LUMASENSE™ TECHNOLOGIES

Infrared Thermometer Handbook

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Foreword

Pyrometry, being a highly specialised field of thermometry, has developed a certain mysterious aura about it. This mystery stems from the false perception that the technology is difficult to master, whereas in truth pyrometers are easy to use in industrial applications so long as some basic principles are known and observed.

Unfortunately, in the past these principles were not always fully taken into account, especially when low-cost pyrometers and infrared sensors were offered for sale by mail order. As a consequence, pyrometers were often used incorrectly, so that the reputation of this really very reliable measuring method suffered tremendously.

This handbook was created with the intention of reassuring users and giving them an idea of what can be measured using pyrometry.

The knowledge and experience of many specialists in the field of non-contact temperature measurement have been incorporated in this document. We would like to thank all those who have contributed their expertise to this handbook. We have striven to heed their suggestions and critiques as best we could, and we hope that we have succeeded in presenting pyrometry as what it really is:

simple!!

Legend

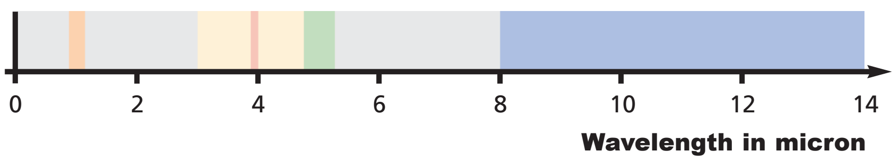
0.8 ... 1.1 µm measurement of metal surfaces

3 ... 5 µm measurements in special applications

3.9 µm measurement of flue gases and flames

4.8 ... 5.2 µm measurement of glass surfaces

8 ... 14 µm measurement of non-metal surfaces



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1 What is Pyrometry?

Pyrometry, or the non-contact measurement of temperature, is the state of the art today. Due to its accuracy, speed, economy and specific advantages, pyrometry is steadily gaining acceptance in new fields. But how is it actually possible to measure temperatures without physical contact?

accurate
fast
economic

Every object whose temperature is above absolute zero (-273.15 °C) emits a radiation. This emission is called heat radiation and depends mainly on temperature. The term infrared radiation is also used because the wavelengths of the majority of this radiation lie above the region of visible red light in the electro-magnetic spectrum, i.e. in the infrared range.

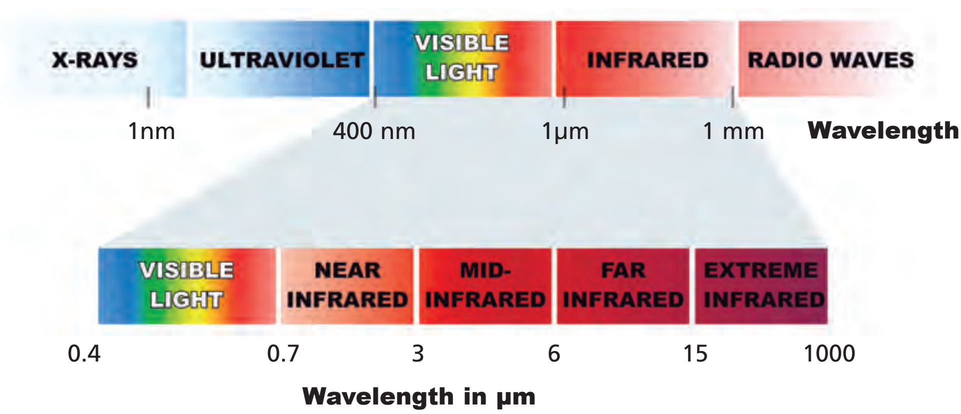


Fig. 1: Electro-magnetic spectrum

Temperature is the determining factor of radiation and energy. Infrared radiation transports energy. This radiated energy is used to help determine the temperature of the body being measured.

Similar to the principle of wireless radio transmissions where energy emitted by a transmitter is captured by a receiver via an antenna and then transformed into sound waves, the heat radiating from an object is received by a sensor and transformed into electrical signals.

This means that non-contact measurements make use of the energy emitted by an object. The instruments which determine the temperature of an object in this fashion are called radiation thermometers, radiation pyrometers, or simply pyrometers[1)].

Fig. 2: Modern pyrometer

Originally, pyrometry was a strictly visual measuring method. Experienced blacksmiths and steel workers could with surprising accuracy gauge the temperature of metal by its brightness and colour. The first pyrometers (disappearing filament pyrometer, 1917) too measured only the visible radiation of an object. Since radiation is visible only when the object is red hot, early pyrometry was suited only to measure high temperatures. But technical advances have made it possible today to measure temperatures far below freezing without making contact with the object to be measured.

Today it would be hard to imagine industrial production processes and process control without pyrometry. Be it in the manufacture of glass, the processing of metals, or the production of foodstuffs, temperature is always one of the most important process parameters.

1) pyr [GR.]: "fire", metron [GR.]: "measure"

The rapidly growing success of pyrometry is driven primarily by the many advantages it offers over contact-making measuring methods. The advantages of pyrometers are:

advantages

- **fast response time**
- **interference-free measurements**
- **capability to measure moving objects**
- **capability to measure objects which are difficult or impossible to reach with contact-making sensors**

Fast Response Time

short adaptation period

- Pyrometers have a very short adaptation period. With contact-making methods a probe indicates the temperature sensed at its tip which is in contact with the object. The probe must first reach the same temperature as the measured object, and this takes some time due to thermal conduction. The pyrometer, in contrast, measures the radiation and shows the correct temperature within fractions of a second.

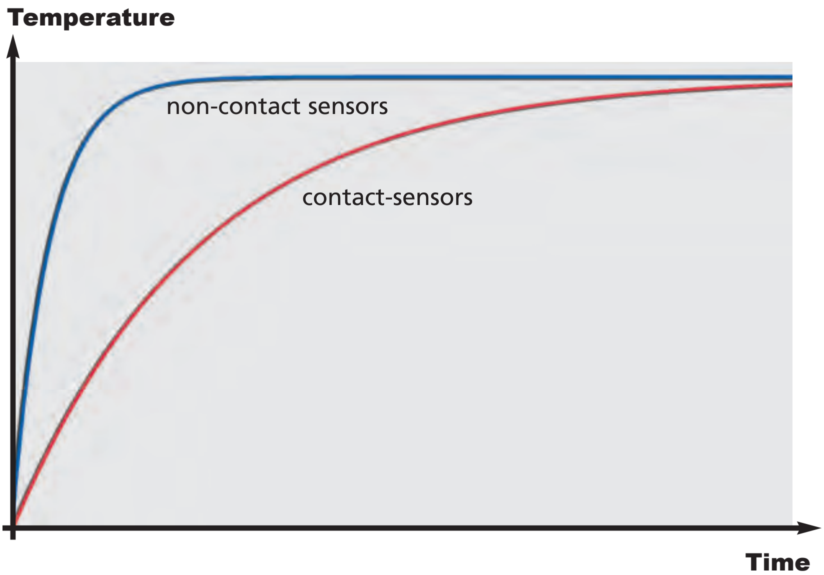


Fig. 3: Response time

Interference-Free Measurements

- To measure temperature, a radiation pyrometer uses a portion of the energy that is being emitted by the object anyway.

no effect on temperature

This means that the act of measuring itself does not influence the temperature of the object.
A contact thermometer must first reach the temperature of the object at the point of contact to obtain a correct reading. This process draws heat from the object which may change the temperature at the measuring point.

no sensor wear

- With non-contact measuring methods, sensors cannot be damaged or destroyed in the same way that can happen when using thermocouples. This is why the service life of a non-contact measuring device is considerably longer than that of thermocouples which are subject to wear and tear.

Measuring Moving Objects

- The fast response times of pyrometers allow temperatures of moving objects to be determined accurately.
- Contact thermometers may influence temperature readings because of friction heat caused by the temperature probe scraping along on the surface.

no marks

- Contact-making measuring methods may leave scrape marks on the measured object.

no damage to measured objects

- No holes or locating points are needed on the measured object.

Measuring Objects Which are Difficult or Impossible to Reach with Contact-Making Sensors

small objects

- The optical units of pyrometers can be optimized for the object to be measured, making it easy to determine the temperatures even of small objects. Today it is possible to accurately measure objects as small as only 0.1 mm in diameter. Note that the error caused by the heat conductance of a contact-making probe is amplified when measuring small objects!
  Example: thin wires

- High temperatures can be sensed as there is no direct contact with the heat source. NiCr-Ni thermocouples, for example, undergo physical changes at 1300 °C and are then no longer able to provide repeatable readings.
  Example: forging of steel components

high temperatures

- Aggressive materials can be measured without contact and thus without damage to the sensor.
  Example: acids in chemical processes

aggressive materials

- Hard-to-reach objects can be measured because pyrometers are very compact, can be installed nearly anywhere, and only need an unobstructed line of sight to the object.
  Example: measuring the temperature of metal during heating in an induction coil

inaccessible objects

- Live objects can be measured without hazard to the user due to short-circuits or electrical shock.
  Example: checking the temperatures of terminals in switchgear cabinets

live measuring objects

- When objects having poor heat conductance, low heat capacity or little mass are measured, the flow of heat to the contact-making sensor is very slow and often insufficient. This leads to major measurement errors which will not occur with non-contact measuring methods.
  Example: thin film plastics

poor heat conductance, low heat capacity, little mass

- Long distances can be covered with the help of appropriate optical units.
  Example: monitoring pilot flames of stack flares

long distances

- It is possible to measure through windows so long as the windowpane material is compatible[2].
  Example: measuring temperatures in furnaces and vacuum chambers

viewing windows

2) see pages 51, 633

2 Physical Principles

Already in the 19th century, renowned scientists investigated the physics of radiation theory.

