What do "infrared thermometers" measure?

A laboratory experiment from the Little Shop of Physics at Colorado State University

Overview

These days, infrared—or "non-contact" thermometers are popular items in hardware stores, auto parts stores, and stores that carry high-end cooking equipment. You point a thermometer at an object, and it reads the temperature. You can see how this could be useful in cooking, in working on your car.

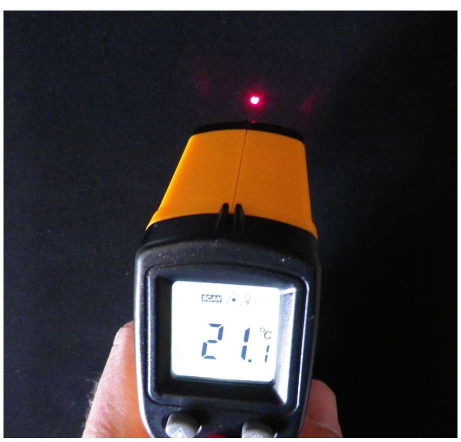
But... What does such a thermometer actually measure? If you are cooking a roast, there's a good chance that the reading will correspond to the surface temperature. But the truth is not always so simple, as we'll see!

In the title, we've put "infrared thermometer" in quotes because this device doesn't measure temperature directly; rather, temperature is inferred from a different measurement.

So just what *does* the device measure? This is a good open question that you can ask your students to explore.

Necessary materials:

- Infrared thermometer. There are two important properties to look for:
  - ***Wide temperature range.*** If you are going to use the thermometer for making environmental measurements, the low end is most important; -50°C is a very good lower end. The radiation emitted from the sky can be quite minimal, so it will give a low reading.
  - ***Small area for measurement.*** The thermometers collect radiation from a certain angle. We use a thermometer with a 12:1 distance-to-spot ratio; this means that, at a distance of 1 foot, the spot from which radiation is collected is 1 inch in diameter. This corresponds to an angle of about 5°.
- Mug warmer
- Can of juice or other non-carbonated beverage. Whatever you pick, it should have areas with paint, bare metal, and clear coatings.



The device's reading is a temperature. But the reality is a bit more complicated!

Theory

All matter is made of atoms, and the atoms are in constant motion; this is the molecular view of thermal energy. And one of the basic tenets of physics is this: When you accelerate a charged particle, it emits electromagnetic waves. Does this mean that all objects will emit electromagnetic waves?

Indeed it does. This *thermal radiation* is emitted by all solids and all liquids; gases are another story that we'll turn to later. Hotter objects emit more, objects at different temperatures emit different wavelengths, and some objects (metals, for instance) are pretty poor emitters. But the ground, clouds (which are made of solid or liquid water), your body, the walls of the room in which you are sitting... All of these emit thermal radiation in measurable and important amounts.

The intensity of the emitted thermal radiation from a source at a temperature T (in kelvin) is:

$$I = e\sigma T^4$$

The constant e in this equation is the emissivity, a measure of the effectiveness of the surface in emitting thermal radiation. The emissivity is dimensionless; it varies between 0 and 1. σ, the Greek letter sigma, is the Stefan-Boltzmann constant, which has the value $\sigma = 5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$.

Most objects that you are apt to measure with an infrared thermometer are good emitters. Your skin has an emissivity of $e = 0.98$, no matter your skin color. Water has $e = 0.98$, paper $e = 0.94$, plastics $e = 0.95$, painted surfaces $e = 0.94$. But metals are very poor emitters; aluminum foil has $e = 0.03$.

An infrared thermometer is typically calibrated assuming $e = 0.95$, which is typical of most surfaces.

When you aim the thermometer at a surface, a lens and sensor collect emitted thermal radiation. If you aim the thermometer at a warm surface, the sensor heats up. The hotter the surface, the more warming takes place. The final temperature of the surface is used to deduce the temperature of the emitting surface.

Most thermometers have an integrated laser, which shows the area of the surface for which emission is being measured. But the laser doesn't work as a "probe"; it has nothing to do with the measurement. And the thermometer measures emitted energy from a large area; a typical thermometer will have a distance to spot ratio of 8:1, meaning that, at a distance of 8 cm, radiation is measured from a spot 1 cm in diameter. If you stand 8 feet from a wall and point the thermometer at it, you are measuring the radiation from an area 1 foot in diameter, and the temperature displayed will be an average of the temperatures over this spot.

The thermometer estimates the temperature of the emitting surface by assuming $e = 0.95$. If you aim the thermometer at your forehead, this works pretty well; the emissivity of your forehead is $e = 0.98$, which is pretty close. But if you are measuring a baked potato wrapped in aluminum foil, you'll get an erroneous reading; the foil's emissivity, $e = 0.03$, is lower by a factor of 30 than what the thermometer assumes!

For this reason, we tend to call the thermometers "thermal sensors." They detect emitted thermal radiation, and use this to deduce a temperature. A high temperature reading means that a good deal of radiation is collected; a low temperature reading means that very little radiation is collected.

This way of interpreting the results of a measurement is very important for making environmental readings. If you point the thermometer at the sky and measure -20°C, this doesn't mean that this is the temperature of the sky; it just means that the total thermal radiation emitted by the sky above you is rather modest.

Before students can make sense of this, it makes sense to do a "warm up" activity with the thermometers in which the temperature readings vary depending on the surface the thermometer measures.

Doing the Experiment

To prepare, choose a (full) can of a non-carbonated beverage; we find that canned lemonade works nicely. It's good to have a can with parts that are painted different colors, or that is only painted on part of the surface.

Now, Place the can on a mug warmer to allow it to warm up to about 50° to 60 °C. If you have students work in groups, warm up one can for each group. The can is made of aluminum, which is a good thermal conductor; if you shake the can to mix up the liquid, the temperature of the liquid inside will be quite uniform. The net result is that every point on the can is, to a very good approximation, at the same temperature.

But that's not what your students will measure...

- Give the students the warm can, and have them measure the temperature of different parts of the surface. Have them try the (painted) sides, the top, the bottom. Have them record the temperatures they observe.
- Let students know that, to a very good approximation, all parts of the outside of the can are, truly, at the same temperature.
- Ask your students to explain the odd results. Why do they measure different values from different points on the can?

This is a good experiment for open-ended exploration. When students measure the temperature of a shiny surface, they'll pick up radiation from other sources that reflects from the can. And the curved bottom surface of the can will give different results depending on how far the thermometer is from the focal length of the concave mirrored surface.

Ultimately, your students can determine what surfaces are good radiators, what surfaces are poor radiators. And they'll understand the thermometers well enough to set them up for further experiments in which they'll use these devices as an experimental tool.

Summing Up

This is an interesting exercise, a fun open-ended investigation, and an important activity to do before your class uses these devices to measure temperatures.

For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu