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Infrared Thermometry

Introduction, History, and Applications

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In manufacturing environments, measuring the temperature of an object without contact has proven to be a complex and daunting task. Objects in motion are often difficult to touch, and objects that are too hot will damage the temperature sensor. Dependable means for gauging high temperatures have evolved over the centuries, from the primitive visual methods used by blacksmiths as they forged steel, to today's highly accurate means of industrial temperature measurement.

This paper discusses newer methods that yield repeatability irrespective of the process operator and the environment. With the introduction of optical fiber thermometry (OFT), an entirely new and repeatable method of measuring temperature was born. The introduction of new sensor types and integration of multiple optical detectors and electronics into a single instrument resolved many of the issues that traditional pyrometers faced.

Optical Pyrometry

It is a well known phenomenon that hot objects emit light. The hotter, the brighter. In fact, this phenomenon is one of the more important cornerstones of many modern technologies. Among them is radiometric temperature measurement, otherwise known as optical pyrometry.

This emission occurs according to some fairly well known and understood physical principles. Before going any further, we introduce several concepts that are important to understand.

The Concept of a Blackbody

Briefly speaking, a blackbody is the ultimate emitter. A blackbody is a theoretical construction so named because it appears infinitely black. Light incident on the surface of a blackbody will yield no reflections because the object is completely black. Thus, it is the ultimate absorber of energy.

If such an object is in equilibrium, or balance, with its surroundings, it must both absorb and emit the same energy. This means that a blackbody, being the ultimate absorber, must also be the ultimate emitter. The more an object absorbs, the more it must emit in order to remain in equilibrium.

The energy emitted by a blackbody has been experimentally observed to be a function of its temperature. Early physicists mapped the distribution of energy of near-blackbody emitters across many wavelengths at different temperatures. Their results are shown in Figure 1 on page 2.

In 1900, Max Planck accurately described the fundamental relationship between the absolute temperature of a blackbody, the intensity of that emission, and the wavelength of the emitted energy, thus explaining the observed data. From the principles of quantum mechanics, he was able to clearly predict the energy distribution that one would observe looking at a blackbody at a given temperature.

$$E_{\lambda,T} = \frac{C_1\lambda^{-5}}{e^{\frac{C_2}{\lambda T}}-1}$$

E is the energy, λ is the wavelength of the light, or energy, and T is the absolute temperature of the body in question. C_1 and C_2 are compilations of fundamental constants.

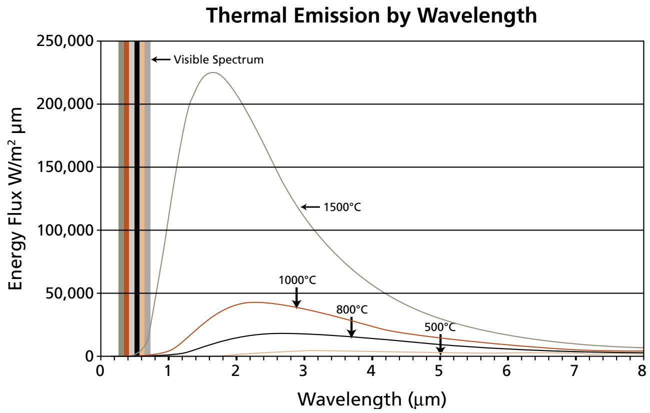


Figure 1. Distribution of energy of near-blackbody emitters across many wavelengths at different temperatures

If we look at Figure 1 in more detail, there are several noteworthy points that pertain to optical pyrometry:

- *Hotter objects emit more energy at one fixed wavelength (color) of light.*
- *The peak emission of an object trends to the left, towards the blue-violet end of the spectrum, as its temperature increases. This explains the commonly seen phenomenon of color temperature, also known as* Wien's displacement law. *The hotter an object is, the more its appearance shifts to the blue end of the spectrum.*
- *For objects of "ordinary" temperatures (i.e. < 100°C), the vast proportion of the energy emitted from them as a result of their temperature is at wavelengths beyond the visible portion of the spectrum.*

Emissivity

The degree to which an object is "black" is termed its *emissivity*. Objects that absorb all incident energy (blackbodies) have an emissivity of 1. Objects that absorb no energy (perfect mirrors or perfect windows) have an emissivity of 0. Real objects typically fall somewhere between emissivity 0 and a theoretical blackbody with emissivity 1.

