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February 1999

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TEMPERATURE MEASUREMENT OF A MINIATURE CERAMIC HEATER IN THE PRESENCE OF AN EXTENDED INTERFERING BACKGROUND RADIATION SOURCE USING A MULTIWAVELENGTH PYROMETER

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Introduction

Temperature measurement of small (millimeter size) objects is generally difficult and demanding. Measurement involving ceramic materials using the traditional one- and two-color pyrometer is difficult because of their complex optical properties, such as low emissivity which may vary with both temperature and wavelength. Pyrometry applications in an environment with an interfering radiation source of extended dimension adds extra complexity to the process. We show that the multiwavelength pyrometer successfully measured the temperatures of a millimeter (mm) size ceramic heater under these demanding conditions.

Method

The multiwavelength pyrometer consists of a spectrometer and a computer(1). The light (signal) gathering function of the spectrometer is provided by a 3 meter (m) focal length parabolic mirror. When operated at a field of view of 1 milli-radian from 3 meters away, the spectrometer detects radiation coming from an area about 3 mm in diameter. The ceramic heating element consists of a very fine (<75 μm) wire with an alumina bead (diameter 1 to 1.5 mm) at its center. The ends of the heater element are supported from two electrodes protruding through a base plate encased in a metal cylindrical tube about 10 mm in length and diameter. Heating action is accomplished by the passage of an electric current conducted through the electrodes. Radiation detected by the spectrometer, therefore, comes not only just from the bead of the ceramic heater, but also from its base plate. The computer controls the spectrometer to acquire a spectrum, from which subsequent data analysis determines the temperature. To measure temperatures between 300 K and 1,300 K, the spectrometer was operated from 1.3 to 14.5 μm. Radiation detection is provided by an indium antimonide detector and a mercury cadmium telluride detector. The intensity of emitted heater radiation, L_λ, is given by the product of its emissivity and the equation describing Planck's law of black body radiation(2) (Eqn. 1) where c_1, c_2 are the radiation constants, ε_λ is the emissivity, and λ is the wavelength of the radiation source.

$$L_\lambda = \varepsilon_\lambda \frac{c_1}{\lambda^5}\frac{1}{\exp(c_2/\lambda T)-1} = \varepsilon_\lambda \frac{c_1}{\lambda^5}\exp(-c_2/\lambda T)\frac{1}{1-\exp(-c_2/\lambda T)} \qquad \textbf{(1)}$$

For data analysis, Eqn. 1 is rewritten as

$$y \equiv \left(\frac{\mathrm{Ln}\left(\frac{c_1}{\lambda^5}\frac{1}{L_\lambda}\right)}{\frac{c_2}{\lambda}} \right) - \frac{\mathrm{Ln}\left(1-\exp(-\frac{c_2}{\lambda T})\right)}{\frac{c_2}{\lambda}} = \frac{1}{T} - \frac{\lambda}{c_2}\mathrm{Ln}(\varepsilon_\lambda) \qquad \textbf{(2)}$$

This is the working equation of the traditional 1-color pyrometry method, which requires knowing the emissivity. For the multiwavelength pyrometer, this quantity is not required to determine temperature. Because the quantity $(1-\exp(-c_2/\lambda T))$ is practically unity at short wavelengths, its logarithm would be zero. We observe from Eqn. 2 that plotting the quantity $y = \mathrm{Ln}(c_1/(\lambda^5 L_\lambda))/(c_2/\lambda)$ as a function of λ would result in a straight line of slope $\mathrm{Ln}(\varepsilon_\lambda)/c_2$ if $\mathrm{Ln}(\varepsilon_\lambda)$ is independent of wavelength. The quantity $1/y$ at each wavelength λ is often referred to as the radiant temperature. The intercept of the straight line at $\lambda=0$ is $1/T$, the reciprocal of the desired unknown temperature.

Results

Spectra of the alumina bead from the ceramic heater (designated HPR) at different temperatures are recorded when constant currents pass through it. The magnitude of the currents (to within 0.1 amp) and the voltages (to within 0.001 volt) were recorded. These experimental spectra are shown in Figs. 1 to 4 by the curves indicated by the "+" data symbols. The other data curves will be explained later. Because the radiation of each spectrum contains a component that does not originate from the alumina bead alone, if each spectrum is analyzed directly using Eqn. 2, the determined temperature will be incorrect.

