innovative infrared technology

BASIC PRINCIPLES

of non-contact
temperature measurement

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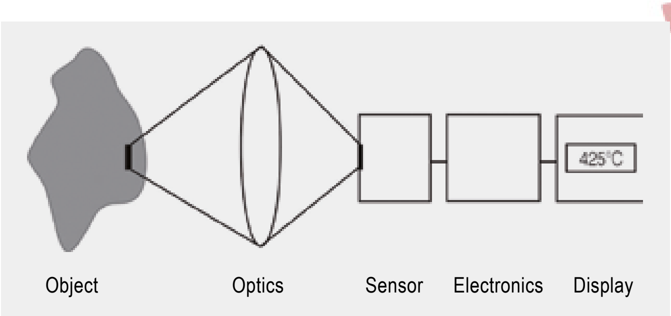
Physical principles

With our eyes we see the world in visible light. Although visible light makes up only a small part of the radiation spectrum, the invisible light covers most of the remaining spectral range. The radiation of invisible light carries much more additional information.

The infrared temperature measurement system

Each body with a temperature above absolute zero (–273,15 °C = 0 Kelvin) emits electromagnetic radiation from its surface, which is proportional to its intrinsic temperature. A part of this so-called intrinsic radiation is infrared radiation, which can be used to measure a body's temperature. This radiation penetrates the atmosphere. With the help of a lens (input optics) the beams are focused on a detector element, which generates an electrical signal proportional to the radiation. The signal is amplified and, using successive digital signal processing, is transformed into an output signal proportional to the object temperature. The measuring value may be

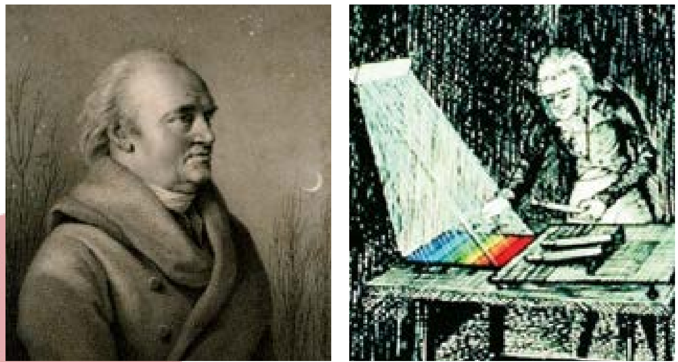


Infrared System

shown in a display or released as analog output signal, which supports an easy connection to control systems of the process management.

The advantages of non-contact temperature measurement are obvious – it supports:

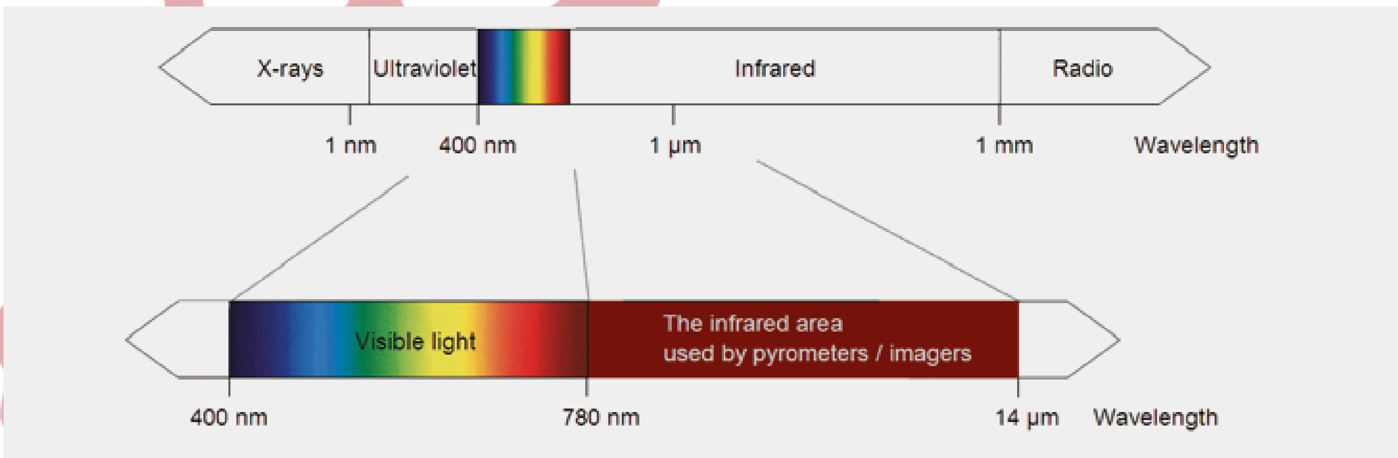
- Temperature measurements of moving or overheated objects and of objects in hazardous surroundings
- Very fast response and exposure times
- Non-interactive measurement, no influence on the measuring object
- Non-destructive measurement
- Measurement point durability, no mechanical wear