Newton

Herschel

But the origins of measuring infrared radiation date even further back. In the 17th century, Isaac Newton (1643-1727) succeeded in decomposing daylight into its spectral colours by using a prism. Around 1800, Friedrich Wilhelm Herschel (1738-1822) measured temperatures in the spectrum of sunlight. He found that the highest temperature occurred with red light. When he measured the invisible region beyond red light, he discovered that the temperature was even higher there. He called this region the infrared band.

Planck
Wien
Stefan
Boltzmann

The important laws relating to pyrometry were formulated by Max Planck (1858-1947), Wilhelm Wien (1864-1928), Josef Stefan (1835-1893) and Ludwig Boltzmann (1844-1906).

black body

Because of their importance, these laws were named after the scientists who formulated them. They are briefly explained below. The formulas all apply to ideal bodies, the so-called black bodies.

Black bodies are bodies that absorb all radiation incident on them in all wavelength regions.

Spectral Intensity

Visible light with all its colours, infrared radiation, x-rays and γ-rays are different forms of radiation, but all similar in nature.

Their differences lie in wavelength, or frequency. The wavelength defines the "colour" of the light (see fig. 4). Now let's consider the energy or the intensity of the radiation emitted by a body.

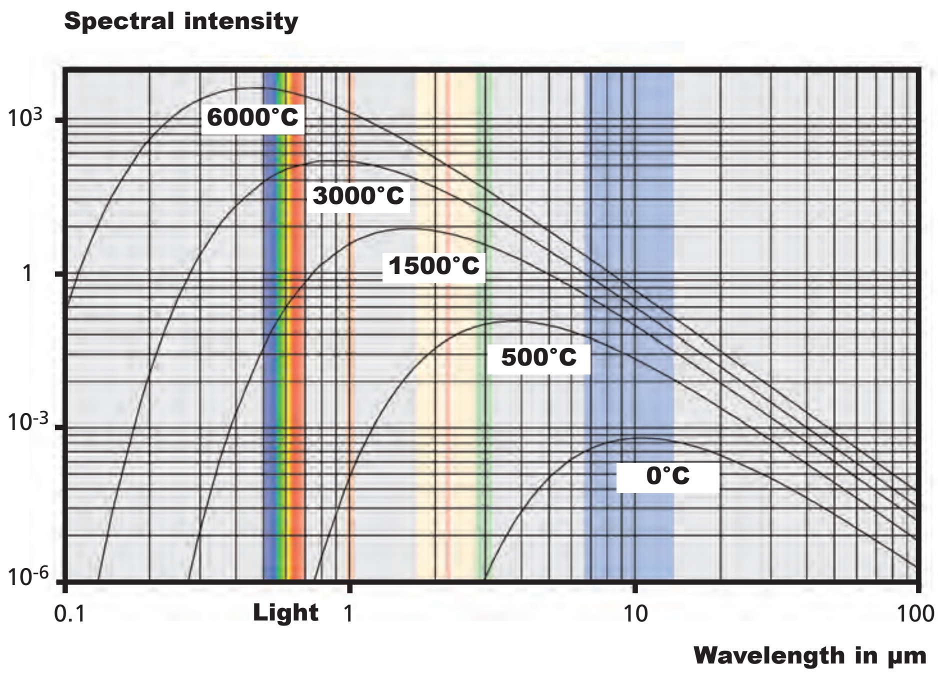


Fig. 4: Distribution of intensity

Fig. 4 shows the relative intensity distribution of heat radiation (spectral intensity) across the wavelengths. The exponential correlation of intensity and wavelength requires double logarithmic scaling for graphic representation.

As can be seen in fig. 4 the intensity curve shifts to the left towards shorter wavelengths as temperature rises. At temperatures above 550 °C the curve reaches the region of visible light.

The measured object starts to glow. As the temperatures increases, the portion of intensity rises in the visible region.

Steel glows red hot at first, then, as the temperature rises, one speaks of white hot, meaning that all visible spectral colours are present.

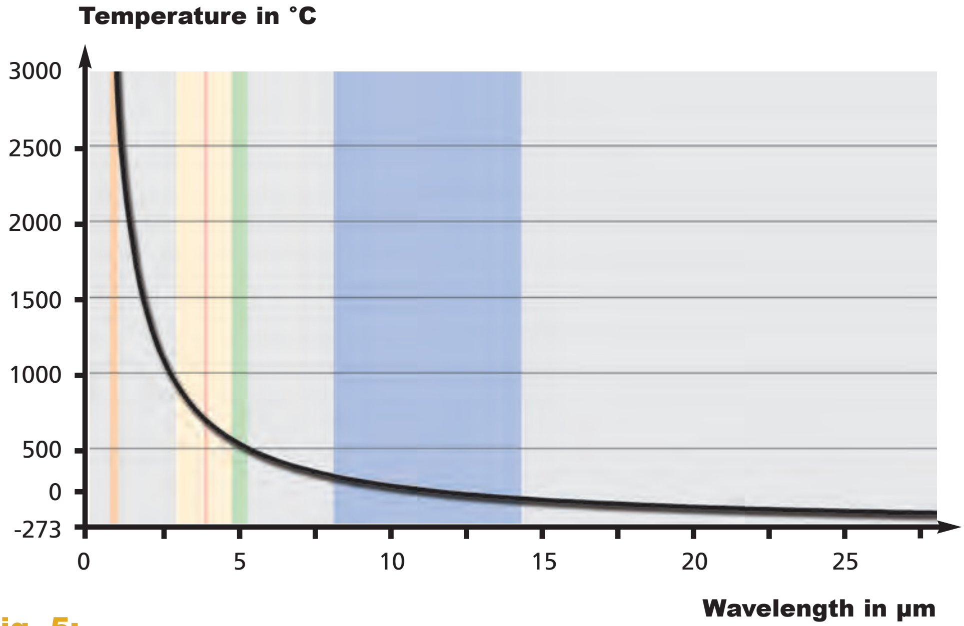


Fig. 5: Wien's distribution law

Wavelength at Maximum Intensity

The curves shown in fig. 4 for various temperatures indicate that the maximum spectral intensity shifts towards shorter wavelengths as the temperature rises.

This relation is shown in fig. 5 and is called Wien's distribution law.

The wavelength of the maximum intensity of the sun's spectrum lies at 550 nm[3], i.e. in the region of green light. The surface temperature of the sun is about 6000 °C.

3) **1 µm = 1000 nm**

Total Intensity

In pyrometry, the intensity of radiation is converted into an electrical signal. The intensity of radiation across the entire wavelength range is formed by the integral of spectral intensity between 0 µm and infinity, at a fixed temperature.

Stefan-Boltzmann law

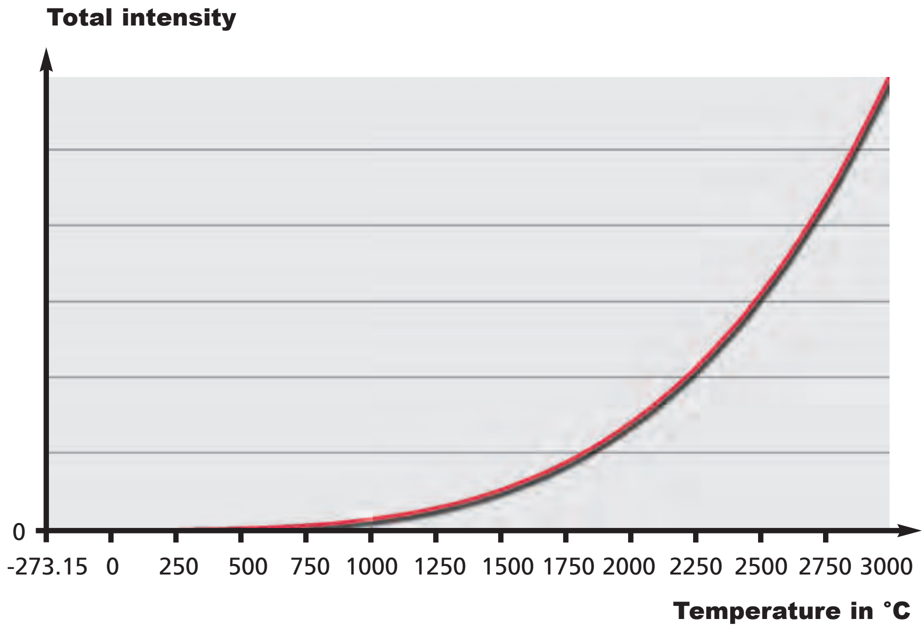


Fig. 6:
Total Intensity

The total intensity represents the region underneath one of the curves shown in fig. 4. Total intensity rises to the fourth power of the absolute temperature. That means that a doubling of the temperature will cause a 16-fold increase in intensity. It follows that the intensity is small at low temperatures.

Restricting the spectral range, as is the case with real-world pyrometers, results in complex relations between the temperature and the intensity occurring at the detector.

3 Properties of Real Objects

All relations discussed so far apply only to black bodies. But real objects often have very different properties. To clarify this we will look at conditions in the region of visible light, which can also be applied to the infrared region.

reflection

Real objects feature material properties which are characterized by terms such as reflection, absorption, and transmission.

A large portion of incident radiation is reflected off bright, smooth surfaces. On the one hand we find specular or directed reflection, such as off a mirror or a high-gloss paint coat. On the other hand, we have diffuse or scattered reflection such as off objects with rough surfaces. Paper, for instance, reflects light in all directions.

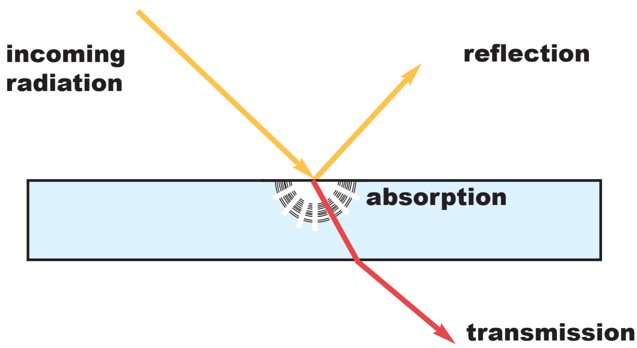


Fig. 7: reflection, absorption, transmission

Absorption

Another portion of the incident radiation is absorbed by dark, rough surfaces. This may happen selectively or across a wide band of the spectrum. In cinemas, as much light as possible must be absorbed by the side walls of the room (which are often fitted with dark velvet curtains) so that the view of the audience is not impaired by reflections. These dark wall hangings absorb nearly all incoming light. Selective absorption occurs with paints and varnishes. A red car "appears" red only because all other colour components are absorbed.

The remaining portion of incoming radiation penetrates the object and is transmitted through it. We speak of transparent materials. This phenomenon too may be selective. While normal window glass lets all of the spectrum of visible light pass through, tinted sunglasses shield the eyes by letting only a certain part of the spectrum through.

transmission

Every object has the properties mentioned above, but they are more or less pronounced according to its material. They are described mathematically as reflectivity ρ, absorptivity α, and transmissivity τ. They refer to the ratio of reflected, absorbed, or transmitted intensity to the intensity of the incoming light. The numerical values for ρ, α and τ lie between 0 and 1[4]. Their sum is always 1.

ρ: **reflectivity**
α: **absorptivity**
τ: **transmissivity**

These values allow us to specify the behavior of a blackbody:
A blackbody is theoretically defined as a body which absorbs all incoming rays. This means that its absorption coefficient $\alpha = 1$. It follows then that $\rho = 0$ and $\tau = 0$.

black body

In thermal equilibrium, a body which absorbs well, emits well (Robert Kirchhoff, 1824-1877). This means that its absorption coefficient α equals its emission coefficient ε. The maximum radiation at a given temperature is generated by a black body. Therefore, this body is also called a blackbody radiation source. In practice, soot or matte black paint come closest to this.

$\alpha = \varepsilon$

black-body radiation source

The emission coefficient or emissivity ε is the relation of the thermal radiation emitted by any object to the thermal radiation emitted by a blackbody radiation source at the same temperature. ε is dependent on the object's material and changes with wavelength, temperature or other physical variables.

ε: **emissivity**

In real life, objects will match the properties of a blackbody radiation source only partially or not at all.

4) one can also say, "between 0% and 100%"

grey body

A body whose emissivity remains constant within a certain spectral range is called a grey body. In visible light it reflects all colours of light evenly and therefore appears grey to the eye of the beholder.

real radiator

Objects which do not match the properties of a black-body or grey-body radiation source are called real or coloured radiation bodies.

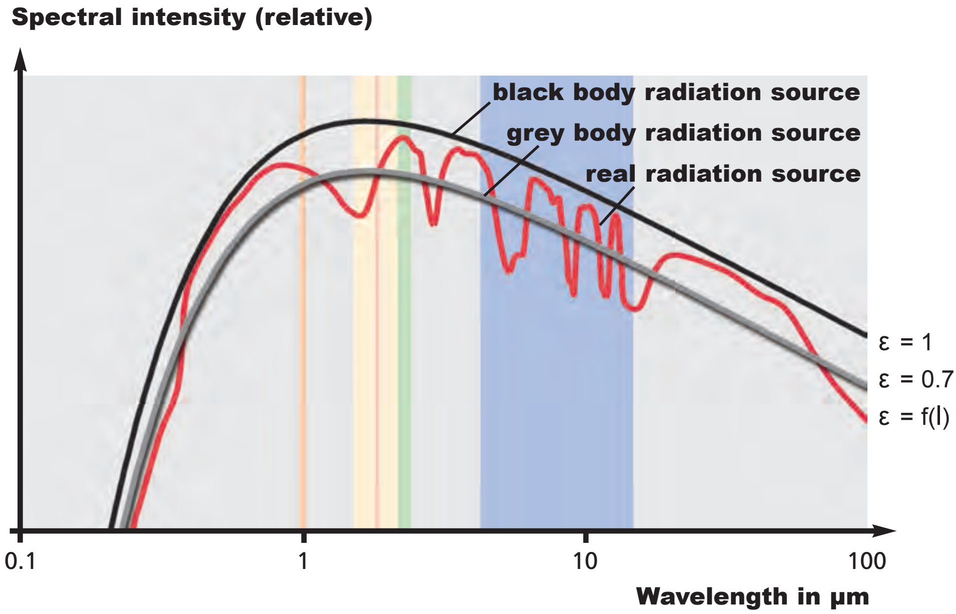


Fig. 8: Black-body, grey-body, real radiation source

4 Emissivities of Various Materials

As already described, the emissivity ε of an object is the most important factor for determining its temperature by means of a pyrometer. If you want to measure the true surface temperature of an object by means of a pyrometer, you must know the emission coefficient, or emissivity, of the object and enter its value in the pyrometric measuring system. To adjust them to the material being measured, pyrometers therefore have an emissivity control. The values for various materials may be looked up in tables[5]. In principle, the emissivity of a material is influenced by wavelength, temperature, etc.

emissivity control

From a purely qualitative viewpoint, most materials can be attributed to one of the following groups because their emissivity is dependent on wavelength:

1. **metals**
2. **non-metals**
3. **transparent materials**

metals

The emissivity of bright metal surfaces is high at short wavelengths and decreases with lengthening wavelengths. In the presence of oxidized and soiled metal surfaces, results are not necessarily consistent; emissivity may be strongly influenced by temperature and/or wavelength.

The emissivity of metals also changes with time due to wear and tear, oxidation or soiling. Metal components are often bright after machining, and their surfaces change when heated. So-called tarnishing colours appear and may be followed by rust and scale. This needs to be taken into consideration to avoid measurement errors. However, so long as surfaces are not shiny, metals can be measured well in most cases.

5) see table 1, page 62: Emissivities of various materials

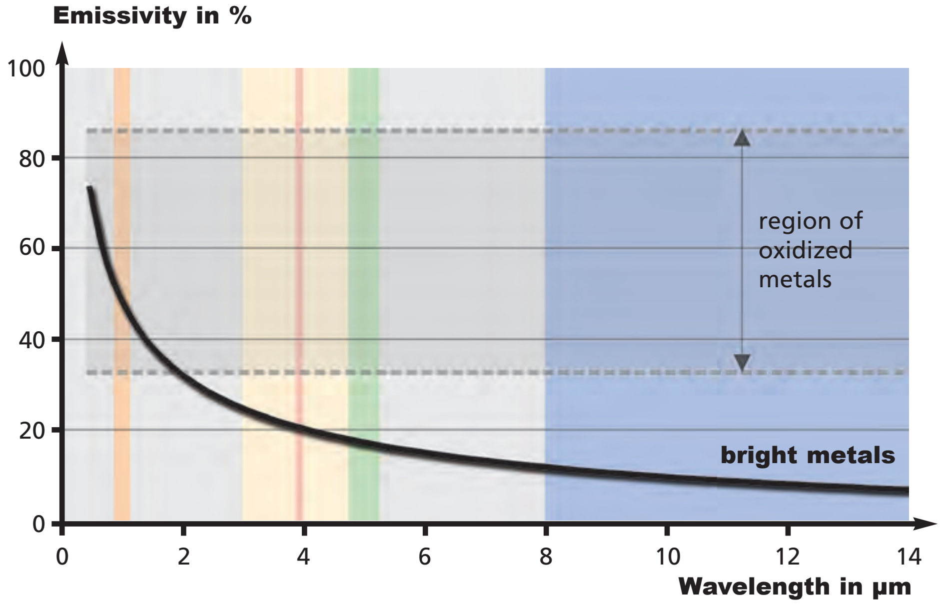


Fig. 9: Emissivity of metals

Shiny metal surfaces reflect light strongly, i.e. their reflection coefficient is high and their emission coefficient low.

A hot object has a high reflection coefficient, and if it is close to where a temperature reading needs to be taken (for example, a furnace ceiling), it may affect the value of that reading. Therefore, shiny metal surfaces are the most difficult objects to measure in pyrometry.

high-emissivity coatings

High-emissivity coatings such as black paint or adhesive plastic film increase the emissivity of metals at low temperatures. Such paints or plastic films have a high and known emissivity and assume the temperature of the metal surface.

non-metals

The group of non-metals includes organic materials, such as foodstuffs, wood or paper, as well as inorganic materials such as ceramics or fire clay. The emissivity of non-metals rises with increasing wavelength. Generally speaking, from a certain wavelength, the emissivity is nearly constant. With dark materials this threshold is found in the visible spectrum, but with light-coloured materials it is above 4 µm.

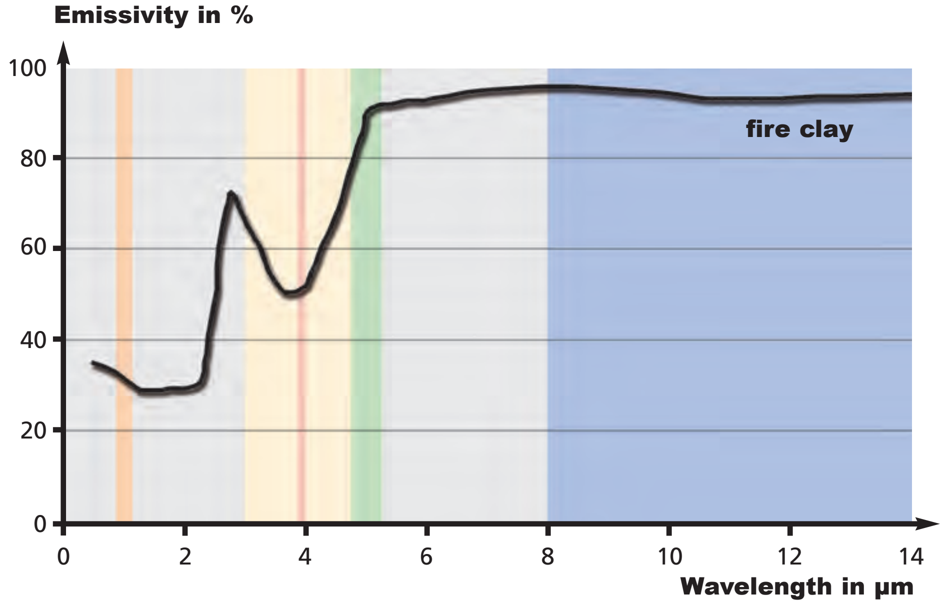


Fig. 10: Emissivity of non-metals

transparent materials

Transparent materials such as glass, quartz, water and plastic films, but also hot gases and flames, each have their own unique, emissivity. The emissivity of glass, for example, is characterized by wavelength ranges where electromagnetic radiation largely passes through the glass material (transmission), and others in which it is absorbed almost completely (absorption). In these absorption bands these materials are opaque to radiation (absorption α = emission ε), which is why these bands are particularly suited for temperature measurements.

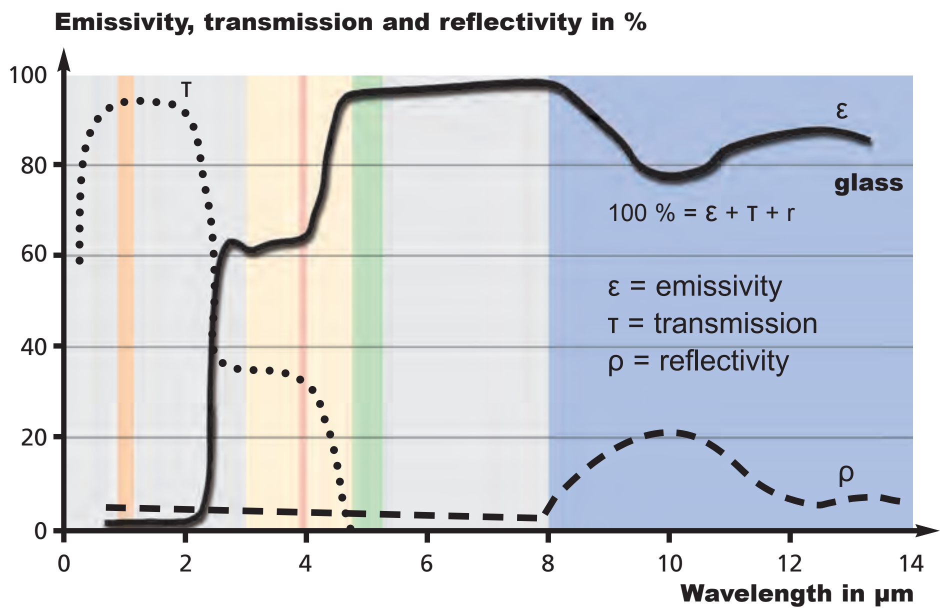


Fig. 11: Emissivity, transmission and reflectivity (qualitative) of glass

emissivity of glass

Glass is transparent in the visible light and near infrared ranges (to about 3 µm), which means that its transmission coefficient τ is high, and consequently its emissivity ε low. As you can see in fig. 11, the emissivity of glass is very high in the range from 4.5 to 8.5 µm, because glass has a wide absorption band in this spectral range. Above 8 µm the reflection ρ of glass increases sharply, making accurate measurements difficult.
As a rule, the wavelength range used for temperature measurements on glass surfaces lies around 5.14 µm (for glass thicknesses of 1 mm and more at medium to high temperatures), or 7.75 µm (for glass thicknesses below 1 mm and low to medium temperatures). This is because in these spectral ranges there is no interference from the absorption bands of water vapour or carbon dioxide contained in the atmosphere.

typical penetration depths for glass materials

Depending on the wavelength chosen for the measurements, there will be different values for emissivity, transmissivity and reflectivity. The question now is to determine the most efficient penetration depth into the glass. The following table is a summary overview. Note that these values apply to glass types which are in general use, and they presume that the main component is silicon dioxide (SiO_2).

	Typical penetration depth at various emissivity settings			
Wavelength/µm	Typ. penetration depth/mm		Typ. penetration depth/mm	
0.78 ... 1.15	20	0.91	40	0.96
1.45 ... 1.75	40	0.91	80	0.96
3.9	3	0.92	6	0.97
4.8 ... 5.4	1	0.92	2	0.97
7.75	0.1	0.94	0.2	0.99
8 ... 14	0.02	0.70 ... 0.85	0.04	0.75 ... 0.90

Table: Examples of penetration depths in glass calculated for typical wavelengths

It is important not to forget some generally applicable rules of pyrometry related to the temperature measurements on glass, such as:

- When measuring high temperatures, shortwave pyrometers should be preferred because of their much steeper characteristic curve.
- For applications in direct gas-fired furnaces you should prefer devices measuring at a wavelength of 3.9 µm (so-called “flame filter”) to allow for flames and fumes.

5 Determining the Emissivity of an Object

As we have already discussed, emissivity has a major influence on the measuring result. This is why it is crucial to establish its value accurately for a given material.

There are several ways to determine emissivity:

tables

- Tables may be consulted to look up the values of the emission coefficient for many different materials (see table 1, page 62). For metals, however, these values are mostly qualitative only.

comparison with contact thermometers

- The temperature of the object is first determined by measuring it with a contact thermometer. Then the pyrometer is aimed at the object. Finally, the emissivity control setting is adjusted until both devices indicate the same temperature. The object must be sufficiently large and accessible for this method to be practical.

partial blackening of the surface

- Part of the object's surface is blackened using a special paint or soot whose emission coefficient is close to 1, precisely known and stable up to the temperature to be measured. The pyrometer is used to measure the temperature of the blackened surface, and then the untouched part of the surface. Next the emissivity control setting is adjusted so that the temperature reading matches the value from the previous measurement.

drilling the object to be measured

- The object is drilled to a depth of at least six times the hole diameter. The diameter must be greater than the measurement spot diameter of the pyrometer. The hole can be considered as a black-body radiation source, with an emission coefficient of nearly 1.
  First, the temperature in the hole is measured. Next, the pyrometer is aimed at the surface. After that the temperature value of the hole is set by adjusting the emissivity control setting.

measuring emissivities of transparent substances, gases and flames

VDI/VDE guideline 3511 (page 4, section 7.2) describes methods how the emissivities of transparent substances, e.g. thin film plastics or hot gases and flames can be determined with relatively simple means with the help of the pyrometer to be used.

6 Choosing the Spectral Response

The selection of the correct spectral response is crucial to the measuring accuracy of the pyrometer.

6.1 Emissivity Errors

The following rule is absolutely critical and must be observed in practice to avoid emissivity errors.

The most important task is to choose a pyrometer that measures in the shortest-possible wavelength range.

rule: use the shortest possible wavelength

This rule may imply a disadvantage because the energy emitted by the measured object is not put to optimum use, but it greatly diminishes the influence of emissivity because of the steeper characteristic temperature/radiation curve for the pyrometer.

