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Non-Contact Heat Flux Measurement Using a Transparent Sensor

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ABSTRACT

A working non-contact heat flux sensor has been demonstrated using a transparent material (sapphire) and a multiwavelength pyrometer. The pyrometer is used to measure the temperatures of the two surfaces of the sensor from the spectrum of radiation originating from them. The heat conducted through the material is determined from the temperature difference of the two surfaces and the thermal conductivity of the material. The measured heat flux is equal to the incident heat flux within experimental error indicating that no calibration would be necessary. A steady state heat flux of 100 kW/m^2 was easily achieved.

Introduction

Traditional heat flux measurement requires installing a heat flux sensor on the surface for which heat flux information is required. Common heat flux sensors are thermocouple based devices generating electrical signals which are carried by contact methods, e.g. lead wires. It is sometimes desirable to measure the heat flux remotely, that is without using wire connections. We describe one such method here.

Method

Schematically a heat flux sensor is shown in figure 1. It consists of a slab of material with thickness t, thermal conductivity K, and a cross-

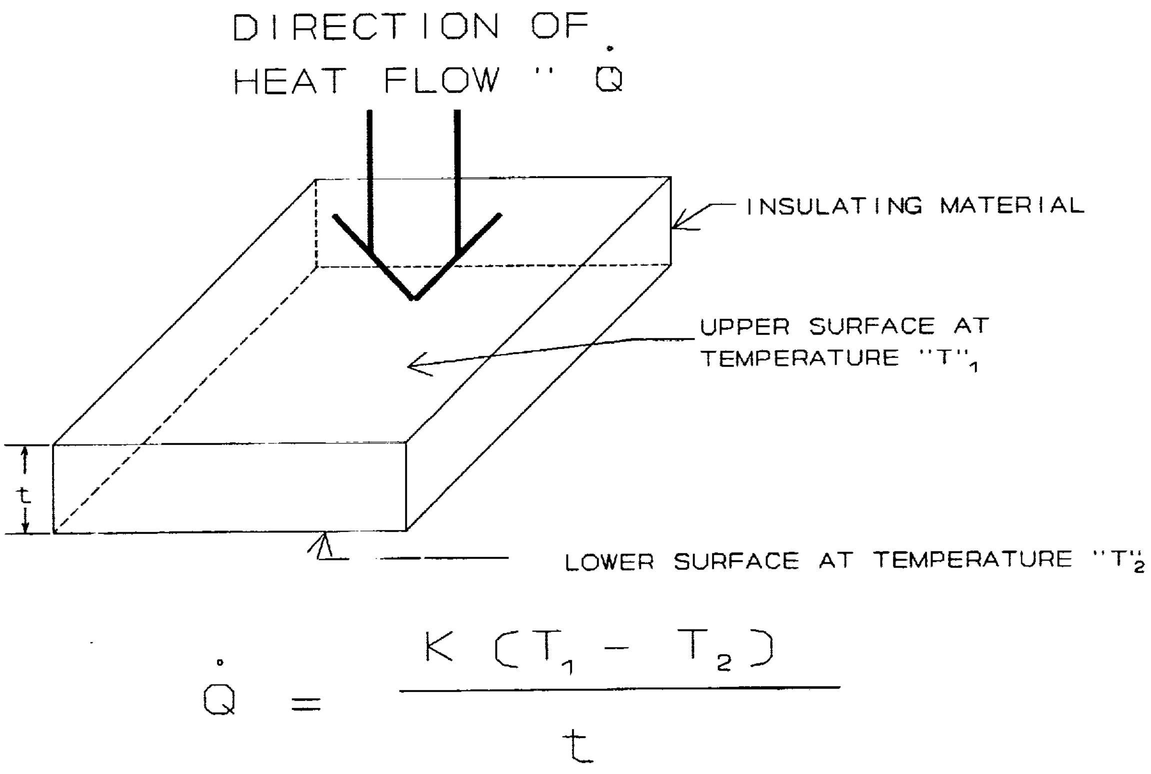

Figure 1 Schematic of a Heat Flux sensor.

sectional area A. Operationally, a heat flux measurement is made by measuring the temperature difference $\Delta T=T_2-T_1$ developed across the surface of this heat flux sensor. The heat flux is determined from the equation

$$\frac{\dot{Q}}{A}=\kappa\frac{\Delta T}{t}$$

where Q is the rate of heat energy transported across the area A arising from the temperature gradient $\Delta T/t$.