William Herschel (1738 – 1822)

Discovery of the infrared radiation

Searching for new optical material, William Herschel accidentally discovered the infrared radiation in 1800. He blackened the tip of a sensitive mercury thermometer and used it as measuring system to test the heating properties of different colors of the spectrum, which were directed to a tapletop by having beams of light shine through a glass prism. With this, he tested the heating of different colors of the spectrum. When he moved the thermometer in the dark area beyond the red end of the spectrum, Herschel noticed that the temperature continued to rise. The temperature rose even more in the area behind the red end of the spectrum. He ultimately found the point of maximum temperature far behind the red area. Today this area is called "infrared wavelength area".



The electromagnetic spectrum with the infrared area used by pyrometers.

The electromagnetic radiation spectrum

In a literal and physical sense, a spectrum is understood as the intensity of a mixture of electromagnetic waves that function as wavelength or frequency. The electromagnetic radiation spectrum covers a wavelength area of about 23 decimal powers and varies from sector to sector in origin, creation and application of the radiation. All types of electromagnetic radiation follow similar principles of diffraction, refraction, reflection and polarization. Their expansion speed corresponds to the light speed under normal conditions: The result of multiplying wavelength with frequency is constant:

$\lambda \cdot \mathbf{f} = \mathbf{c}$

The infrared radiation covers a very limited part in the whole range of the electromagnetic spectrum: It starts at the visible range of about 0.78 µm and ends at wavelengths of approximately 1000 µm.

Wavelengths ranging from 0.7 to 14 µm are important for infrared temperature measurement. Above these wavelengths the energy level is so low, that detectors are not sensitive enough to detect them.

Physical principles

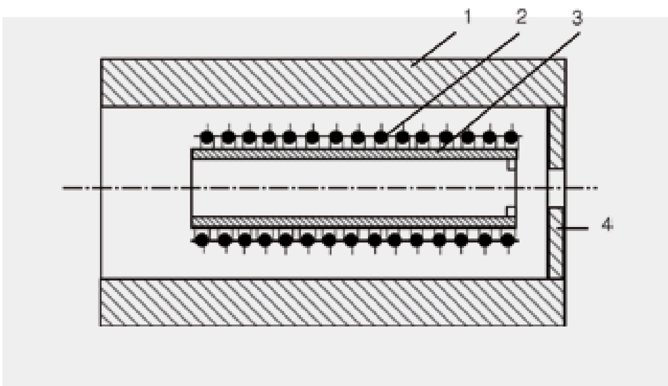
In 1900 Max Planck, Josef Stefan, Ludwig Boltzmann, Wilhelm Wien and Gustav Kirchhoff precisely defined the electromagnetic spectrum and established qualitative and quantitative correlations for describing infrared energy.

The black body

A black body is an abstracted physical body, which absorbs all incoming radiation. It has neither refective nor transmissive properties.

$\alpha = \varepsilon = 1$ (α absorption, ε emissivity)

A black body radiates the maximum energy possible at each wavelength. The concentration of the radiation does not depend on angles. The black body is the basis for understanding the physical principles of non-contact temperature measurement and for calibrating infrared thermometers.



Cross section of a black body:
1 – ceramic conduit, 2 – heating, 3 – conduit made from Al_2O_3, 4 – aperture

The construction of a black body is simple. A thermal hollow body has a small hole at one end. If the body is heated and reaches a certain temperature, and if temperature equilibrium is reached inside the hollow room, the hole ideally emits black radiation of the set temperature. For each temperature range and application purpose the construction of these black bodies depends on material and the geometric structure.
If the hole is very small compared to the surface as a whole, the interference of the ideal state is very small. If you point

Physical principles

the measuring device on this hole, you can declare the temperature emitting from inside as black radiation which you can use for calibrating your measuring device. In reality, simple systems use surfaces, which are covered with pigmented paint and show absorption and emissivity values of 99 % within the required wavelength range. Usually, this is sufficient for calibrations of actual measurements.