A radiation spectrum of the heater recorded by the spectrometer at time t_i is represented by

$$\Sigma_\lambda(t_i) = H_\lambda(t_i) + S_\lambda(t_i) + R_\infty(t_i) = fL_H(t_i) + (1-f)L_S(t_i) + \left[f(1-\varepsilon_H) + (1-f)(1-\varepsilon_S)\right]L_\infty \qquad \textbf{(3)}$$

H_λ , S_λ and R_∞ denote contributions from the heater, its surroundings, and the reflection from a source far away of intensity L_∞, respectively. f is the fraction of the spectrometer's field of view occupied by the heater surface. $L_H(t_i)$, $L_S(t_i)$ and L_∞ are the respective radiation intensities according to Eqn. 1 with their respective emissivities ε_H, ε_S and $\varepsilon_\infty=1$ inserted. When $T_H(t_0)= T_S(t_0)=T_\infty$, as it would be at ambient temperature, the heater and the surroundings are at the same temperature, $\Sigma_\lambda=L_H= L_S =L_\infty$ which is a 300 K Planck curve. If only the heater is at an elevated temperature, $L_S=L_\infty$, then $\Sigma_\lambda=fL_H+(1-f\varepsilon_H)L_\infty$. Increases in intensity at each wavelength of a spectrum at a temperature above ambient is due to increased emission by the heater when a constant electric current is passing through. A spectrum obtained from a wavelength channel by wavelength channel subtraction of the ambient spectrum from one obtained at a higher temperature will be the intrinsic emission spectrum of the heater at that higher temperature. Assuming that $S_\lambda(t_i)$ is almost constant, or varies only slightly, an assumption proven to be true from subsequent analysis, successive subtraction will remove this quantity. The case in which $S_\lambda(t_i)$ varies rapidly will be investigated at a different time. The temperature at t_0 is 300 K. Spectra of the heater at increasingly higher temperatures are systematically obtained from succeeding differences according to the following prescription:

$$H_\lambda(t_1) = \Sigma_\lambda(t_1) - \Sigma_\lambda(t_0) \qquad \textbf{(4)}$$

$$H_\lambda(t_i) = \Sigma_\lambda(t_i) - \Sigma_\lambda(t_{i-1}) + fL_H(t_{i-1}) \qquad \textbf{(5)}$$

$$H_\lambda(t_i) = fL_H(t_i) = f\varepsilon_H \frac{c_1}{\lambda^5}\frac{1}{\exp(c_2/\lambda T_H(t_i)) - 1} \qquad \textbf{(6)}$$

The intrinsic spectra so obtained are shown in Figs. 1 to 4, indicated by the square symbols. These are the spectra used in Eqn. 2 or Eqn. 5 to obtain the heater temperatures produced by the different heater input power listed in the figure captions. The analyses are shown in Figs. 5 to 8. It is immediately obvious from inspection of these figures that at the short and long wavelength regions of the spectrum, the ceramic heater surface exhibits substantially constant emissivities. The two straight lines of different slopes drawn to intersect at the same zero wavelength intercept point determine the temperature of each spectrum. The temperatures of the heater for the four input power settings shown in Figs. 5 to 8 are determined to be 575, 680, 925 and 1210 K, respectively. The quantities controlling the slopes of these curves are related to the heater surface area f and emissivity ε_H in Eqn. 5.

Discussion

Two Planck curves of the same temperature (obtained from the intercept) are scaled by multiplying to them the surface area fraction, and the emissivities (at short and long wavelength). They are shown in Figs. 1 to 4 as continuous curves to fit the extracted intrinsic ceramic heater spectra at their respective temperatures. In these figures, a continuous curve, not drawn through any data points, is the 300 K Planck curve. The two same temperature Planck curves fit the extracted intrinsic heater spectrum well at the short and long wavelength regions. The curve which fits the spectrum well in the short wavelength region would underestimate it in the long wave region. Similarly the other curve which fits the long wavelength region over estimates it in the short wavelength region. The sum of each them in the regions where they are valid and the 300 K Planck curve fit the experimental data well. A composite curve (the sum of the 300 K Planck curve and the curve fitting the long wavelength experimental data) is shown in each figure to give an indication of the good agreement obtainable.