Mathematically speaking, emissivity describes an object's emission relative to that of the ideal blackbody emitter at that same temperature and wavelength.

$$\varepsilon = \frac{\text{Energy}_{\text{Emitted}}(\text{Target})}{\text{Energy}_{\text{Emitted}}(\text{Blackbody})}$$

The spectral distribution in Figure 2 illustrates the concept:

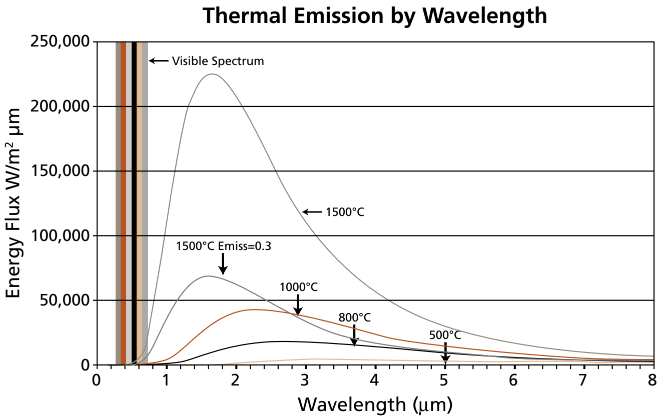


Figure 2. Thermal emission by wavelength

Note the addition of the curve for the emission of a real surface at temperature 1500°C, but with an emissivity of 0.3. We term such a surface a "graybody" if its emissivity is unchanging with wavelength.

If one were to use a pyrometer whose wavelength was 2.6 µm, the emission from this graybody at 1500°C would be indistinguishable from a blackbody at only 1000°C. This creates an error of 500°C. In most circumstances, this is an unacceptable measurement error.

At shorter wavelengths, the problem lessens. The emission of the 1500°C target with e=0.3 at *1 micron* rather than 2.6, is equivalent to a blackbody at 1275°C. The error is therefore decreased to 225°C. Were it possible to construct an optical pyrometer at 0.2 microns (in the ultraviolet), the error would be only 50°C.

As an aside, the lack of available energy to measure is the limitation here. An optical pyrometer that reads below ~1 W/m^2 is technologically impractical at this time. At very short wavelengths, the emission is so low as to make this impractical. (See Figure 3.)

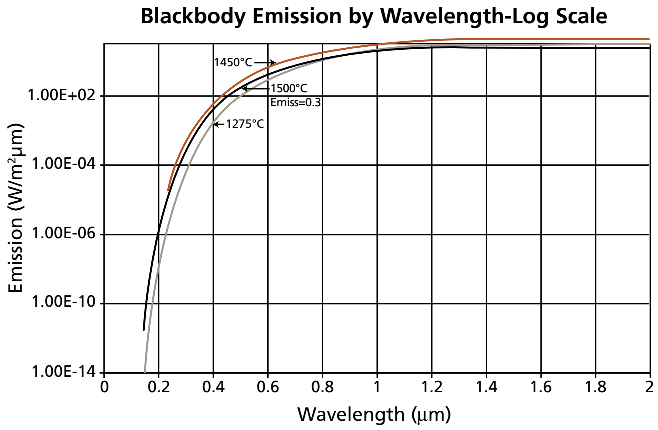


Figure 3. Blackbody emission by wavelength

For many materials, the emissivity has been characterized and published. Some common examples follow:

Material	Emissivity at 1 µm
Graphite	0.95
100 to 300 µm sic coated on graphite	0.93
300 series stainless steel	0.5
Copper, polished or deposited	0.04
Silicon	0.67
Aluminum	0.10

It is therefore possible for the user to program the pyrometer, in effect calibrating the instrument for the emissivity of the target material. This often serves to greatly reduce errors.