Radiation principles of a black body

The radiation law by Planck shows the basic correlation for non-contact temperature measurements: It describes the spectral specific radiation $M_{\lambda s}$ of the black body into the half space depending on its temperature T and the wavelength λ.

$$M_{\lambda S} = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} = \frac{C_1}{\lambda^5} \frac{1}{e^{C_2/\lambda T} - 1}$$

The following illustration shows the graphic description of the formula depending on λ with different temperatures as parameters.

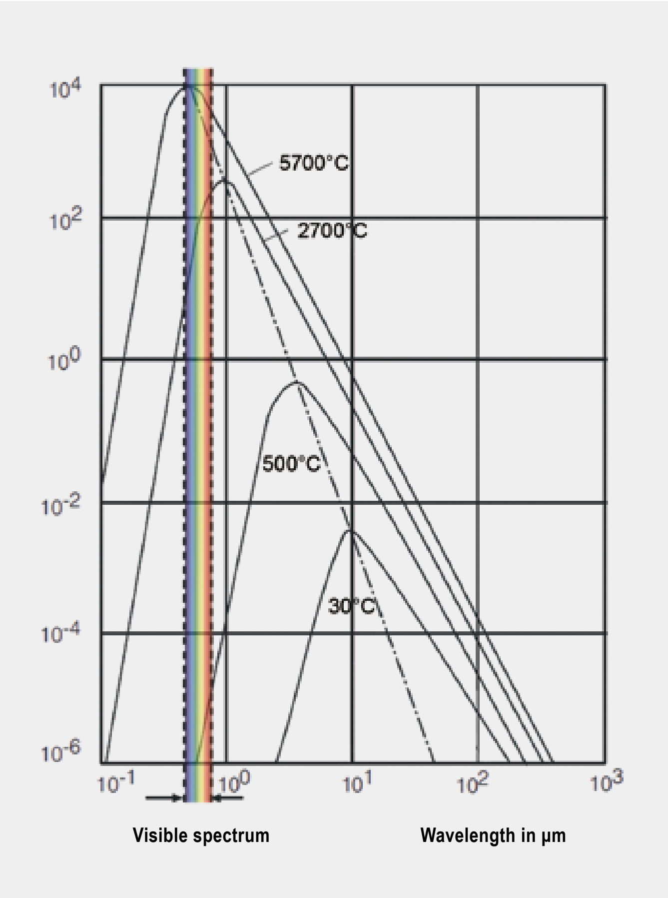
With rising temperatures the maximum of the spectral specific radiation shifts to shorter wavelengths. As the formula is very abstract it cannot be used for many practical applications. But, you may derive various correlations from it. By integrating the spectral radiation intensity for all wavelengths from 0 to infinite you can obtain the emitted radiation value of the body as a whole. This correlation is called Stefan Boltzmann law.

C light speed
C_1 $3.74 * 10^{-16}$ W m^2
C_2 $1.44 * 10^{-2}$ K m
h Planck's constant

$M_{\lambda S} = \sigma \cdot T^4$ **[Watt m²]** $\sigma = 5.67 \cdot 10^{-8}\ WM^{-2}K^{-4}$

The entire emitted radiation of a black body within the overall wavelength range increases proportional to the fourth power of its absolute temperature. The graphic illustration of Planck's law also shows that the wavelength, which is used to generate the maximum of the emitted radiation of a black body, shifts when temperatures change. Wien's displacement law can be derived from Planck's formula by differentiation.

$\lambda_{max} \cdot T = 2898\ \mu m \cdot K$



Spectral specific radiation $M_{\lambda s}$ of the black body depending on the wavelength

The wavelength, showing the maximum radiation, shifts with increasing temperature towards the range of short wavelengths.

The gray body

Only few bodies meet the ideal of the black body. Many bodies emit far less radiation at the same temperature. The emissivity ε defines the relation of the actual radiation value and that of the black body. It is between zero and one. The infrared sensor receives the emitted radiation from the object surface, but also reflected radiation from the surroundings and potentially infrared radiation that has been transmitted through the black body.

$$\varepsilon + \rho + \tau = 1$$

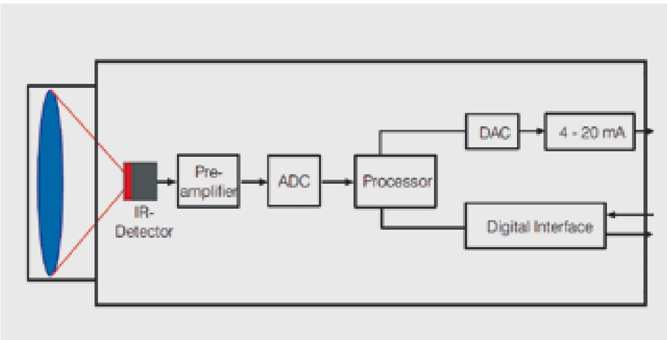
ε emissivity
ρ reflection
τ transmissivity