The reason for the limited validity of the two Planck curves, and hence their inability to account for data at intermediate wavelengths is the complexity of the ceramic heater's emissivity. By dividing the intrinsic spectrum by the Planck function corresponding to its temperature, a quantity that is related to the ceramic's emissivity and its view factor formed at the spectrometer is obtained. If the ceramic heater surface is extensive enough such that it would fill the field of view of the spectrometer, this quantity will be the emissivity. The results are shown in Fig. 9. These curves demonstrate the behavior of the ceramic's emissivity: quite constant and low at the short wavelength, transitioning in a very complex manner to a very constant value at very long wavelengths. It is not clear whether the apparent increase in emissivity at long wavelength with temperature is real or if it is due to a bigger portion of the bead's surface contributing to thermal emission as the ceramic bead temperature increases. Assuming that the radiation emitting region of the heater bead has an effective diameter < 1 mm, that the spectrometer field of view is > 3 mm, then the area fraction f is <1/9, and the constant heater emissivity in the 1 to 3 μm wavelength region in Fig. 9 is about 0.1, which is not an unreasonable number for alumina.

Because of the small diameter of the wire conducting electricity from the electrodes to the heating element, heat loss by thermal conduction by the ceramic heater through these wires is negligible. The electrical energy after conversion into heat energy is transported away mainly by radiation and convection. The heat generation is Q=IV, where I is the electric current flowing through the heater, and V is the potential drop across its electrodes. The heat transport equation is

$$Q = \varepsilon\sigma A\left(T^4 - T_\infty{}^4\right) + h\left(T - T_\infty\right) \qquad \textbf{(7)}$$

where $\sigma = 5.7 \times 10^{-8}$ w/m^2 is the Stefan Boltzmann constant, $A = 4\pi r^2$ is the area of the radiating surface, h is the heat transfer coefficient, T is the radiating surface temperature, $T_\infty = 300$ K is the temperature at far away. By rewriting Eqn. 7 we obtain

$$\frac{Q}{T - T_\infty} = \varepsilon\left[\sigma A\,\frac{T^4 - T_\infty{}^4}{T - T_\infty}\right] + h \qquad \textbf{(8)}$$

The quantity on the left when plotted against the quantity inside the square bracket is a straight line, whose slope is the effective emissivity, and the intercept is the heat transfer coefficient. The result is shown in Fig. 10. From the analysis, the average emissivity is 0.11 ± 0.03, agreeing reasonably with the pyrometer determined value. The heat transfer coefficient is 0.00046 ± 0.00003 w.cm^{-2}.K^{-1}.

Conclusion

The multiwavelength pyrometer operating at the spectral region 1.3 to 14.5 μm was used to measure the temperatures of a miniature electrically powered ceramic heater of dimension less than 2 mm in diameter. Measurements were made at four heating levels. The field of view of the spectrometer is in excess of 3 mm. The recorded radiation spectra included a contribution from a source extraneous of the heater. By subtracting the successively recorded spectra, this extraneous contribution was eliminated to recover the intrinsic spectra for temperature determination. A heat transfer analysis was performed using the electrical power input data and the pyrometer measured temperatures to provide an estimate of an average ceramic emissivity. It agrees reasonable well with the emissivity value obtained from pyrometry measurement. Also determined from the heat transfer analysis is the ceramic heater heat transfer coefficient.

References

1. Ng, D., Temperature Measurement of a Glass Material Using a Multiwavelength Pyrometer, NASA TM–107433, April 1997.
2. DeWitt, D.P., Nutter, G.D., Theory and Practice of Radiation Thermometry, John Wiley & Sons, New York, 1988.

