AN IMAGING RADIATION THERMOMETER

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Introduction

For many years radiation thermometers have been used to make non-contact temperature measurements of hot objects, particularly in industrial situations such as reformer furnaces, steel reheat furnaces, and ceramics kilns. They occupy an important niche in temperature measurement since any other type of thermometer would have very slim chances of surviving in these and other such hostile environments.

More than with any other type of thermometer, good measurements with a radiation thermometer require a detailed knowledge and understanding of the measurement process as well as of the object being measured and its surroundings. At the Measurement Standards Laboratory we have had many years of experience studying and evaluating the errors and uncertainties associated with the use of radiation thermometers, and have recently developed a new type of imaging radiation thermometer based on a CCD camera. This article describes the performance of our CCD camera (CCD stands for charge-coupled device) as a thermometer and demonstrates how it overcomes some of the problems inherent in traditional radiation thermometers.

We will begin by briefly describing the general properties of radiation thermometers and the major problems that all users need to be aware of when making measurements. We will then look at the advantages of our imaging CCD camera.

Radiation thermometers work by detecting the radiant energy, typically over a restricted range of wavelengths, emitted by the object of interest and using Planck's radiation law to relate this energy to temperature. An optical system, similar to that of an everyday camera, is used to focus the energy onto the detector, and a filter is used to select the appropriate wavelength range. Factors that lead to uncertainty and error in a measurement using any type of radiation thermometer include the following:

(i) The emissivity, ε, of the object's surface needs to be accurately known. Emissivity is a quantity that describes the object's ability to emit thermal radiation. A value of $\varepsilon = 1$ corresponds to a perfect emitter (called a blackbody), and $\varepsilon = 0$ to a perfect reflector. Radiation thermometers are always calibrated against a blackbody source; however, real objects have an emissivity value somewhere between 0 and 1, and so the thermometer reading needs to be compensated accordingly.

(ii) As implied above, real objects both emit and reflect thermal radiation. It is the radiation *emitted* by the object that determines its temperature; therefore the reflected component leads to an over-estimate of the object's temperature. A sufficiently detailed determination of the radiation distribution surrounding the object (e.g. due to flames, hot walls, the Sun, etc.) is needed to correct this error.

(iii) Thermal radiation must travel a certain distance from the object to the radiation thermometer. The atmosphere between the target and the thermometer often contains hot gases and dust particles that can absorb, emit or scatter the radiation, leading to further errors in the temperature assessment. For example, despite air being transparent in the visible part of the spectrum, a few metres of air is almost completely opaque to some wavelengths in the infrared. Radiation thermometers are designed to operate over spectral ranges where these atmospheric effects are minimised. However, this requires the thermometers to have very narrow bandwidths, which can lead to problems with signal detection. The narrower the bandwidth, the less radiation available at the detector, and thus the higher the sensitivity required for the detector. For commercially available radiation thermometers a compromise often has to be made between bandwidth and detector sensitivity.

(iv) The object of interest needs to over-fill the field of view of the radiation thermometer to obtain an accurate reading. For small or distant objects this criterion becomes difficult or impossible to fulfil. Reducing the field of view again leads to problems with detector sensitivity.

The CCD Camera

Unlike a traditional radiation thermometer that measures temperature at a single spot on the target, a CCD camera is capable of measuring a temperature distribution over a reasonably large area. There are a great variety of CCD cameras commercially available today, with a range of different specifications. The camera studied here is a Photometrics Star I CCD camera. As the name suggests, the camera was principally designed for use in astronomy, a field that has recently been revolutionised by such instruments. The rapid technological advances in CCD technology have led to the suitability of CCDs for temperature measurement.

At the heart of the CCD camera is a CCD chip. This is essentially an array (576×384) of silicon detectors (pixels) that convert incident radiation (photons) into stored electrons, which build up over time. One of the major advantages of CCDs is their very high sensitivity to incident photons. Combined with an optical system and a shutter, the array converts the radiation distribution in the camera's field of view into an accumulated charge distribution. This charge distribution is read using an amplifier, then transferred to a computer with each pixel represented as a count value ranging from 0 to 4095.

Conversion to Temperature

The measured count for each pixel of the CCD camera is proportional to the incident radiant flux multiplied by the exposure time. For a given exposure time, the higher the temperature of the source, the higher the pixel count. At a sufficiently high temperature the pixel count saturates, corresponding to a value greater than 4095, in which case the exposure time must be reduced. The minimum available exposure time thus determines the maximum measurable temperature, which for our system is about 1200°C. Higher temperatures can be reached using neutral density filters.