The temperature difference is normally measured using thermocouples or differential thermocouples. The heat flux is obtained from the geometry of the sensor, the thermal conductivity and the measured temperature difference.

In the design of a remote heat flux sensor, we will use a transparent material, specifically sapphire, on the measured surface. An ideal material would be one which has a step in its transmissivity from totally transparent to totally opaque (ignoring scattering), and a corresponding complementary step in its emissivity as a function of wavelength. Sapphire serves to demonstrate the concept well. In principle, any material which is transparent at some wavelength and opaque at others would work.

The spectral transmissivity $\tau(\lambda)$ of the piece of sapphire used in this experiment is shown in figure 2. Similar results have been published[1]. The rapid decrease in transmitted intensity approximates the step desired. This transmissivity is measured experimentally at room temperature by comparing the spectral intensities of a black body source when the sapphire sample is inserted between the source and the detector and when it is removed. These spectra are shown in figure 3.

From optics, the reduction in the measured intensity is due to (1) refractive index related reflections at the surfaces and (2) absorption of

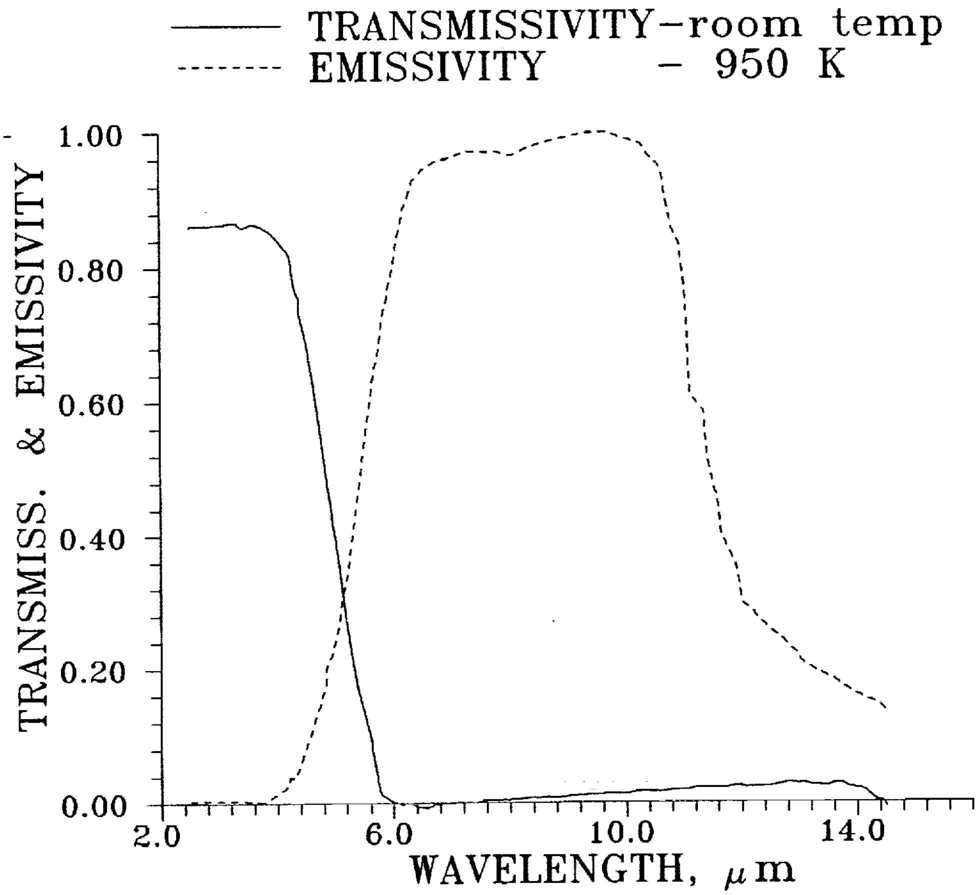

Figure 2 The emissivity (Ref. 1) and transmissivity of sapphire (8 mm thick).

radiation by the sapphire. At short wavelengths, below 4 μm, absorption by sapphire is almost negligible at room temperature. The reduction in intensity in this region is due almost entirely to reflections. Absorption becomes important at longer wavelengths. Above 6 μm, there is no transmission.

The spectral emissivity $\epsilon(\lambda)$ of sapphire has been reported by Sova et al.[2] at various temperatures. The values measured at 950 K are reproduced and

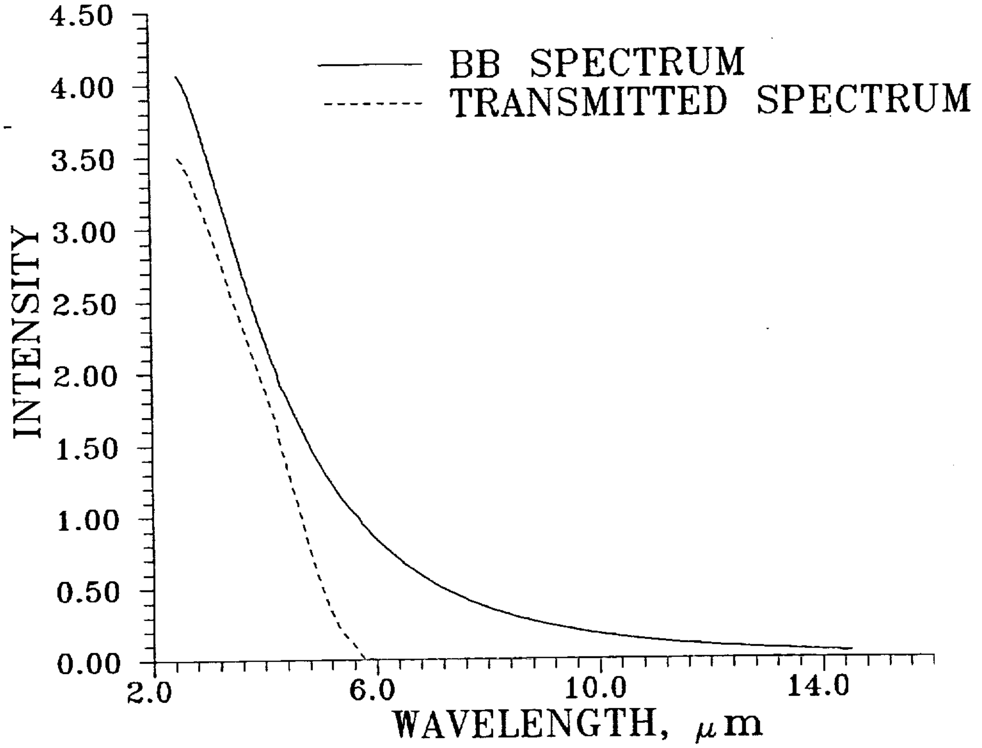

Figure 3 The spectra of a black body source with and without sapphire.

shown here together with the transmissivity in figure 2. Comparison of the emissivity with the transmissivity shows they are almost complementary. At the short wavelength region where the transmission is high, the emissivity is almost zero; in the region where transmission is low, the emissivity is almost unity, the intermediate region is between 4 and 6 μm. In general, both the transmissivity and emissivity of materials can change with temperature. For our present purpose, and for simplicity, as a first approximation, we will assume that these quantities are temperature independent. We hope to solve