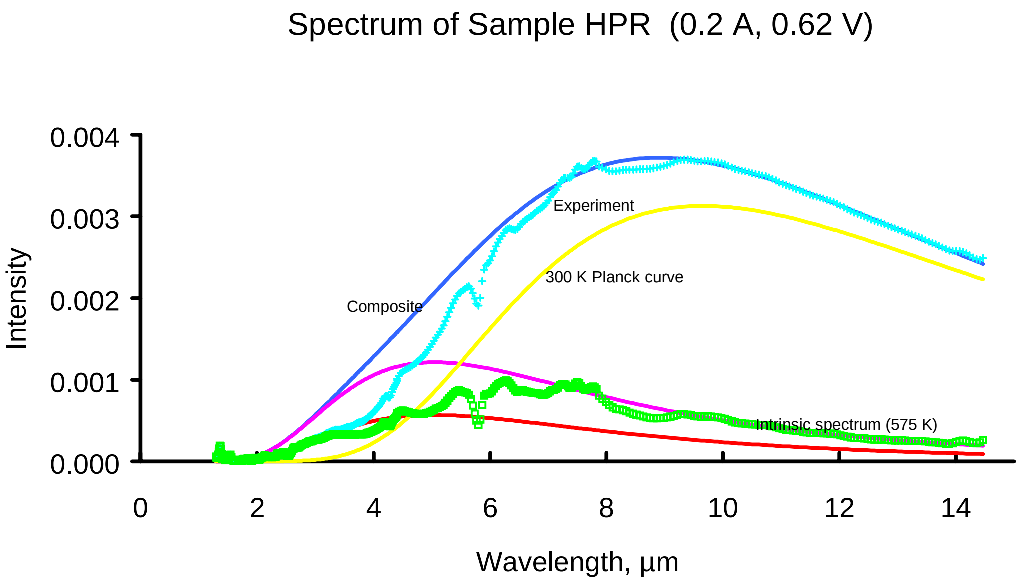

Fig. 1 Spectrum of ceramic heater, current = 0.2 A, voltage = 0.620 V

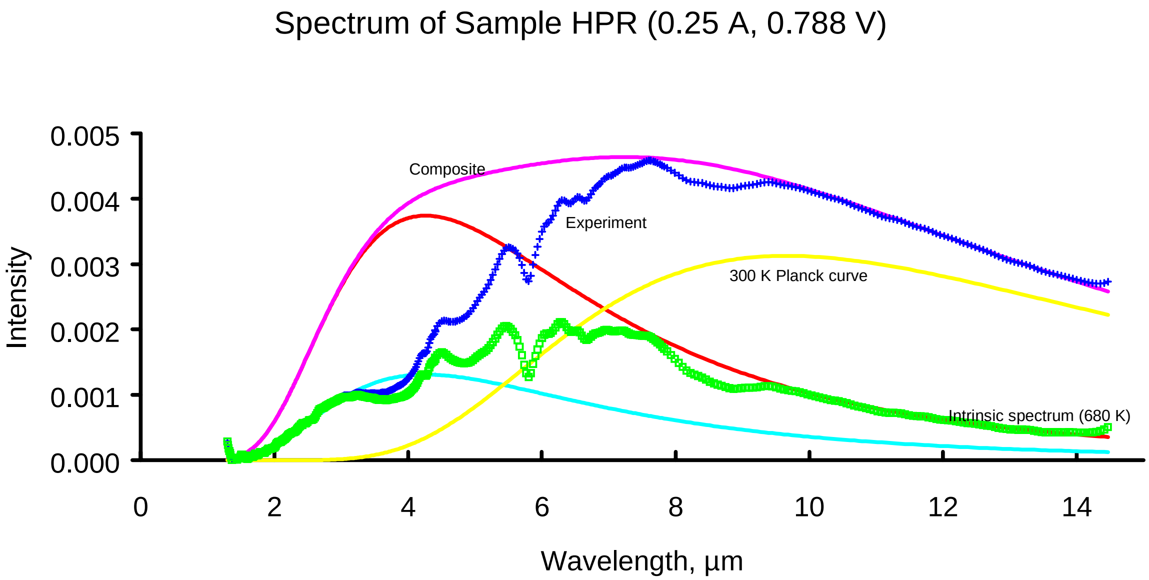

Fig. 2 Spectrum of ceramic heater, current = 0.25 A, voltage = 0.788 V