Careful consideration of material properties is necessary to avoid serious errors in some cases. The situation is often complicated by temperature-dependant emissivities of materials. Further, the surface treatment of materials is often of more importance than the bulk materials themselves. A common example of this would be anodized aluminum, whose emissivity can be very nearly 1, depending on the details of the anodization process, whereas the bulk material has a very low emissivity (~0.1).

Applications and History

Planck's law is the primary relationship that is used to measure the temperature of an object without the necessity of contacting it, which is useful because it may be inconvenient or impossible to do so. A moving object is often difficult to touch. An object that is too hot will simply melt or damage the temperature sensor. The object of interest also may be easily damaged by contact, thereby precluding measurement of its temperature.

In days past, the blacksmith would gauge by sight the correct working temperature of the steel being forged. After some training, it is possible to fairly accurately discern the temperature of hot steel and iron with the unaided eye. The color of heated steel appears first red, then orange, and then yellow as its temperature rises (Wien's law). The normal practice is to heat the workpiece to the correct color, work it, and maintain its temperature by repeated immersion in the fire.

Process control in a factory obviously cannot depend on such methods, making it necessary to measure the temperature to some degree of accuracy and repeatability irrespective of the process operator and the environment.

Early attempts to solve this problem used a variety of techniques. One important and fairly widely used method is the technique of disappearing filament pyrometry. The principle is simple; a hot target is viewed through an optical device, and a hot glowing filament is superimposed on the image of the target. The temperature of the filament is then varied until the image of the filament "disappears" into the target's image. The setting of the control knob for the filament is calibrated such that the temperature may be read from the instrument.

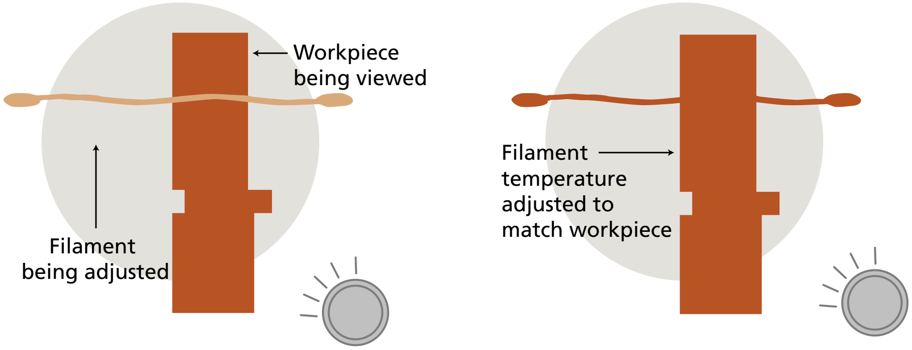


Figure 4. Disappearing filament pyrometry

This method allowed non-contact measurement of fixed temperatures and established one very important attribute of the measurement: traceability. For example, a measurement could be clearly matched to an absolute standard elsewhere, enabling the duplication of results at multiple locations, essentially independent of the device operator.

This method posed two main problems in that the measurement was slow, and automation was impossible. Therefore, control feedback for industrial processes was poor at best. The method was also limited to incandescent temperatures, which meant that no temperature measurement below ~700°C was possible.

With the advent of more modern electronics (circa 1950), modern optical pyrometry was born. The essence of the system is that an object of interest, or target, is viewed with some type of optics. The object is imaged on an electronic detector of some type that has been accurately calibrated to produce a known relationship between input (light intensity) and output (temperature reading). The output is typically routed into a control system and used as feedback to adjust the process in real time. A display of some sort is also common on the instrument.

