature. To test the accuracy of these techniques, they were both used to measure the temperature of thermocouple beads, externally heated, and compare the obtained temperature with that of the thermocouple voltage-to-temperature conversion. In the process, the spectral emissivities of the thermocouple beads were also obtained. Previous research by Yan et al.[1] used a multi-wavelength spectrometer and measured the surface temperature and the spectral emissivity of an R-type thermocouple. A similar multi-wavelength spectrometer and a three-wavelength pyrometer [2] were used in this research. Moreover, previous research by Ma and Long [3] reported on the emissivity of S-type thermocouples. In this research, a laminar premixed methane-air flame (at an equivalence ratio $\varphi \approx 0.9$) heated both S-type and B-type thermocouples. The surface temperature deduced from both the spectrometric and the pyrometric methods were compared with the temperature read from thermocouple temperature tables based on their generated voltage.

Methods and Thermocouples

An *Avantes* AvaSpec-2048 spectrometer measured the radiation intensity in the range of 600-1000 nm. The three-wavelength pyrometer of Levendis Estrada and Hottel [2] was used to measure the radiation intensity at chosen distinct wavelengths (centered at 640, 810 and 998 nm). Both instruments were calibrated with a pre-calibrated tungsten filament lamp with a *Pyrometer, LLC* lamp. The calibration setup for the pyrometer is shown in Fig. 1.

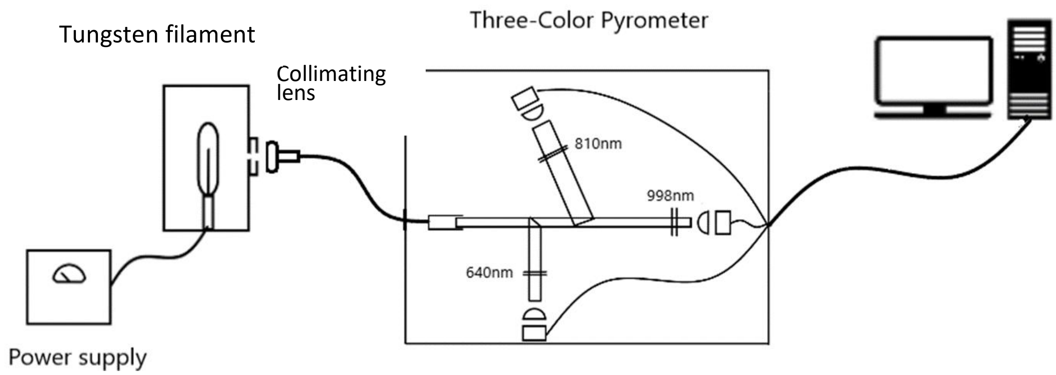

Figure 1. Schematic of the calibration setup for the pyrometer.

Pyrometric temperatures were deduced based on Wien's approximation to Planck's law.

$$T_{\mathrm{p}} = \frac{c_2(1/\lambda_2 - 1/\lambda_1)}{\ln\left[\frac{1}{C_{\lambda_1\lambda_2}}\frac{\varepsilon_{\lambda_2}S_{\lambda_1}}{\varepsilon_{\lambda_1}S_{\lambda_2}}\right]} \quad (1)$$

where λ_1 and λ_2 are any two wavelengths from the three wavelengths of the pyrometer; c_2 is the second Planck constant; $c_{\lambda_1\lambda_2}$ is the calibration constant; $\varepsilon_{\lambda_2}/\varepsilon_{\lambda_1}$ is the ratio of the object surface emissivities at two different wavelengths, $S_{\lambda_1}/S_{\lambda_2}$ is the signal ratio of the two wavelengths.

Spectrometric temperatures and spectral emissivities were calculated again based on Planck's law using the Newton iteration method and expressing the spectral emissivity as a polynomial function:

$$I(\lambda_j) = \varepsilon_{(\lambda_i)} \frac{c_1}{\lambda_i^5\left(e^{\frac{c_2}{\lambda_j T_S}} - 1\right)} \qquad j = 1,2,3,\dots n \quad (2)$$

$$|f|^2 = \sum_{j=1}^{n} \left(I_m - (a_0 + a_1 \cdot \lambda_j + a_2 \cdot \lambda_j^2 \dots + a_n \cdot \lambda_j^m) \cdot \frac{C_1}{\lambda_i^5\left(e^{\frac{C_2}{\lambda_j T_S}} - 1\right)}\right)^2 \quad (3)$$

where $I(\lambda_j)$ is spectral radiation intensity; I_m is the measured intensity; $\varepsilon_{(\lambda_i)}$ is spectral (monochromatic) emissivity; j is the number of measured effective wavelengths in range; c_1, c_2 are Planck 1st 2nd constant. $|f|$ is the absolute residual number. The surface temperature and the spectral emissivities are obtained when f^2 reaches the minimum value.

The thermocouples used in this study were S-type (90%Pt/10%Rh–Pt, by weight) and B-type (70%Pt/30%Rh–94%Pt/6%Rh, by weight) both received from *Omega Engineering*. The wire diameter of both thermocouples was 0.1 mm. A Bunsen burner heated both thermocouples with premixed natural gas flame at 1550±30 K (from thermocouple voltage/temperature table, published by *Omega Engineering*). Instabilities in the flame caused some temperature fluctuation.

A schematic of the setup for measuring the signal from the thermocouple by the spectrometer is shown in Fig. 2. A collimating lens and two pinholes were used to ensure that only the thermocouple bead was "seen" by the optical instruments. The pyrometer used the same setup, including the lens and pinholes.