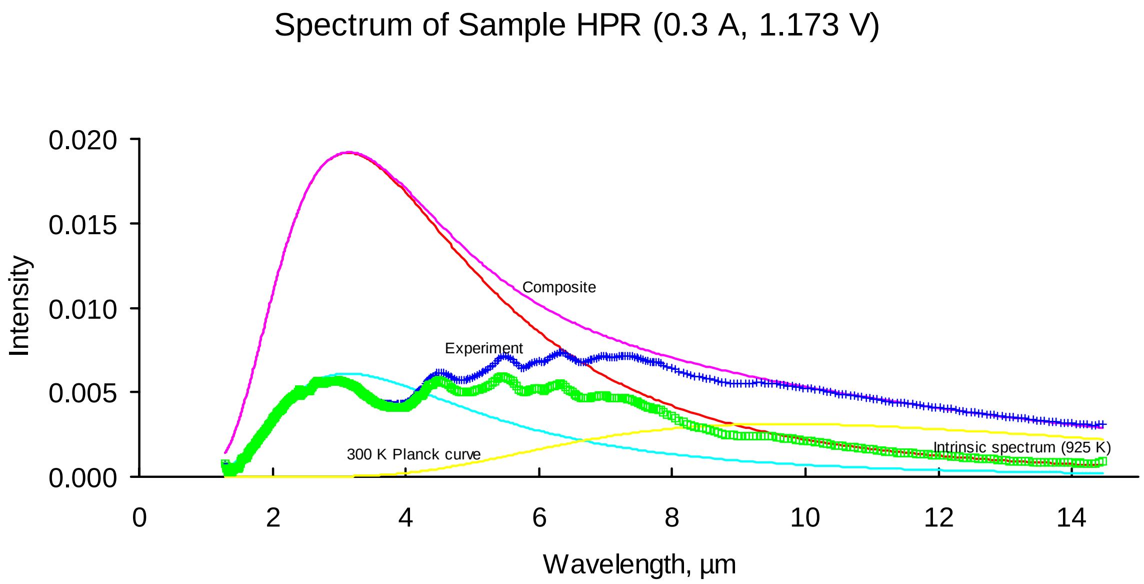

Fig. 3 Spectrum of ceramic heater, current = 0.3 A, voltage = 1.173 V

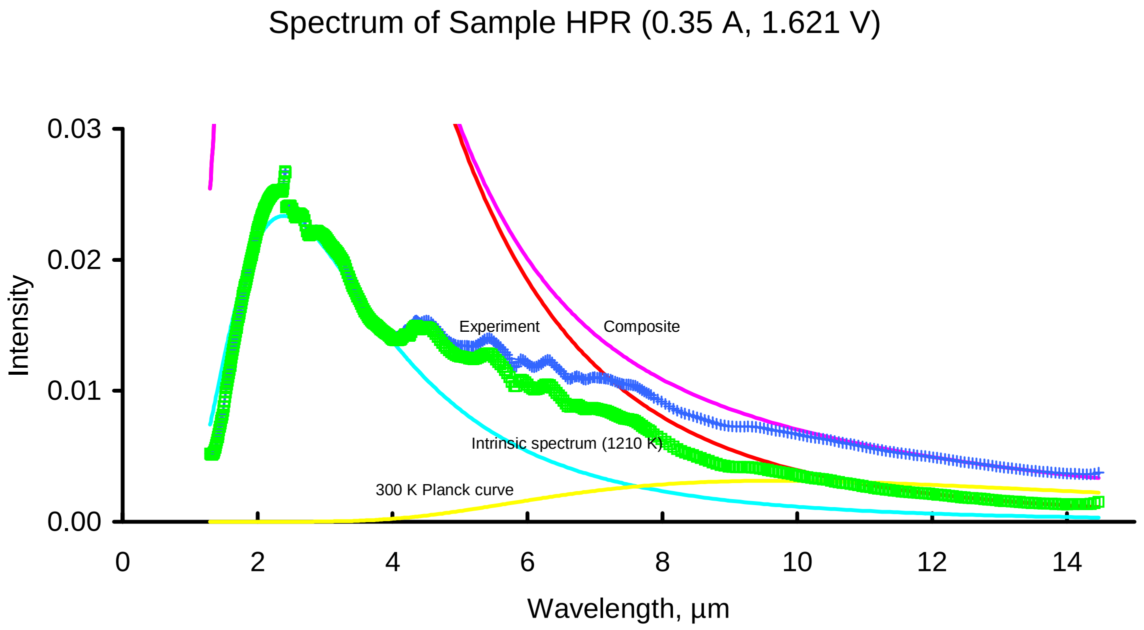

Fig. 4 Spectrum of ceramic heater, current = 0.35 A, voltage = 1.621 V