For the CCD camera to function as a thermometer the pixel count needs to be related to temperature. This is done by calibrating the measured signal, $S(T)$, for each pixel (the count divided by the exposure time) against a blackbody at known temperatures. A small amount of physics tells us that an appropriate calibration equation is

$$S(T) = C\exp\left(\frac{-c_2}{AT+B}\right).$$

In this equation c_2 is a quantity known as the second radiation constant, and has a value of 0.014388 m.K, and A, B, and C are parameters related to the camera specifications, which are determined by calibration of the CCD camera.

Two important points need to be made concerning the above calibration equation. First, because of the manufacturing process each pixel does not respond identically to same incident flux, thus each pixel has different A, B, and C values. Rather than calibrating each pixel individually, this problem is easily overcome by creating a "flat-field" image, that is an image of a uniform source. This image reveals the relative pixel variations. Subsequent images are divided by the normalised flat-field image, meaning that a single set of A, B, and C values can be applied to the entire array.

The second point is that the calibration equation applies to the measurement of blackbodies (i.e. $\varepsilon = 1$) at temperature T. For non-blackbodies ($\varepsilon < 1$), T refers to the "radiance" or "brightness" temperature of the object and is written T_λ. This is the temperature that a blackbody would have if it were to give the same signal on the CCD camera as that when measuring the object. The λ subscript indicates that the value of T_λ is dependent upon the operating wavelength range of the CCD camera (or radiation thermometer in general).

Reflection Errors

In most measurement situations reflections are the most serious source of error and uncertainty in radiation thermometry. Any hot body in the hemisphere in front of the object of interest is a potential source of reflected radiation. It is sometimes possible to shield the extraneous source, but this is not always the case. It is usually necessary to apply a correction. In the presence of reflections, the measured signal may be written as the sum of two terms:

$$S(T_\lambda) = \varepsilon S(T) + (1-\varepsilon)S(T_{\lambda,\mathrm{w}}).$$

The first term on the right-hand side corresponds to the radiation emitted by the object at the temperature T (which we are attempting to measure) and emissivity ε, and the second term corresponds to the radiation reflected by the object. The quantity $T_{\lambda,\mathrm{w}}$ is approximated by the average radiance temperature of all the bodies contributing to the reflected radiation (which are referred to here as the walls).

This measurement equation implies that at least two measurements need to be made, one of the radiance temperature T_λ of the object of interest, and one of the average radiance temperature $T_{\lambda,\mathrm{w}}$ of the walls. This latter measurement is easily performed using the CCD camera, since the entire walls may be imaged with one or a small number of exposures, and an average value calculated from each pixel. For a traditional single-detector radiation thermometer on the other hand, this averaging process relies on measurements at a sufficient number of individual points on the walls. For walls with large temperature variations it is difficult to obtain an unbiased average.

With these two radiance temperature measurements, and an estimate of the object's emissivity (often obtained from published tables), the true temperature of the object can be calculated from the above measurement equation and the calibration equation.