It is best to disregard this rule when strong daylight or artificial light influences the measurement, when the emissivity in the short wavelength range is poor (white paint, for example), or when a certain region of the spectrum is needed for the measurement (on glass, for example).

Fig. 12 shows the measurement errors of five pyrometers having different spectral responses and where the emissivity setting was off by 10 %. If, for example, you measure the temperature of an object heated to 750 °C with a long wavelength pyrometer having a spectral response from 8 to 14 µm, a relative emissivity error of 10 % produces an overall error of 60 °C. But if you use a short wavelength pyrometer with a spectral response from 0.7 to 1.1 µm the measurement error is reduced to 7 °C in otherwise identical conditions.

Just by choosing the right spectral response, the measurement errors can be reduced almost nine-fold.

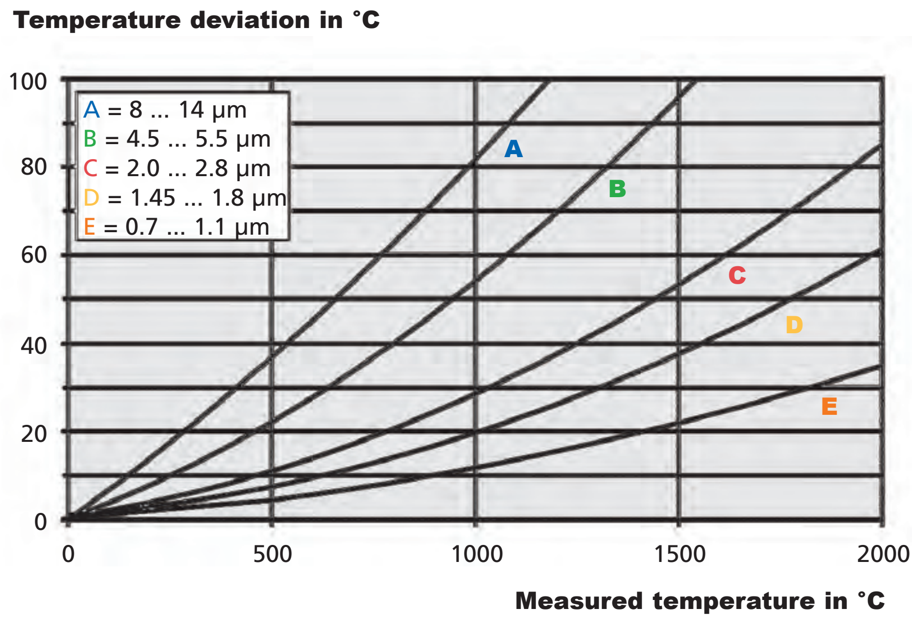


Fig. 12: Measurement errors with emissivity setting off by 10%

metals

It is very important to observe this rule metal objects are to be measured. With metals the emissivity rises at shorter wavelengths, which further contributes to reducing the error. Also, with metals, the relative fluctuation of emissivity diminishes as a function of material composition and surface condition.

For example:

The emissivity of bright steel in the spectral range from 0.85 to 1.15 µm show values between 0.4 and 0.45. The emissivity values in the spectral range from 8 to 14 µm however are between 0.1 and 0.3. A potentially incorrect setting of the emission coefficient is reduced to about 6 % in the short wavelength range, but it can reach up to 50 % in the long wavelength range.
A table with temperature deviations caused by 1% emissivity change is shown on page 65.

non-metals

Because of their emissivity characteristics, non-metals are easier to measure by means of pyrometers than metals.

Here the objective is to choose a pyrometer which the manufacturer qualifies as suitable for given materials (for instance, glass, plastics, ceramics, textiles, etc.).
The spectral responses of quality pyrometers are always chosen so that they are in the wavelength ranges where emissivity is high and as constant as possible. At these wavelengths, the material is opaque and absorption bands of water vapour and carbon dioxide are not found in these regions.

In cases where emissivity varies strongly, such as in metal-working processes, it is advisable to use pyrometers which can measure in more than one spectral range. Ratio pyrometers have proven to be especially useful[6)] in such applications.

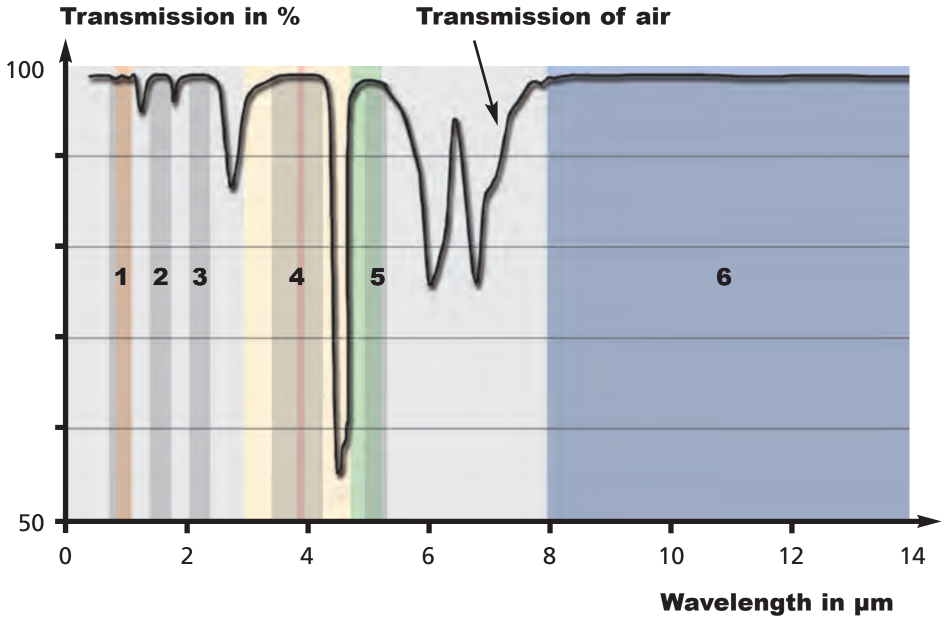
6.2 Atmospheric Window

The atmosphere is normally the medium through which radiation must pass to reach the pyrometer. This is why the spectral ranges of quality pyrometers are selected so that the atmosphere will not influence the temperature measurement. These ranges are called atmospheric windows. In these windows there are no absorption bands of water vapour and carbon dioxide in the air, so that measurement errors caused by atmospheric humidity or changes in measuring distance are definitely eliminated.

no absorption bands

Fig. 13 shows where the atmospheric windows are located within the spectrum in comparison to the transmission of air as a function of wavelength.

6) see chapter 8.2: Pyrometer types



Window	Detector type/material
1	Silicon (Si)
2	Germanium (Ge) Indium gallium arsenide (InGaAs)
3	Lead sulphide (PbS)
4	Lead selenide (PbSe) Thermopile Pyroelectric detector
5	Thermopile Pyroelectric detector
6	Thermopile Pyroelectric detector

Fig. 13: Atmospheric windows, transmission of air

- In the spectral range labelled **"1"** in fig. 13, temperatures above approx. 550 °C can be measured. Pyrometers with silicon detectors measure the radiation in this window. This spectral range is normally used to measure metals. Because of its good depth of penetration it is also suited to measure the temperature of molten glass. Selected, very narrow spectral ranges in this window permit to measure temperatures of silicon wafers and aluminium.

silicon

- In **window "2"**, temperatures above approx. 250 °C are measured. Germanium or indium gallium arsenide detectors (InGaAs) are used in conjunction with optical filters. This window is mostly used to measure metals.

germanium
InGaAs

- **Window "3"** allows you to measure temperatures from about 50 °C upwards. Lead sulphide (PbS) detectors are used in conjunction with optical filters. Metals with low temperatures are measured in this spectral region.

lead sulphide

- **Window "4"** allows you to measure temperatures of about 30 °C and higher. It is especially useful for measuring the temperatures of objects located behind flames, or of glass with a penetration depth of approx. 20 mm. Pyrometers using this window have lead selenide (PbSe) detectors, thermopiles, or pyroelectric detectors, in conjunction with optical filters.

lead selenide
thermopile
pyroelectric

- **Window "5"** allows you to measure temperatures from approx. 100 °C upwards. This works extremely well with glass surfaces with a penetration depth of only 0.7 mm. Pyrometers used for such applications have thermopiles or pyroelectric detectors in conjunction with an optical filter.

thermopile
pyroelectric

- **Window "6"** allows you to measure temperatures from approx. -50 °C upwards. It is used by pyrometers with thermopiles or pyroelectric detectors in conjunction with an optical filter. This spectral range is used to measure organic materials.

thermopile
pyroelectric

7 Measurement Spot and Distance to Target

The optical unit of a pyrometer transmits the image of a segment of the target area of the measured surface to the detector. This segment is called the measurement spot[7)]. Depending on the aperture used in the pyrometer, the measurement spot may be round or rectangular.

According to the laws of optics, the image is magnified as the distance from the lens increases. This is common knowledge in photography. It is possible to implement small spot sizes with pyrometers which are designed for short measuring distances. The larger the distance between pyrometer and object, the larger the measurement spot size diameter.