Most bodies do not show transmissivity in infrared. Therefore the following applies:

$$\varepsilon + \rho = 1$$

Construction and operation of infrared thermometers

The illustration shows the basic construction of an infrared thermometer. Using input optics, the emitted infrared radiation is focused onto an infrared detector. The detector generates an electrical signal that corresponds to the radiation, which is subsequently amplified and can be used for further processing. Digital signal processing transforms the signal into an output value proportional to the object temperature, which is then either shown on a display or provided as an analog signal.



Block diagram of an infrared thermometer

To compensate environmental temperature influences, a second detector records the temperature of the measuring device or its optical channel. The calculation of the temperature of the measuring object is done in three basic steps:

1. Transformation of the received infrared radiation into an electrical signal
2. Compensation of background radiation from device and object
3. Linearization and output of temperature information

In addition to the displayed temperature value, the thermometers also support linear outputs such as 0/4 – 20 mA, 0 – 10 V and thermocouple elements, which allow easy connection to process management control systems. Furthermore, due to internal digital measurement processing, most of the currently used infrared thermometers also feature digital interfaces (e.g. USB, RS485, Ethernet) for data output and to enable access to device parameters.

Infrared detectors

The most important element in each infrared thermometer is the radiation receiver, also called detector. There are two main groups of infrared detectors.

Infrared Detectors

Thermal Detectors
Thermopile
Pyroelectrical detector
Bolometer FPA (for IR cameras)

Quantum Detectors

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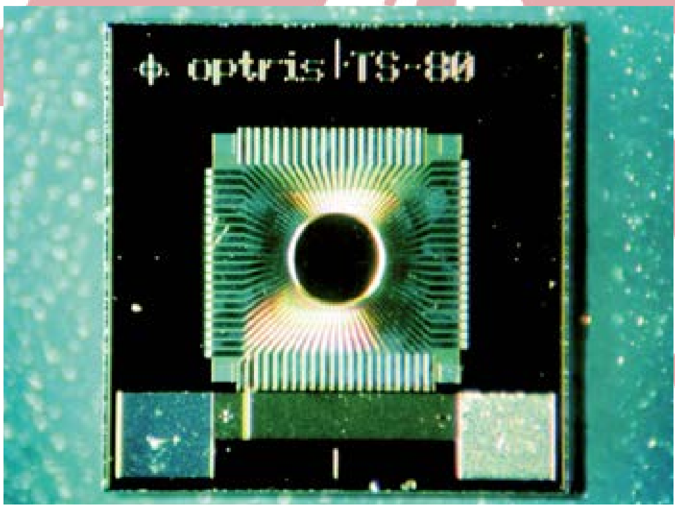
Thermal detectors

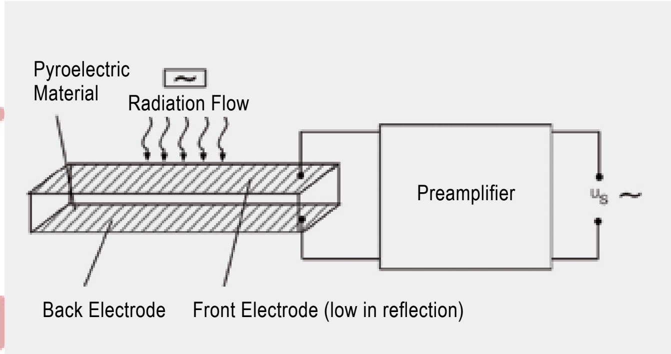
With these detectors, the temperature of the sensitive element changes due to the absorption of electromagnetic radiation. The temperature chance causes a modification of the temperature-dependent property of the detector, which is electrically analyzed and serves as a measure for the absorbed energy.

Radiation thermocouple elements (thermopiles)

If the connection point between two different metallic materials is heated, the thermoelectrical effect results in an electrical voltage. The contact temperature measurement has been using this effect for a long time with the help of thermocouple elements. If the connection is warm because of absorbed radiation, this component is called radiation thermocouple. The illustration shows thermocouples made of bismuth / antimony which are arranged on a chip round an absorbing element. In case the temperature of the detector increases, this results in a proportional voltage, which can be caught at the end of the bond isles.