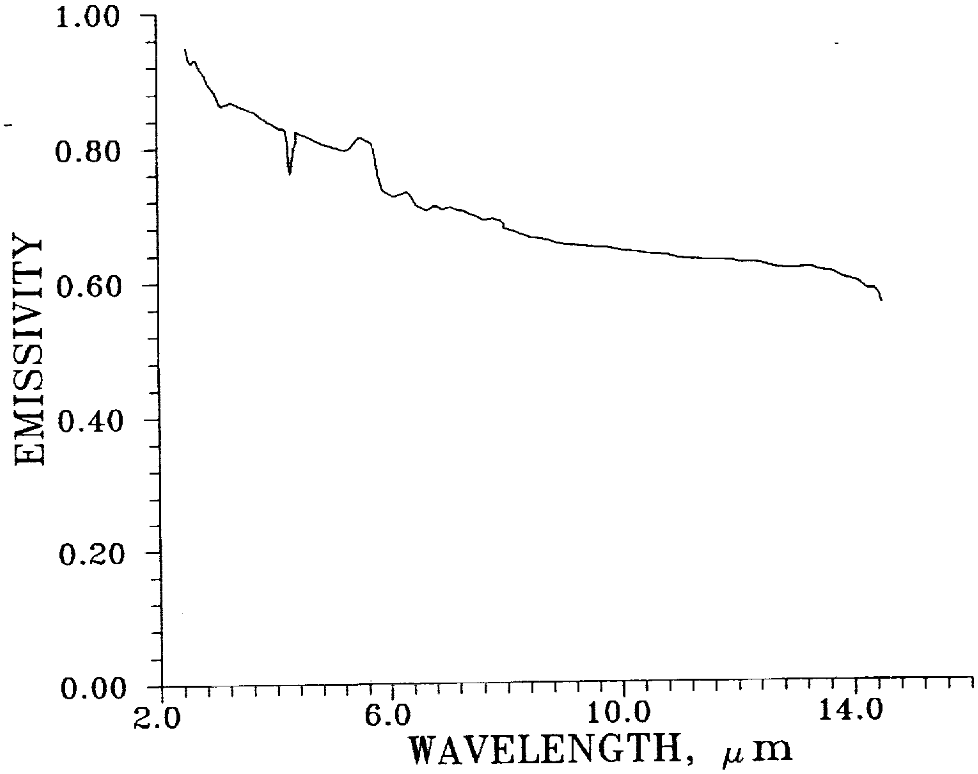

Figure 4 Emissivity of graphite paint.

the added complication introduced by temperature dependent emissivity and transmissivity using factorization multiwavelength pyrometry[3].

The thermal conductivity of sapphire is known[4]. If the temperatures of the surfaces of sapphire can be measured by remote means, we have a working heat flux sensor to measure heat flux quantitatively.

A multiwavelength pyrometer is used to measure the temperatures of the sensor's surfaces. Because the sapphire is transparent at the short wavelengths where its emissivity is almost zero, the radiation detected by the pyrometer at short wavelengths originates from the surface in contact with the back surface of the sapphire. At the longer wavelengths, sapphire is opaque and the radiation detected originates from the front surface. Multiwavelength pyrometry separates the radiation into two components, and thus measures two temperatures.

Results

To demonstrate the working of the non-contact heat flux sensor, an available piece of sapphire measuring 8 mm thick was used. The piece is of irregular cross section. One of its surfaces is covered with a graphite paint used in scanning electron microscopy. Heat flux measurement is carried out by positioning it in front of a calibrated black body furnace partially covering the furnace opening with the surface covered by the black paint pointing towards the furnace. The heat flux incident on the sapphire surface is varied by changing the black body furnace setting (temperature) and allowing the furnace to equilibrate. In this demonstration, the graphite paint is subject to the radiation heat flux. In other application geometries, it would be subject to the conduction heat flux of the surface in contact with the heat flux sensor.