Pyrometers come with different types of optics:

1. **fixed optics**
2. **variable-focus optics**

fixed optics

With fixed optics the minimum measurement spot diameter applies to a fixed measuring distance, which is called the nominal measuring distance. The result is a sharp image of the measured object on the detector. Different optical units with different measuring distances and spot sizes enable you to adapt the instrument to the task in hand.

variable-focus optics

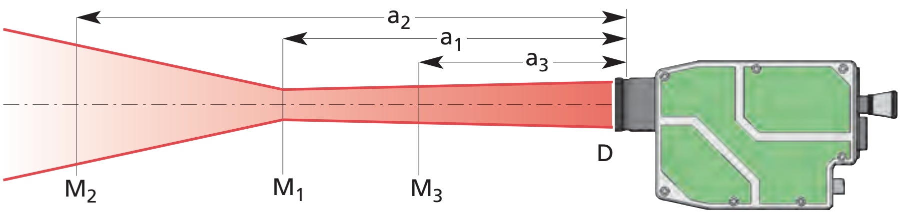
These optics allow the pyrometer to be focused on the target from various distances. This kind of optics is preferred for portable pyrometers. The diameter of the measurement spot can be calculated by using the distance-to-spot size ratio, for example, 100:1. The resulting value expresses the relation between distance to target and measurement spot diameter for the nominal measuring distance. But there are also tables and field-of-view diagrams which you can consult to determine the measurement spot diameter.

7) or field of view

Fig. 14 shows the basic relation between measurement spot diameter and measuring distance. The values apply equally to fixed optics and optics with variable focus. The focal point (M1) in the diagram represents the distance from the pyrometer at which the lens focuses the measured object sharply, and consequently produces the smallest spot diameter.

If this distance changes, the spot size diameter becomes larger, irrespective of the direction of the change. So long as the object to be measured can fill the spot size, even a blurred image on the detector will not cause a measurement error due to the changed measuring distance.

M_1 = spot size at nominal measuring distance a_1
M_2 = spot size at measuring distance $a_2 > a_1$
M_3 = spot size at measuring distance $a_3 < a_1$
D = aperture (clear diameter of optics)



$$M_2 = \frac{a_2}{a_1}(M_1 + D) - D \qquad M_3 = \frac{a_3}{a_1}(M_1 - D) + D$$

Fig. 14: Field-of-view diagram

In their technical documentation, manufacturers either supply the field-of-view diagrams as they relate to various optical units, or only specify the measuring distances with the associated spot size diameters. With the help of a formula for the close range respectively the long range, you can calculate the measurement spot diameters for changing distances (see fig. 14).

filling the measurement spot

In order to obtain accurate readings, the measured object must at least fill the measurement spot (see fig. 15).

To avoid errors that could arise from minor misalignments occurring during operation, the object to be measured should be slightly larger than the measurement spot. If the object does not completely fill the field of view, measurement errors will occur.

measuring through openings

If you need to measure through openings, e.g. through protection tubes, it is crucial that you take account of the radiation cone required by the pyrometer when selecting the opening diameter. If the opening is close to the pyrometer, it must be at least as large as the aperture of the pyrometer, even though the measurement spot measuring distance may be considerably smaller.

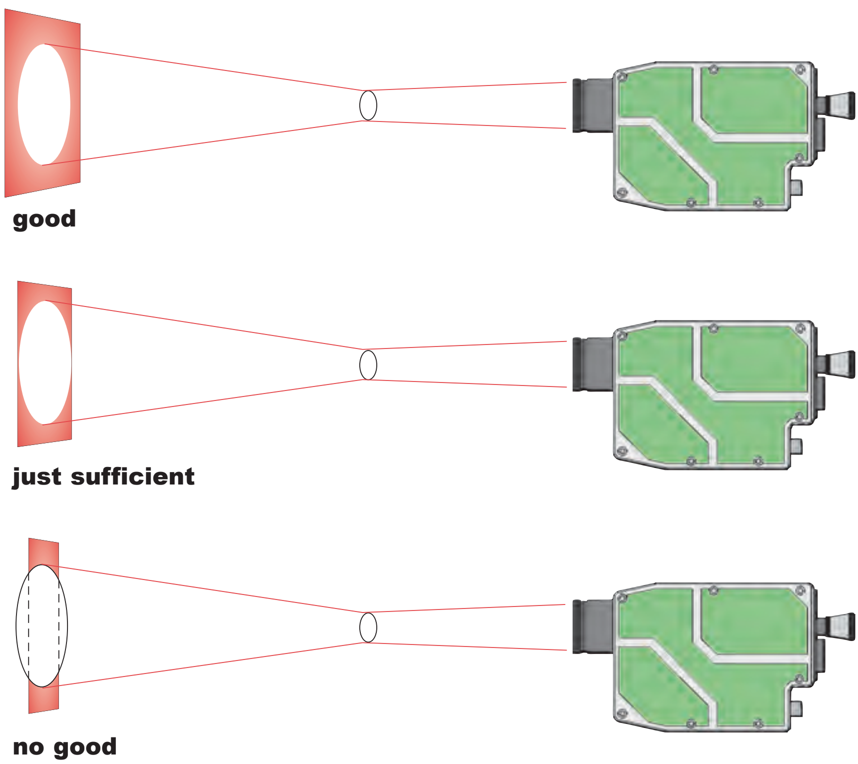


Fig. 15: Filling the measurement spot

8 The Pyrometer

This chapter describes the basic design and function of a pyrometer. The most widely-used types are also presented. The differences between the designs are hardly noticeable from the outside, but become evident when you examine the internal components.

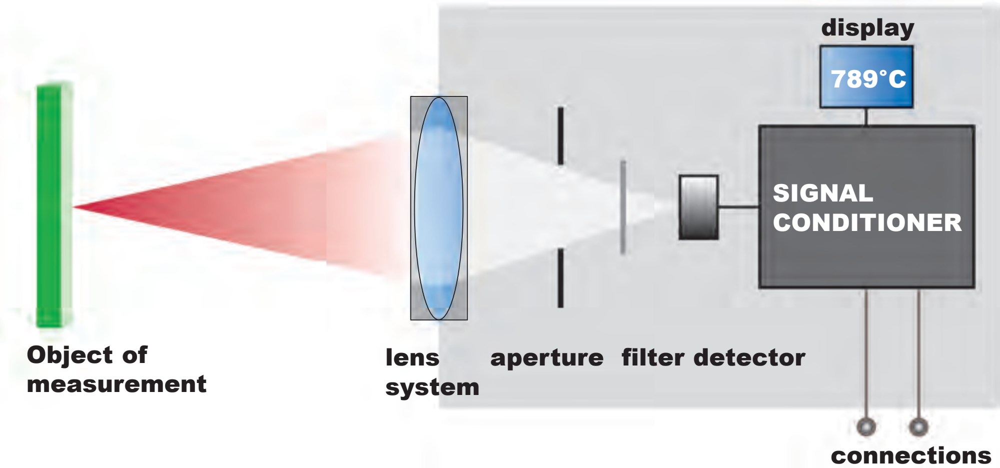


Fig. 16: Components of a pyrometer

8.1 Design and Function

The basic components of a pyrometer are the lens system, aperture, filter, detector, and signal processing unit (see fig. 16). The infrared radiation emitted by the object of the measurement is collected by the lens. The aperture blocks unwanted peripheral rays. The filter lets only the selected spectral range pass through. The portion passing the filter falls on the detector which transforms the infrared radiation into an electrical signal. This signal is then linearized in the mostly digital signal processing unit and output as a temperature value via a digital interface or in the form of an analog signal at the pyrometer connections. This value can be displayed and used for control purposes.

8.2 Pyrometer Types

The differences between radiation pyrometers, ratio pyrometers, and multicolour pyrometers are described below.

radiation pyrometers

This category comprises spectral pyrometers, narrow-band and broadband pyrometers. Spectral and narrow-band pyrometers were at some time also referred to as partial radiation pyrometers, in contrast to broadband or total radiation pyrometers.

spectral pyrometers

These pyrometers measure the radiation off an object in a very tight wavelength range, practically at just one wavelength. A given wavelength or spectral region is selected by means of an interference filter and appropriate detectors. Spectral pyrometers are frequently used to measure the temperature of glass at 5.14 µm. Metals are also measured with spectral pyrometers as their emissivity is high only in a narrow spectral range[8)].

narrow-band pyrometers

Their design is similar to that of spectral pyrometers, but other filters and detectors are used so as to measure a wider wavelength band (for example, from 8 to 14 µm). These pyrometers are used to measure organic materials, which generally have a high and constant emissivity at longer wavelengths.

broadband (total) radiation pyrometers

These pyrometers are designed to detect more than 90% of the radiation emitted by an object. This requires special detectors, lenses and filters which are sensitive or transparent to almost the whole spectrum.

Today, broadband (total) radiation pyrometers are rarely used due to the large measuring errors they imply (atmospheric windows, emissivity).

8) see chapter 4, Emissivities of various materials

ratio pyrometers

Ratio pyrometers, also referred to as 2-colour pyrometers, measure the radiant flux at two different wavelengths, then the temperature is calculated from these signals using ratioing techniques. In the course of the ratioing process, emissivity is eliminated; in other words the temperature measurement becomes independent of the emissivity of the object.