Thermopile TS80



Construction of a pyroelectric detector

Pyroelectric detectors

The illustration shows the basic construction of a pyroelectric detector. This sensitive element consists of pyroelectric material with two electrodes. As a result of the temperature change of the sensitive detector element, caused by the absorption of infrared radiation, the surface loading changes due to the pyroelectric effect. The so created electric output signal is processed by a preamplifier.

Due to the nature of how the loading is generated in the pyroelectric element, the radiation flow has to be continuously and alternately interrupted. The advantage of the frequence selective preamplifying is a better signal-to-noise ratio.

Bolometers

Bolometers exploit the temperature dependency of electric resistance. The sensitive element consists of a resistor, which changes when it absorbs heat. The change in resistance leads to a changed signal voltage. The material should have a high temperature factor of the electrical resistance in order to achieve high sensitivity and high specific detectivity. Bolometers that operate at room temperature use the temperature coefficient of metallic resistors (e. g. black layer and thin layer bolometer) as well as of semiconductor resistors (e. g. thermistor bolometers).

Nowadays, infrared imagers are based on the following technological developments:

The semiconductor technology replaces mechanical scanners. FPAs (Focal Plane Arrays) are produced on the basis of thin layer bolometers. Consequently VOX (Vanadium oxide) or amorphous silicon are used as alternative technologies. These technologies significantly improve the price-performance ratio. Today, common detector sizes are 160 x 120, 320 x 240 and 640 x 480 pixels.

Quantum detectors

The decisive difference between quantum detectors and thermal detectors is their faster reaction on the absorbed radiation. The mode of operation of quantum detectors is based on the photo effect. The visible photons of the infrared radiation lead to an increase of the electrons into a higher energy level inside the semiconductor material. When the electrons fall back, an electric signal (voltage or power) is generated. Also, a change of the electric resistance is possible. These signals can be precisely evaluated. Quantum detectors are very fast (ns to µs).

The temperature of the sensitive element of a thermal detector changes relatively slowly. Time constants of thermal detectors are usually bigger than time constants of quantum detectors. Roughly approximated, one can say that time constants of thermal detectors can be measured in milliseconds whereas time constants of quantum detectors can be measured in nanoseconds or even microseconds.

Despite the fast development in the field of quantum detectors, there are many applications where thermal detectors are more suitable. That is why they share an equal status with quantum detectors.

Transformation of infrared radiation into an electrical signal and calculation of the object temperature

Since per the Stefan Boltzmann law, the electric signal of the detector is as follows:

$$U \sim \varepsilon T_{obj}^4$$

As the reflected ambient radiation and the self-radiation of the infrared thermometer must also be considered, the formula is as follows:

$$U = C \cdot [\varepsilon T_{obj}^4 + (1 - \varepsilon) \cdot T_{amb}^4 - T_{pyr}^4]$$

U *Detector signal*
T_{obj} *Object temperature*
T_{amb} *Temperature of backround radiation*
T_{pyr} *Temperature of the device*
C *Device-specific constant*

$\rho = 1 - \varepsilon$ Reflection of object

Since infrared thermometers do not cover the total wavelength range, the exponent n depends on the wavelength λ. At wavelengths ranging from 1 to 14 µm.

n is between 17 and 2 (at long wavelengths between 2 and 3 and at short wavelengths between 15 and 17).

$$U = C \cdot [\varepsilon T_{obj}^n + (1 - \varepsilon) \cdot T_{amb}^n - T_{pyr}^n]$$

Thus the object temperature is determined as follows:

$$T_{obj} = \sqrt[n]{\frac{U - C \cdot T_{amb}^n + C \cdot \varepsilon T_{amb}^n + C \cdot T_{pyr}^n}{C\varepsilon}}$$

The results of these calculations for all temperatures are stored as curve band in the EEPROM of the infrared thermometer. This guarantees quick access to the data and fast calculation of the temperature.

Emissivity

The formula shows that the emissivity ε is essential, if you want to determine the temperature with radiation measurement. The emissivity measures the ratio of thermal radiation, which is generated by a gray and a black body of equal temperature. The maximum emissivity for the black body is 1. A gray body is an object, that has the same emissivity at all wavelengths and emits less infrared radiation than a black radiator (ε <1). Bodies with emissivities, which depend on the temperature as well as on the wavelength, are called non-gray or selective bodies (e.g. metals).