In the working heat flux sensor described here, we need to know the emissivity of the graphite paint. Assuming that the emissivity is temperature independent but wavelength dependent, we obtain its value by recording its radiation spectra at two different unknown temperatures. The ratio of these two spectra is a function depending only on these temperatures[5]. Least squares curve fitting the ratio spectrum to this function determines the unknown temperatures T_1 and T_2. With their temperatures determined, their corresponding Planck functions are evaluated and used to divide the measured spectra to obtain the spectral emissivity. The resulting graphite paint emissivity is shown in figure 4.

At each black body furnace setting, the radiation emitted from the sapphire is recorded using the multiwavelength pyrometer. One such spectrum is shown in figure 5. This spectrum is the sum of three components. One component is radiation emitted by the graphite paint on the sapphire and is represented by a Planck function of temperature T_2, multiplied by the sapphire transmissivity $\tau(\lambda)$ and the graphite emissivity $\epsilon_2(\lambda)$, the second component is emitted from the front sapphire surface and is represented by a Planck function of temperature T_1 and the sapphire emissivity $\epsilon_1(\lambda)$, the third

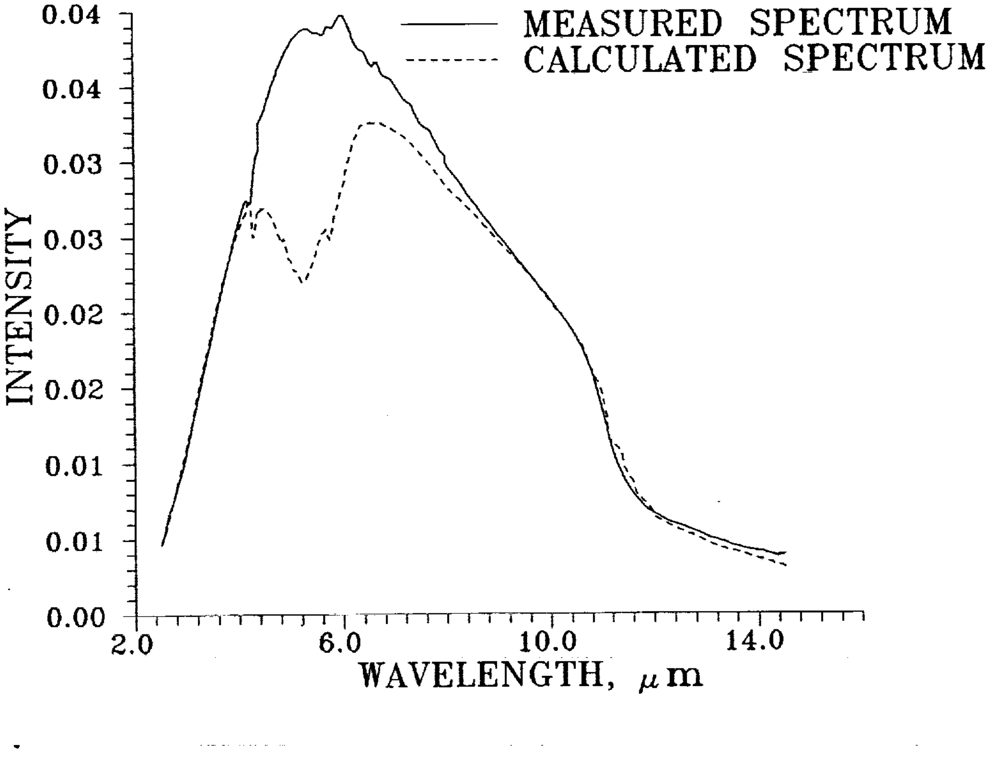

Figure 5 Spectrum of radiation from sapphire.

component arises from the absorption and re-emission of radiation in the wavelength region where absorption by the sapphire is significant. Shown also in figure 5 is the calculation obtained by including only the first two components. The excess of the measured spectrum over the calculated spectrum is due to absorption and re-emission. Quantitative calculation of this excess component is currently being carried out. By adjusting the values of T_1 and T_2 we can cause the spectra to match at the short and long wavelength regions, in this way, the temperatures of the sapphire surfaces are determined.