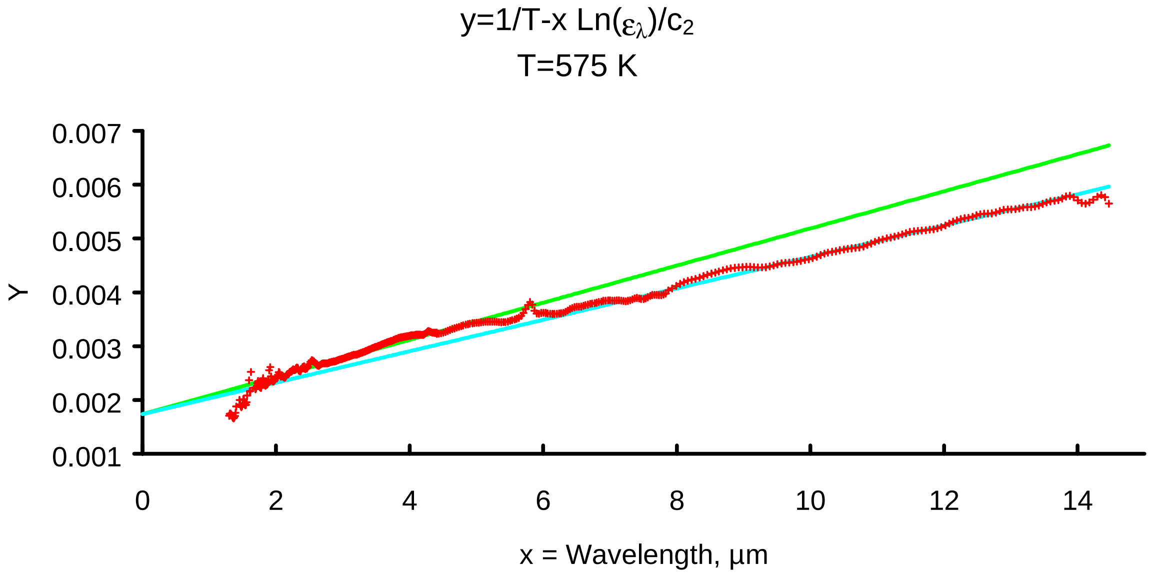

Fig. 5 Transformed spectrum, current = 0.2 A, voltage = 0.620 V

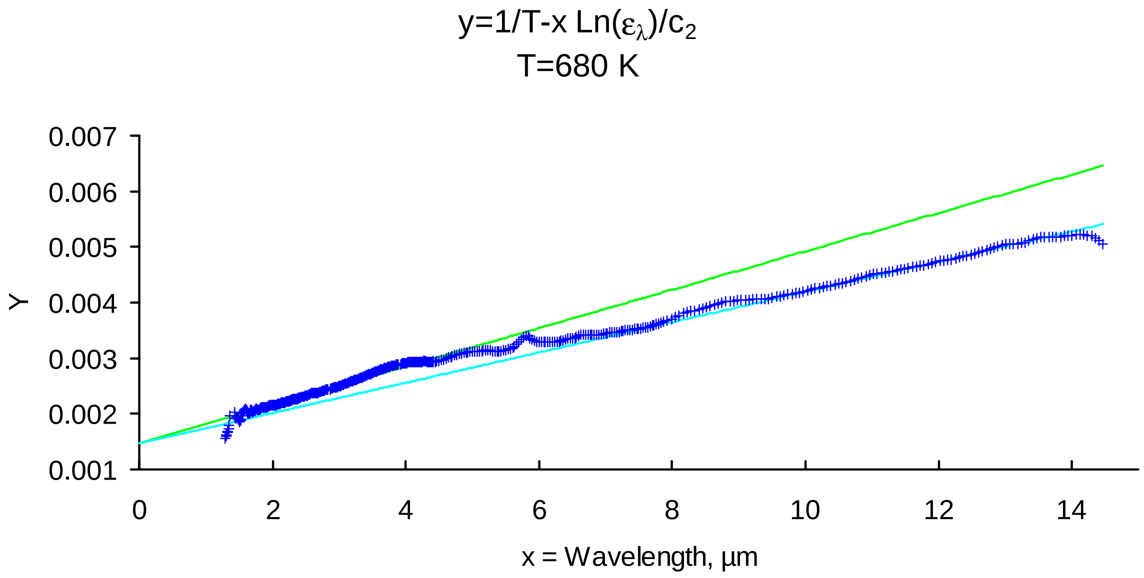

Fig. 6 Transformed spectrum, current = 0.25 A, voltage = 0.788 V

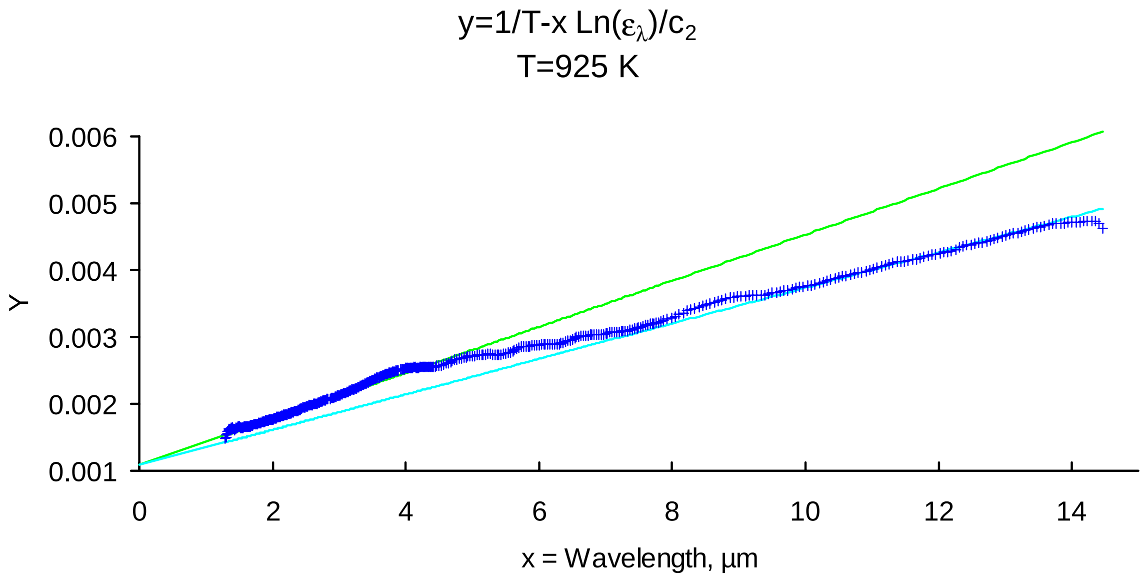