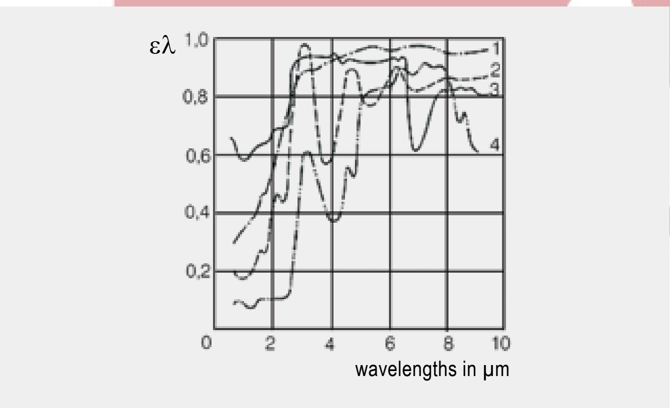
see emissivity table starting page 34

Emissivity and temperature measurement

Emissivity and temperature measurement

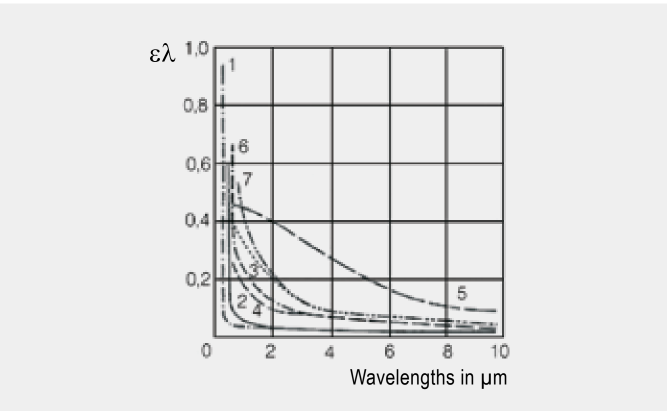
Emissivity is a key factor for the accurate measurement of temperatures. It depends on various influences and must be adjusted according to the application.

Theoretically, emissivity depends on the material, its surface, temperature, wavelength, measuring angle and sometimes on the measuring arrangement. Many objects consisting of non-metallic material show high and relatively constant emissivity independent of their surface consistency, at least in long-wave spectral ranges.



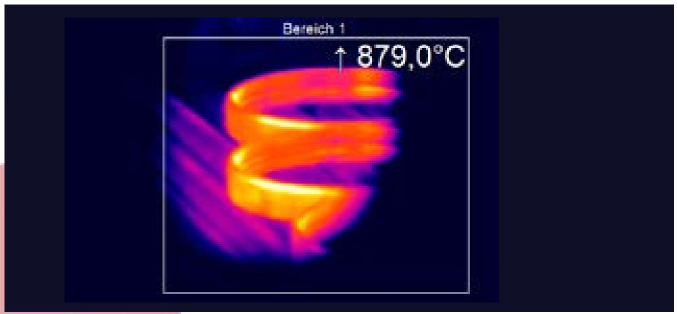
Spectral emissivity of some materials: 1 Enamel, 2 Plaster, 3 Concrete, 4 Chamotte

Generally, metallic materials show a low emissivity, which strongly depends on the surface consistency and which drop in higher wavelengths.



Spectral emissivity of metallic materials: 1 Silver, 2 Gold, 3 Platinum, 4 Rhodium, 5 Chrome, 6 Tantalum, 7 Molybdenum

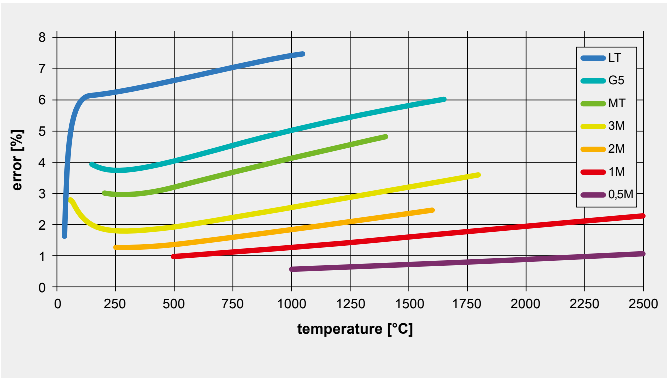
Temperature measurement of metallic materials



Measurement on bearing rings during hardening process

This may result in varying and unreliable measuring results. When selecting a suitable temperature measurement device, please ensure that the infrared radiation is measured at a specific wavelength and in a specific temperature range, in which metallic materials display a relatively high emissivity. The graph below shows that it makes sense to use the shortest possible wavelength available for measuring, since measuring errors increase in correlation to the wavelength for many types of metals. For metals, the optimal wavelength at high temperatures is 0.8 to 1.0 µm, which lies at the limit of the visible area.