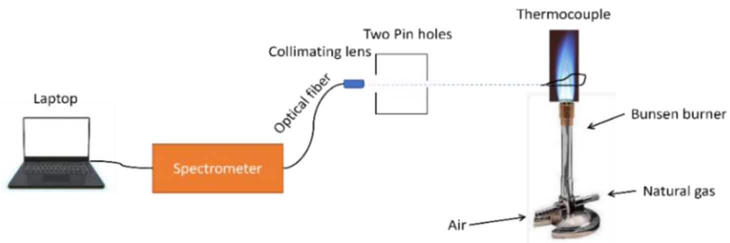

Figure 2. Schematic of the experimental setup of the spectrometer.

Results and Conclusions

The spectral emissivities are shown in the figure below, along with pertinent data from the literature[1,3].

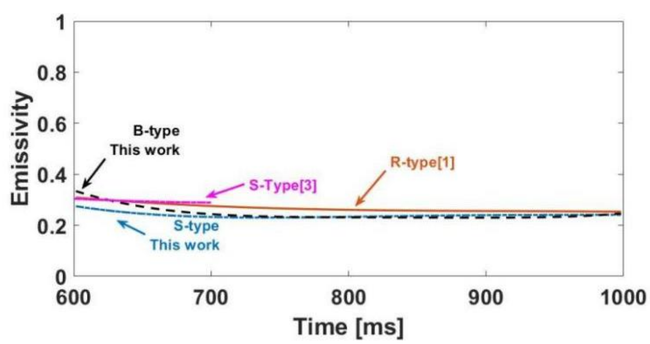

Figure 3. Spectral emissivity for both thermocouples in the wavelength range of 600 nm-1000 nm [1,3].

The spectral emissivity of the B-type thermocouple does not differ much from those of the S-type and the R-type thermocouples, indicating that the percentage of the rhodium component in the thermocouple does not significantly alter the platinum emissivity in the examined wavelength range. Comparing three types of thermocouples (B, R and S) confirms a similar conclusion reached in Ref. [1], where two types of thermocouples (R and S) were compared. Moreover, in the wavelength range of 750 nm-1000 nm, it is reasonable to assume that both types of thermocouples behave as graybodies, whereas in the 600 nm -750 nm wavelength range there is some variation in emissivity.

Temperature profiles of thermocouple beads type-S and type-B are shown in Fig. 4. The flame where both thermocouples were placed was premixed. By varying the fuel to air ratio of the flame its temperature was controlled so that each thermocouple (either B or S) read a comparable during the spectrometric and the pyrometer measurements. The measured point was the bead of each thermocouple. Since the signal for 640 nm is weak and close to the background noise, the only pyrometric temperature shown in each figure is derived from the 998 nm/810 nm ratio. The spectrometric temperatures are integrated over a sampling time of 1800 ms. Therefore, they are depicted as a straight line. The standard deviation is ± 20 K. The pyrometric temperatures are instantaneous readings and show a fluctuation of about ±20 K for B-Type and ±30 K for S-Type. The flame was not totally stabilized because of apparent fluctuations in the fuel or air supplies. This causes some of the errors in thermocouple readings and the readings of the instruments.

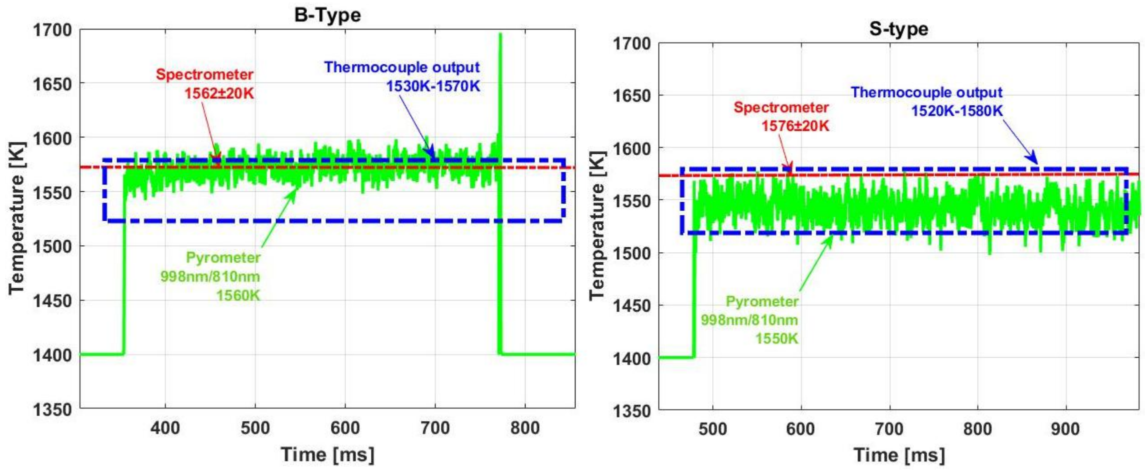

Figure 4. Type B and S thermocouple bead temperatures, obtained with three different measuring methods.

In the case of the B-type thermocouple, the average spectrometric temperature coincides with the average pyrometric temperature and both are within the range of thermocouple output values. The temperature for the pyrometer was obtained by using the emissivity output of the spectrometer. However, even when the gray body assumption was made, a similar temperature would result. This is because, as mentioned above the thermocouple emissivities are nearly constant in this range. In the case of the S-type thermocouple, there is some disagreement between the spectrometric temperature and the pyrometric temperature by as much as 30 K. This temperature difference between pyrometer and spectrometer may have been caused by the fact that the bead at the junction of the wires of the S-type thermocouple was not as well defined as was the bead of the B-type thermocouple. Also, the exact positions of the two beads in the flame may have been slightly different when thermocouples were switched. Thus, it is possible that the two instruments viewed a slightly different section of this thermocouple. Nevertheless, the temperatures detected by both instruments are within the fluctuation range of the thermocouple output.

References

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