Fig. 7 **Transformed spectrum, current = 0.3 A, voltage = 1.173 V**

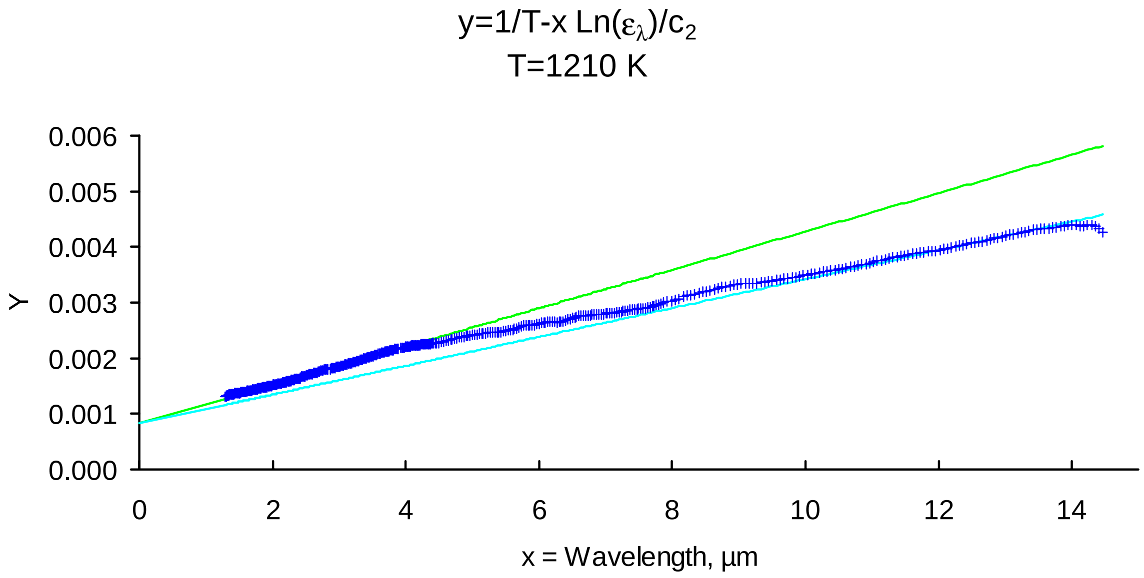

Fig. 8 **Transformed spectrum, current = 0.35 A, voltage = 1.621 V**

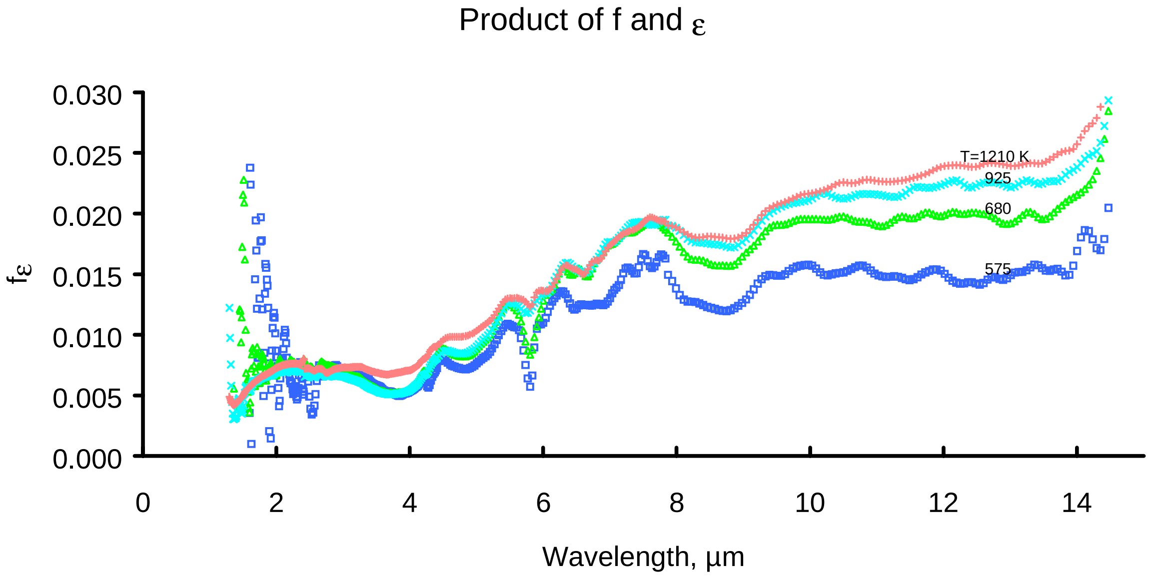

Fig. 9 **Plot of product of emissivity and view factor vs wavelength**

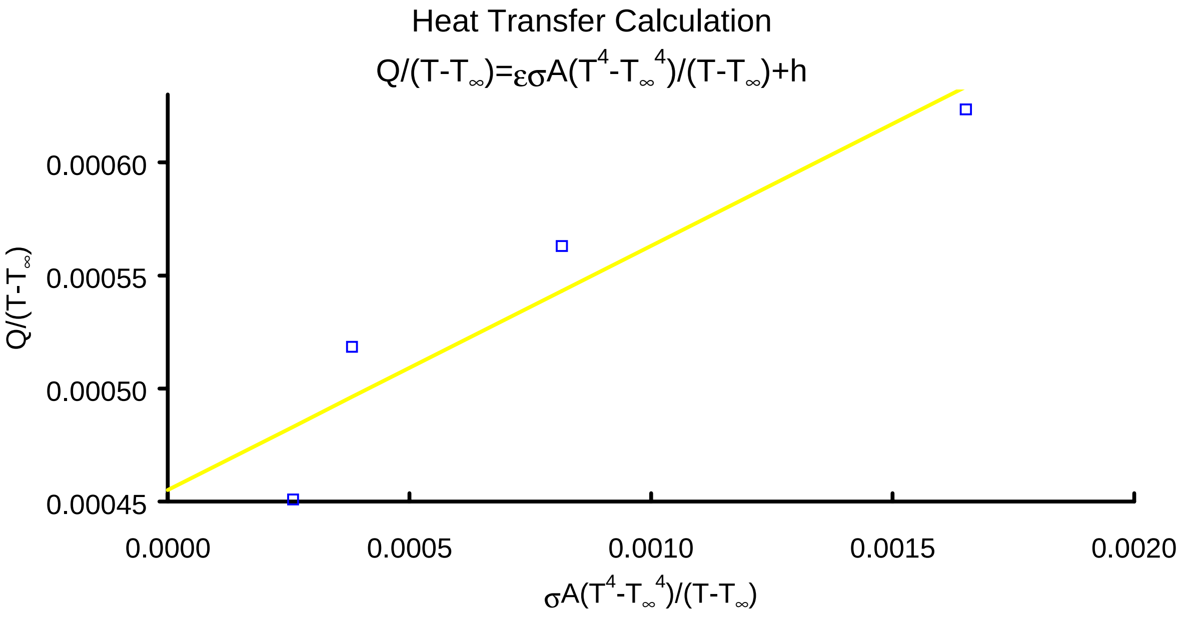

Fig. 10 **Plot of heat transfer calculation data**

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