In addition, wavelengths of 1.6 µm, 2.2 µm and 3.9 µm are possible.



Measurement error of 10 % as result of wrongly adjusted emissivity and in dependence on wavelength and object temperature (LT: 8 – 14 µm; G5: 5 µm; MT: 3.9 µm; 3M: 2.3 µm; 2M: 1.6 µm; 1M: 1.0 µm); 05M: 525 nm.

Further information in our High Temperature Applications brochure: ***http://www.optris.com/metal***

Temperature measurement of plastics

Transmission rates of plastics vary according to wavelength. They react inversely proportional to the thickness, whereas thin materials are more transmissive than thick plastics. Optimal measurements can be carried out with wavelengths, where transmissivity is almost zero. Independent of the thickness. Polyethylene, polypropylene, nylon and polystyrene are non-transmissive at 3.43 µm; polyester, polyurethane, Teflon, FEP and polyamide are non-transmissive at 7.9 µm. For thicker and pigmented films, wavelengths between 8 and 14 µm can be selected.

Spectral transmissivity of plastic films made from polyethylene

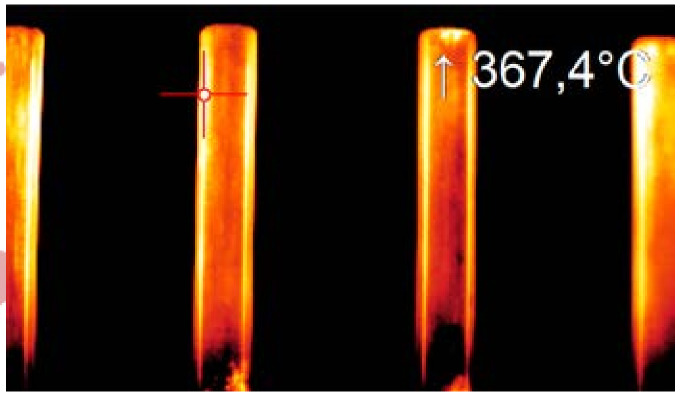
Spectral transmissivity of plastic films made of polyester

The manufacturer of infrared thermometers can determine the optimal spectral range for the temperature measurement by testing the plastics material. The reflection is between 5 and 10 % for almost all plastics.

Detailed analysis of preforms during bottle manufacturing

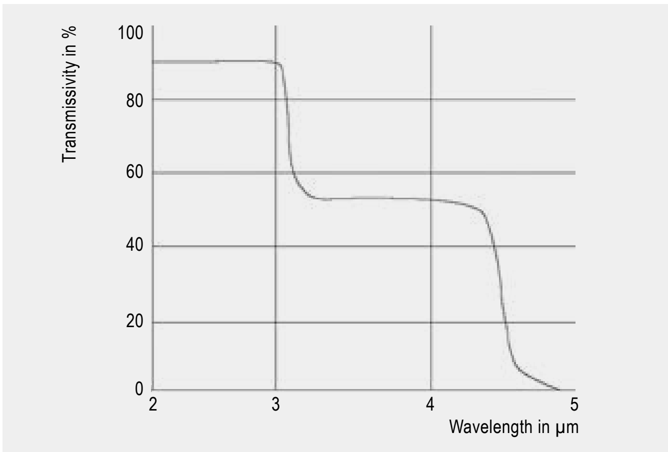
Further information about plastics applications in our brochure:
http://www.optris.com/plastics

Temperature measurement of glass



Hot spot measurement on glass tubes

If temperature measurements are performed on glass with IR thermometers or the special IR camera optris PI G7, both reflection and transmissivity must be considered. A careful selection of the wavelength facilitates measurements of the glass surface as well as of the deeper layers of the glass. Wavelengths of 1.0 µm, 2.2 µm or 3.9 µm are appropriate for measuring deeper layers, whereas 5 µm and 7.9 µm are recommended for surface measurements. At low temperatures, wavelengths between 8 and 14 µm should be selected in combination with an emissivity of 0.85 in order to compensate reflection. For this purpose, a thermometer with short response time should be used, since glass is a poor heat conductor and the surface temperature can change quickly.