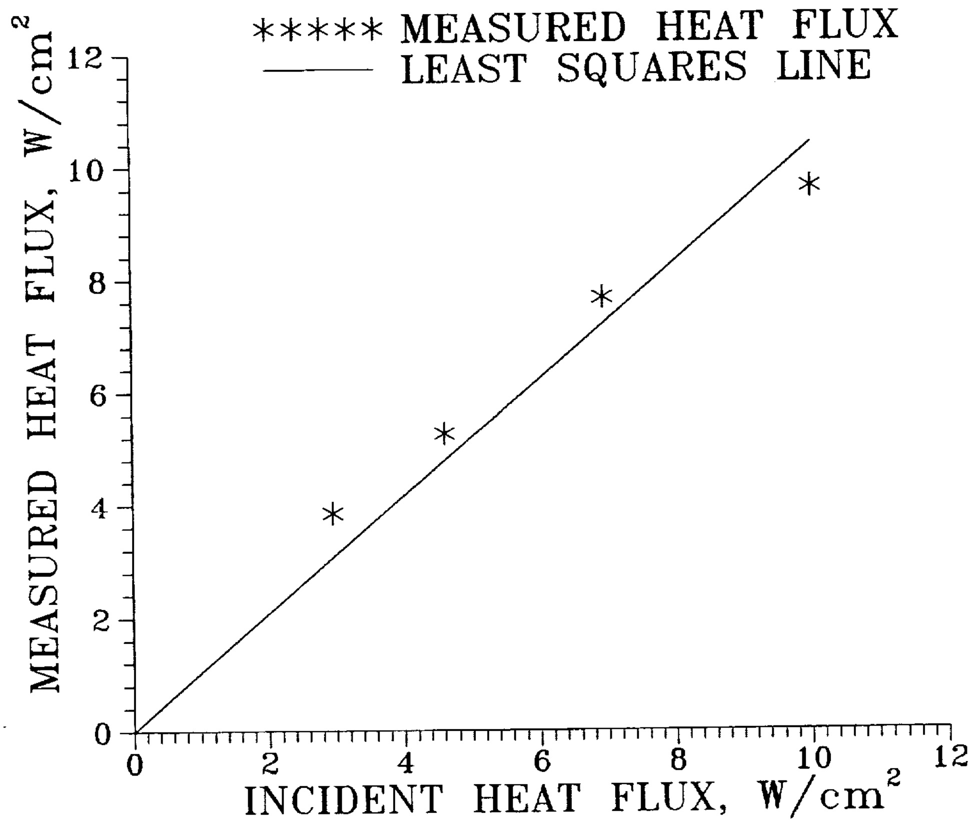

Figure 6 Comparison of measured heat flux and incident heat flux.

The heat flux from the calibrated black body furnace at four different temperatures (settings) are calculated from the surface temperature difference, thickness and the published thermal conductivity[2] of sapphire. Shown in figure 6 is the comparison between the heat flux values obtained using the Stefan-Boltzmann law and those measured using the heat flux sensor. The agreement is good. The slope of the least squares fitted line is 1.023, showing that these heat flux gauges would require no calibration for use.

Conclusion

A working non-contact heat flux sensor has been demonstrated using a transparent material (sapphire) and a multiwavelength pyrometer which measures the temperature difference across the sensor surfaces from the spectrum of radiation originating from the two surfaces. The measured heat flux is equal to the incident heat flux within experimental error indicating that no calibration would be necessary.

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