The wavelengths are situated close together (for example 0.95 µm and 1.05 µm) in order to equalise emissivity as much as possible. The output signal will not change when the object does not fully cover the measurement spot, or when sources of interference such as smoke or suspended matter are present, providing they occur equally in both wavelengths. If emissivities are not the same at the two wavelengths, this can be corrected by setting a ratio compensation factor.

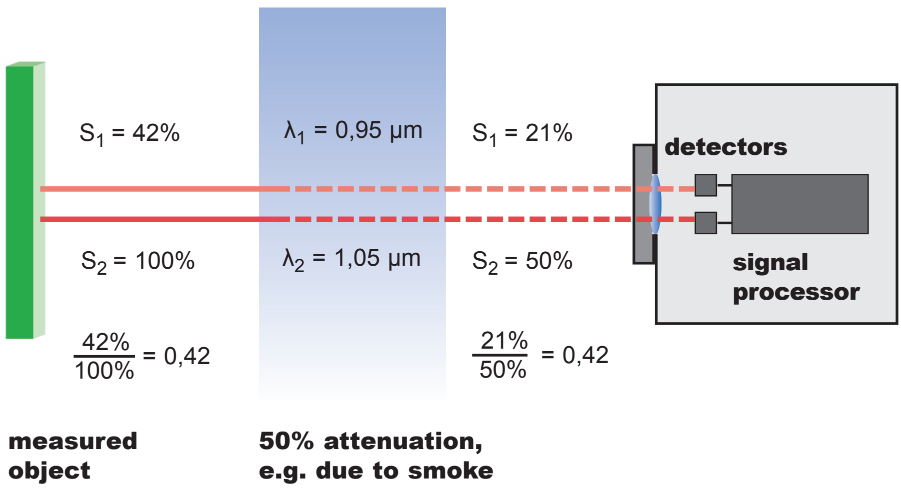


Fig. 17: Principle of a ratio pyrometer

The advantages offered by ratio or 2-colour pyrometers make them the instrument of choice for difficult measuring tasks:

- in high-temperatures applications
- in the presence of obstructed sight paths or interference in the atmosphere (for example, smoke, suspended matter)
- when the measured object is smaller than the measurement spot (down to 10% of the spot size)
- in the presence of varying, low or unknown emissivity (for example, molten metal).

Various design principles exist in order to realize the measurement of the two signals:

1. **sandwich detector**
2. **two separate detectors with different filters**
3. **one single detector with a rotating filter wheel**

The disadvantage of pyrometers with rotating filter wheel is that the signals in the two channels are picked up one after the other instead of simultaneously. But the ratioing process implemented in the pyrometer increases its sensitivity to signal changes in one of the two channels. If temperatures change quickly or if moving objects are measured, the readings output by a ratio pyrometer with rotating filter wheel may deviate from the real temperature.

luminous flames flame pyrometer

To measure temperatures of luminous flames (which is the most common type of flame), specially designed flame pyrometers have been found to work best. With this type of flame, the radiation incident on the pyrometer stems from glowing particles of soot and fuel. In this case, the soot factor "n" must be adjusted on the pyrometer to ensure correct measurements.

non-luminous flames

non-luminous flames The temperatures of non-luminous flames, for example on gas burners, are measured ideally with spectral pyrometers measuring the radiation of hot carbon dioxide in a very narrow wavelength range. This range region is situated between 4.5 and 4.65 µm.

multi-wavelength pyrometers

Multi-wavelength pyrometers use three or four spectral ranges to measure radiant flux density. Most often, several ratios are determined between the individual spectral values. The true measured temperature is then calculated with the help of correction algorithms and empirical spectral emissivity models. Despite being technologically challenging, these instruments have proven their worth in particularly difficult applications in the metal-processing industry (rolling, forging and pressing of non-ferrous metals, galvanizing lines etc.).

9 Pyrometers and their Variants

disappearing filament pyrometers

The very first temperature measuring devices were the so-called disappearing filament pyrometers, which are still in use today! This purely electrical measuring instrument allows users to compare intensities – and thus determine the temperature of the object – by juxtaposing the intensity of the object radiation and (in the same visual channel) of a manually set filament temperature. In this set-up the human eye acts as the detector, and gives surprisingly good results. The disadvantage of this method is the **subjective comparison**, meaning that every user will read a slightly different temperature off the instrument scale. Also, this method is suitable **for high temperatures only**, as objects will start to glow only at temperatures of 600 °C and higher.

analog pyrometers

When this concept was introduced, an **objective measurement of low and high temperatures** became possible for the first time. At the time, however, engineers could only use analog components for signal processing. For several decades to follow this meant that the accuracy of temperature readings was rather poor.

fast analog pyrometers

Even today, analog pyrometers still have their place in measurement methods. This is because their internal measuring rate is still faster than that of digital pyrometers. Fast data acquisition devices such as digital storage oscilloscopes can then digitize the analog output signals and make them available through PC interfaces (such as USB).

digital pyrometers

With advancing miniaturisation and integration, digital pyrometers have been around since about 1983.
Linearization and signal processing are **completely digital** in these pyrometers. This means that a microprocessor are built into the pyrometer which handles all calculations and memory functions.

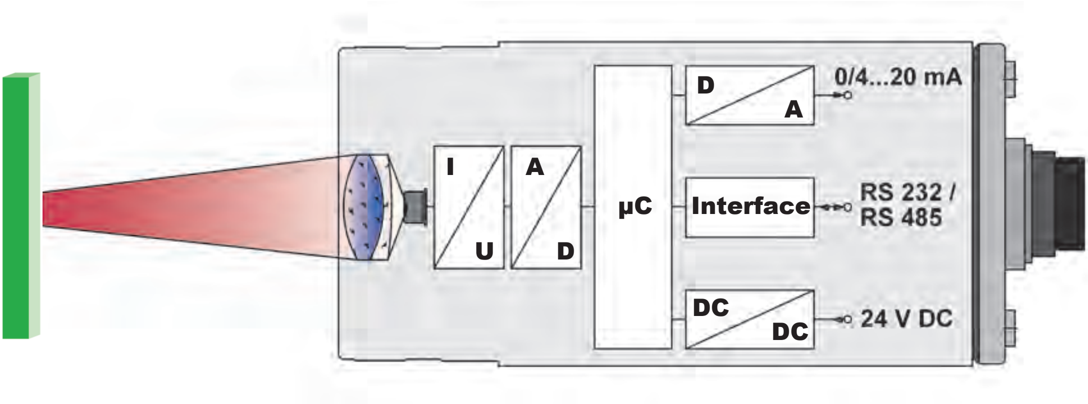


Fig. 18: Components of a digital pyrometer

Fig. 18 shows the basic design.

detector signal

The detector signal is digitized either immediately, or the analog signal is first pre-amplified and then digitized in an A/D converter. This digital signal can now be processed in the microprocessor

output signal

Normally, the available outputs are digital and analog standard signals. Digital interfaces are usually RS 232 and RS 485. Analog output signals are 0-20 mA, 4-20 mA, 0-10 V, etc.

advantages of digital pyrometers

The **advantages of digital signal processing** are:

high accuracy

- The characteristic detector curve is linearized between many points. This produces much better results than a linearization realized by electronic components. Today we are able to achieve accuracies to within ± 0.3 % of the measured value.

mathematical functions

- All functions which were implemented by an additional device in analog units can now be integrated in the pyrometer. One of these functions is maximum value storage (also called peak picking).

Integrating these functions in the pyrometer eliminates the need for peripheral or additional equipment.

digital communication

- The built-in interface permits communication with the pyrometer. A connected PC with the appropriate software is usually all it takes. All relevant data can be set in the pyrometer, such as emissivity, response time, measuring range, maximum value storage, etc.

changing the measuring range
parameter set-up via PC

- Inside the basic temperature measuring range, nearly any sub-range can be set via the PC. Accuracy is not affected by changing the measuring range. The advantages are obvious:

old equipment

  - When old equipment is replaced the same measuring range can be set. Other existing peripheral equipment and even the cables can all be reused without modifications.

spares inventory

  - Spares provisioning is greatly simplified and reduced.

optimum adaptability

  - Optimum adaptation to a specific application.

easy calibration

Digital pyrometers are recalibrated easily and quickly by means of an appropriate black-body radiator and suitable software.

software

Communication with the pyrometer always requires a special software. With the appropriate software all settings are easy to make.

Real-time displaying of a measured curve is the state of the art today. The following pictures show screenshots from an application software running under Windows.

As a rule, it is also possible to read digital signals into a dedicated software. The protocols for communication with the pyrometer are open-source, simple and transparent.