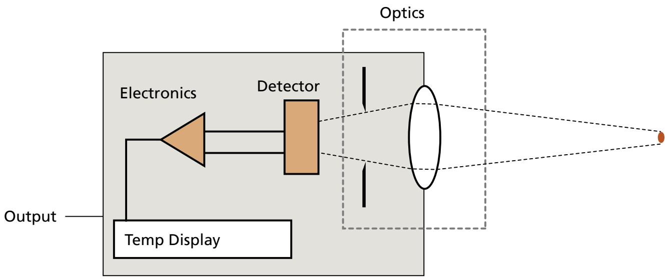


Figure 5. Modern optical pyrometry instrumentation

Figure 5 shows the critical elements of the system. Many different detector technologies are used for monitoring the hot object, and the choice is typically application dependant. The instruments typically offer output in standard (0 to 10 V, 4 to 20 mA, etc.) industrial control formats to facilitate their integration into processes.

Once pyrometers were available to monitor processes and provide feedback for temperature control, other issues arose:

First, the target of choice must be imaged correctly and consistently. With a traditional pyrometer, typically a simple lens arrangement is used, much like a common telescope looking directly at the intended target. In many cases, a direct optical path is not consistently available. The design of the manufacturing machinery may simply preclude it. Smoke and other particulate material may contaminate optics, or sensors may be accidentally moved.

Second, sensitive detector electronics often did not do well in industrial environments. Stray electrical signals often impacted measurement and caused accuracy, repeatability, and resolution issues.

Stray light is a third source of optical error common to all pyrometry. An optical pyrometer collects radiation from its target at its functional wavelength. If the source of that radiation is from something other than the target, then measurement errors will be induced. A common example is seen in Figure 6.

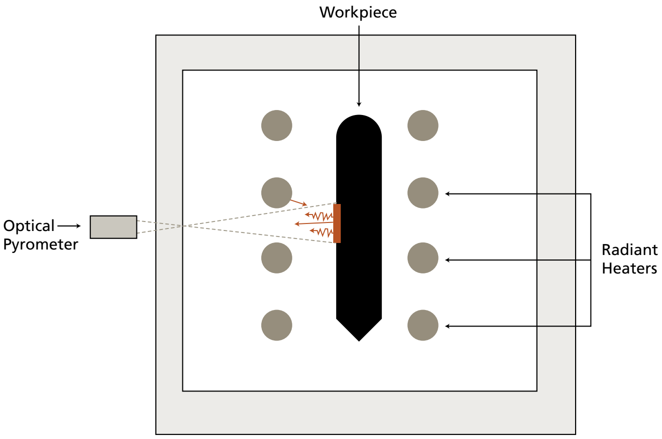


Figure 6. Stray light error

In this example, the optical pyrometer viewing the workpiece receives radiation from a specific area on its side. The inaccuracy in the measurement comes about because the radiant heaters are at a higher temperature than the target (after all, they need to heat it). They emit light, which is reflected off of the workpiece and enters the pyrometer. If the target is particularly reflective, then the bulk of the energy received by the pyrometer is actually reflected signal from the heat source, and thus the sensor error can be quite large.

In an effort to reduce many of the errors inherent in pyrometry, optical fiber thermometry (OFT) was developed in the 1980s. The essence of the system is similar to a standard optical pyrometer with one important distinction: the optical detector and electronics are in one box, and an optical fiber connects the detector to the sensor, which can be one of several different types.