Furnace Measurements

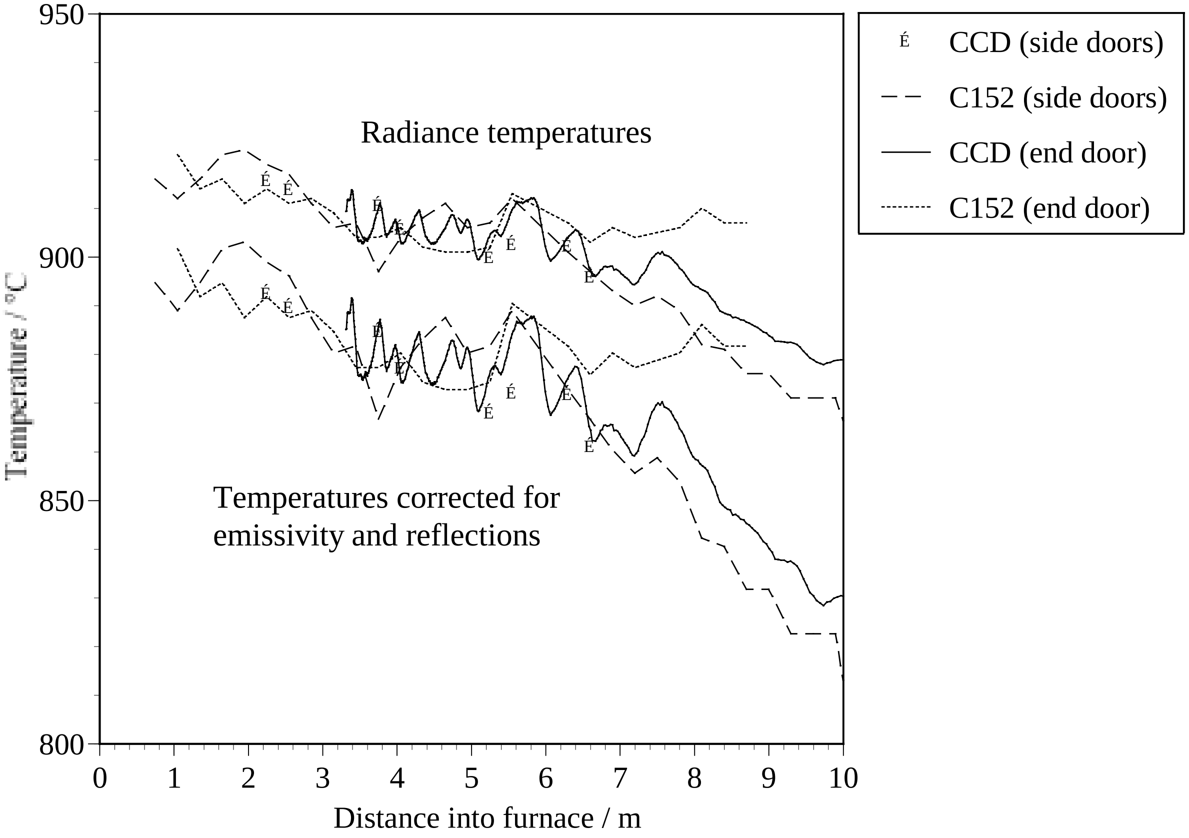
To demonstrate the utility of the CCD camera we compare measurements made of process tubes in a large industrial furnace with those made using a Land Infrared C152 single-detector radiation thermometer. These are shown in the figure. The tubes are surrounded by hot walls and are in a line parallel to one wall. Measurements were made from sight doors in the wall parallel to the tubes (side doors), and from a single sight door at the end of the line of tubes (end door). For the measurements taken from the side doors the tubes were always about 2.4 m distant, while for those from the end door the measuring distance increased as indicated by the horizontal axis of the graph.

The upper curves in the figure are the radiance temperatures as measured by both instruments and the lower curves are the corrected temperatures calculated from the measurement equation with a value of $\varepsilon = 0.85$. The average wall radiance temperature was measured with the CCD camera to be $T_{\lambda,\mathrm{w}} = 995$ °C.

There are several points of interest. First, the CCD camera and the C152 values from the side doors are in excellent agreement, and these also agree with the CCD camera values from the end door. Secondly, the C152 values from the end door show an increasing divergence with measurement distance from the other readings. This is due to the relatively wide spectral bandwidth for the C152, centred near 1 μm. The furnace gas contains water vapour, which has spectral emission lines within the bandwidth of the C152. This emission augments the signal measured by the C152. The amount of water vapour emission increases with distance explaining the absence of the effect in the C152 measurements from the side doors. On the other hand, while the spectral range of the CCD camera overlaps that of the C152, its bandwidth is about 10 times narrower, and thus lies outside of the water vapour emission lines. This narrow bandwidth is possible because of the very high sensitivity of the CCD. Thirdly, the spread of corrected temperatures is larger than the spread of radiance temperatures by a factor of almost 2. This means that a furnace will always look more uniform than it actually is; this fact is due to the averaging effect that the reflected radiation has on the overall temperature distribution within the furnace. Fourthly, the relatively large field of view of the C152 limited the reliable identification of objects in the furnace to those within a distance of about 9 m. Although not shown in the figure, the CCD camera could resolve objects up to about 23 m distant because the field of view for a single pixel is very small.

Conclusion

The high sensitivity of CCDs enables them to be used effectively as radiation thermometers operating over narrow spectral bandwidths, thus avoiding atmospheric effects that degrade accuracy. The thermal images obtained contain large amounts of information revealing thermal gradients and enabling a good assessment of background radiation distributions to be made in correcting for reflections.


950
900
850
800
Temperature / °C
0
1
2
3
4
5
6
7
8
9
10
Distance into furnace / m
Radiance temperatures
Temperatures corrected for emissivity and reflections
É CCD (side doors)
C152 (side doors)
CCD (end door)
C152 (end door)