Spectral transmissivity of glass

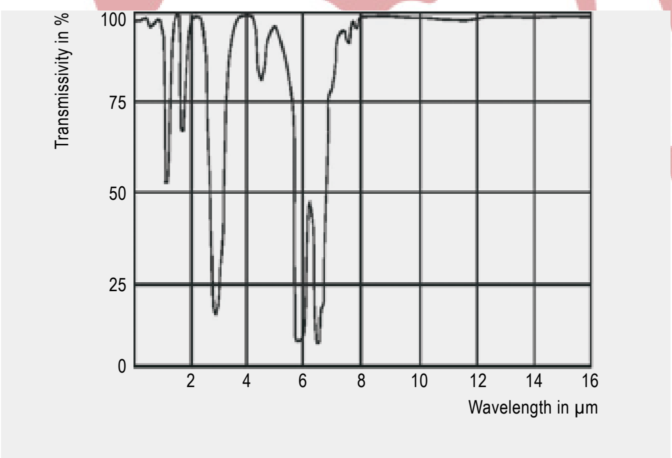
Further information in our glass applications overview:
http://www.optris.com/temperature-monitoring-glass-industry

Emissivity and temperature measurement

Environmental influences

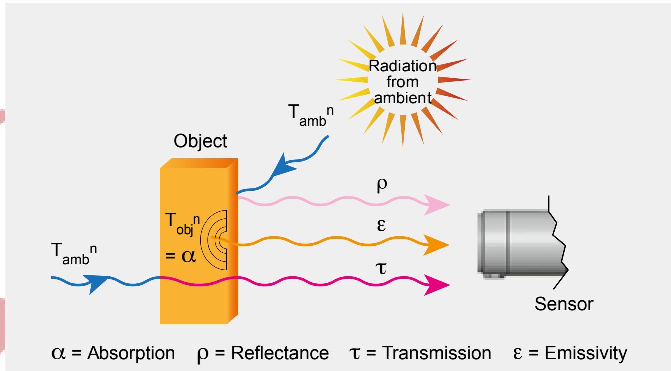
The chart below shows that the transmissivity of air strongly depends on the wavelength. Areas of high damping alternate with areas of high transmissivity – the so-called atmospheric windows. The transmissivity in the long-wave atmospheric window (8 – 14 µm) is constantly high, whereas, due to the atmosphere, there are measurable reductions in the shortwave area, which may lead to false results. Typical measuring windows are 1.1 … 1.7 µm, 2 … 2.5 µm and 3 … 5 µm.

Additional influencing variables are potential from heat sources in the environment of the measuring object. To prevent wrong measuring results due to increased ambient temperatures, the infrared thermometer compensates the influence of ambient temperatures beforehand (e.g. when measuring temperatures of metals in industrial ovens, where the oven walls are hotter than the measuring object). A second temperature measuring head helps to generate accurate measuring results by automatically compensating the ambient temperatures and correctly adjusting emissivity.



Spectral transmissivity of air (1 m, 32 °C, 75 % r. F.)

Dust, smoke and suspended matter in the atmosphere can pollute the lens and result in false measuring results. The use of air purge units (screw-on pipe socket connections with compressed air) prevents partivles in the air from collecting on the lens. Accessories for air and water cooling support the use of infrared thermometers even under harsh environmental conditions.



Compensating ambient influences

Experimental determination of emissivity

In the appendix you will find emissivity data for various materials from technical literature and measurement results. There are different ways to determine emissivity.

Method 1: With the help of a thermocouple:
With the help of a contact probe (thermocouple), the real temperature of an object surface is measured simultaneously to the radiation. The emissivity is subsequently adjusted so that the temperature measurement of the infrared thermometer corresponds to the value shown by the contact measurement. The contact probe should have good temperature contact and only low heat dissipation.

Method 2: Creating a black body with a test object from the measuring material:
A drilled hole (ratio diameter to drilling depth ≤ ⅓) in thermal conducting material reacts similarly to a black body with an emissivity near 1. It is necessary to aim at the bottom of the drilled hole due to the optical properties of the infrared device and the measuring distance. Emissivity can be subsequently determined.

Method 3: Applying reference emissivity:
A band or color with a known emissivity is applied to the measurement object. This emissivity is set on the infrared measurement device and the temperature of band or paint can be measured. Subsequently, the temperature next to this reference point will be measured, whereby the emissivity must simultaneously be adjusted until the same temperature measurement of the band or paint is displayed. Emissivity is subsequently displayed on the device.