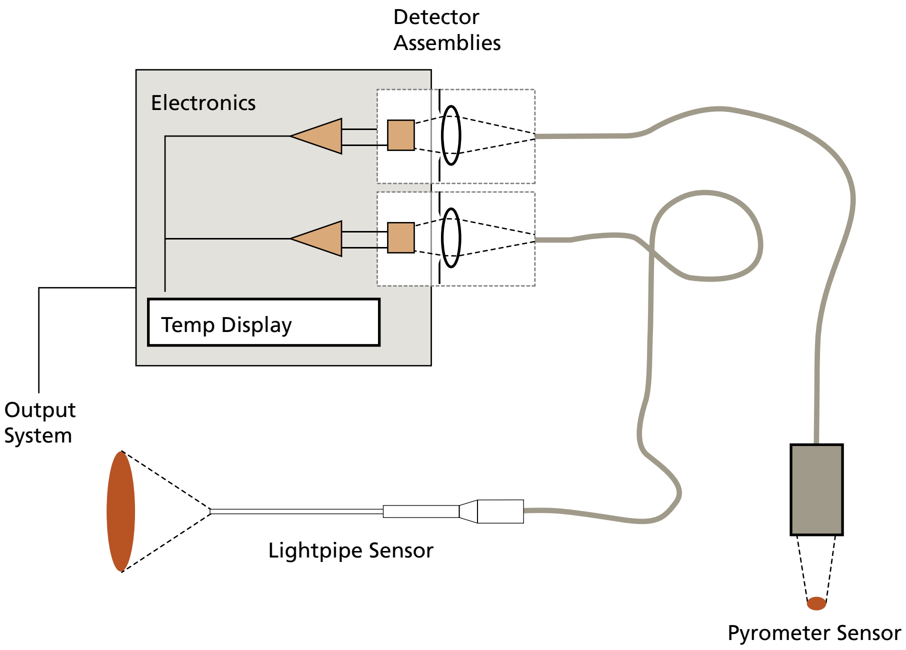


Figure 7. A radiometric optical fiber thermometer

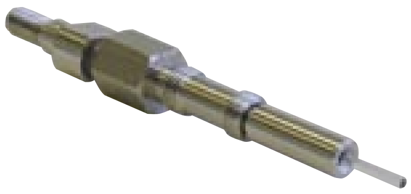
At the same time, multiple optical inputs were integrated into one instrument, reducing the cost for multiple measurement sites.

This method of delivering signals to the detector provides several key advantages:

- *Sensors become quite small and can be inserted into a process in locations where size constraints make traditional pyrometry impossible.*
- *Sensitive detector electronics are placed in a safe, remote location away from stray electrical fields. This allows the unit to resolve lower temperatures by removing electrical noise from the measurement.*
- *Intrusion into a process environment often allows the user to engineer the measurement to block stray light, or allows the use of other elements and tricks to eliminate the emissivity and stray light problems.*

The sensor itself is typically either a lensed arrangement like a conventional pyrometer, or a transparent optical waveguide known as a lightpipe. The lightpipe is an element unique to OFT technology. When inserted inside the process chamber, the sensor typically comes into very close proximity to the target.

This will often allow the engineer to add light-obstructing baffles to the chamber to eliminate stray light. It also frequently allows the user to add purge gas to the sensor assembly to keep it clean and to get close enough that contaminants in the process do not significantly interfere with the line of sight.



The lightpipe's optical field of view is divergent. (Cone angle can be tailored to some extent.) In making an optical temperature measurement, it often proves desirable to gather energy from a fairly wide area. This allows for signal averaging over an area, making the measurement less sensitive to local surface variations in emissivity and temperature.

Lightpipes can be made of quartz or other crystalline materials, but sapphire (single-crystal Al_2O_3) is the most effective and most common material in use today.

Typical sensor sizes are diameters from 1 to 4 mm, and lengths vary from 25 to 400 mm. A wide variety of mechanical fittings, including feedthroughs, vacuum fittings, positionable probes, and customer-specific accessories are available. The details of the sensor are almost always application-specific, so there is no standard configuration. It is advisable to consult an applications engineer with specific requirements.

The introduction of OFT into a process is easiest when it is designed into an application from the beginning. Placement of feedthroughs into a process and accessibility to elements of the process that are important to measure and control should ideally be preconceived and accounted for early in the application engineering process.

Specifications are subject to change without notice.

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ENG-THERMOMETRY-270-01 0M 11/06