Fig. 19:
Menu

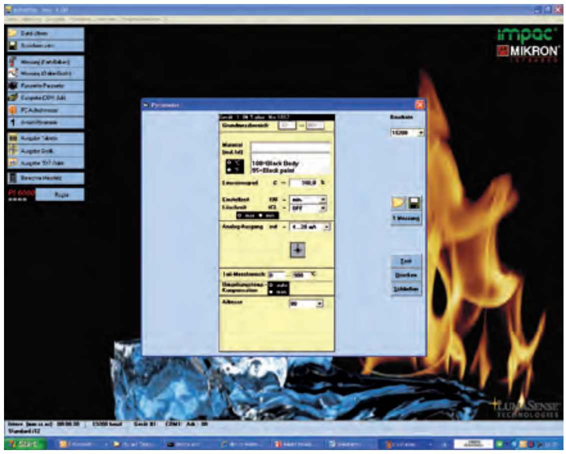


Fig. 20:
Parameter set-up

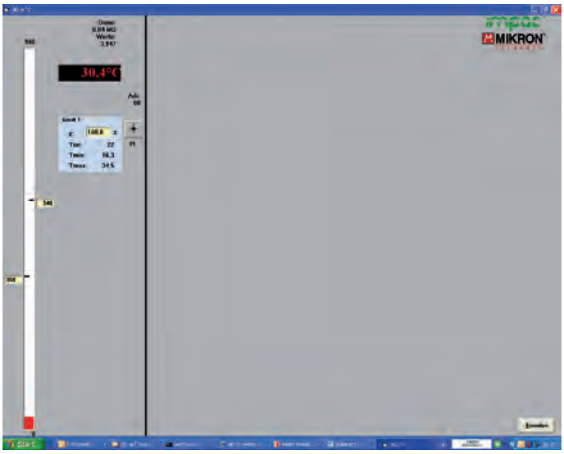


Fig. 21:
Colour bar graph
with limit values

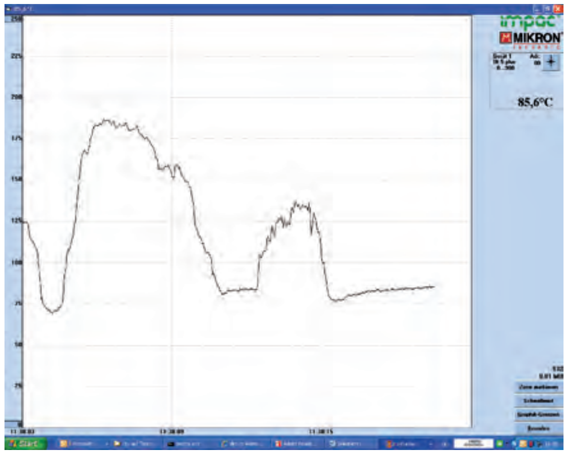


Fig. 22:
On-line chart

bus capability

Thanks to digital interfaces such as RS 485, pyrometers can be addressed (interrogated) in a measuring circuit, giving them bus capability. Manufacturers of quality pyrometers offer gateway solutions for most bus systems. For the most common bus protocols, integrated solutions are also available.

10 Fibre Optic Pyrometers

Fig. 23: Fibre optic pyrometer

In fibre optic pyrometers, the transmission of radiation between the optical unit and the measuring transducer is handled by an optical fibre. The measuring head, in the following also referred to as optical head, houses the lens system only. The measuring transducer, which is the actual pyrometer, comprises the detector and signal processor.

The radiation collected by the optical head enters the optical fibre via the lens system and can be transmitted to the transducer over longer distances (up to 30 metres). At higher wavelengths the optical fibre is no longer transparent, therefore fibre optic pyrometers can only be used for temperatures upwards of 100 °C.

advantages

Fibre optic pyrometers have proven to be reliable in especially difficult conditions. The fact of splitting the two major components offers decisive advantages for following requirements:

high ambient temperatures

- High temperatures resistance: the optical head and fibre contain no electronic components and can easily withstand temperatures up to 250 °C. The measuring transducer is installed at a cooler location where it won't suffer any damage.

- Installation in confined spaces: as the optical head is small it will fit even in small holes close to the object of the measurement.

confined spaces

- Strong electromagnetic fields do not interfere with the measurement as the optical head and optical fibre don't contain any electronics and consist of non-magnetizable material.

strong electromagnetic fields

- Measuring in a vacuum: thanks to the use of connector gaskets and feedthrough flanges for the optical fibre, the optical head may be installed inside a vacuum chamber, close to the object to be measured.

measuring in vacuum

The cross-section of an optical fibre can be changed to obtain a line-shaped cross-section, which produces a line-shaped field of view at one end. Ratio pyrometers can be used with such an optical unit, for example for automatic temperature measurement of a continuously drifting pouring stream.

linear field of view

Radiation transmission in an optical fibre is based on the total reflection of the rays at the core-cladding boundary. Thus, the transmission is practically without losses (see fig. 24).

optical fibre

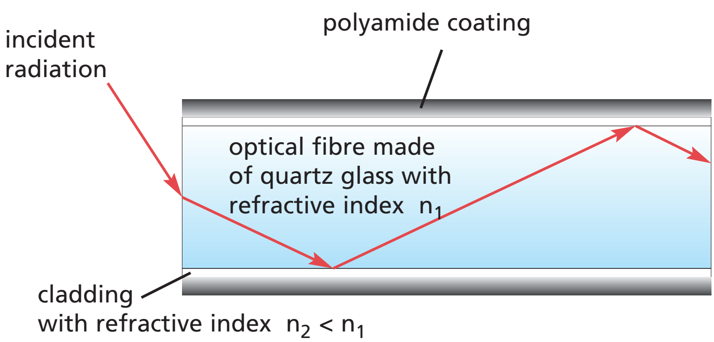


Fig. 24: Longitudinal section of an optical fibre cable

Optical fibre cables consist either of a single fibre (monofibre) or a bundle of fibres (multiple strands). Monofibre cables offer following advantages over fibre bundles:

- Smaller external diameter for the same cross-sectional area:
  In a fibre bundle losses may occur due to the space between the fibres. This means that a monofibre cable and consequently the field of view has a smaller diameter for the same optical area (see fig. 25-A).

- Immediate detection of fibre breakage:
  Any break in a monofibre is recognized instantly by the lack of a signal. Breakage of a few fibres in a bundle is not immediately apparent and will entail measurement errors (see fig. 25-B).

- No wear and tear due to friction between individual fibres:
  The cladding of fibre bundles may be damaged by the individual fibres rubbing against each other, or by the filler material (see fig. 25 C).

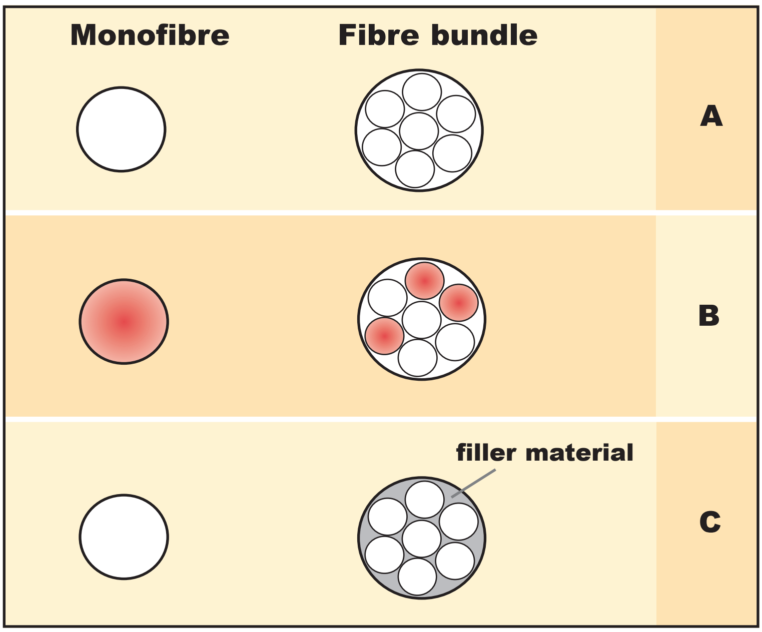


Fig. 25: Comparison between monofibre and multifibre optical cables

The advantage of fibre bundles lies in their smaller minimal bend radius, and in their lower cost compared to monofibre optical cables.

11 Sighting Devices

Following sighting devices are provided for targeting of the measuring object:

1. **through-the-lens-sighting device**
   (internal, external)
2. **integrated video camera module**
3. **integrated pilot light**
   (halogen lamp, LED, laser)
4. **sighting attachment**
   (sighting rod, laser pilot light attachment)

In general, we distinguish between devices that are built into the pyrometer and use its optical unit, and sighting aids which are mostly attached externally and whose sight path is separate from the pyrometer optical unit. Built-in devices show the field of view and spot size fairly accurately, and by focalizing the light spot the distance to target is easily adjusted.

through-the-lens sighting

- To align the pyrometer the user looks at the target as though he were looking through a camera. In the centre of the viewing area are marks which indicate the measurement spot. To protect the eye, filters eliminate UV and infrared radiation, and brightness at very high temperatures can be reduced by using polarizing filters. Through-the-lens-sighting systems are generally built-in, but are also available as add-on attachments.

video camera module

- In view of the high degree of miniaturization, it is now possible to replace through-the-lens sighting with full-scope video cameras. With such a camera, a remote operator can view not only the temperature readings but also the actual visual scene via a monitor screen. If need be, this imagery can be recorded along with the temperature measurements for documentation purposes (either by VCR or PC with frame grabber card).

pilot light

- The pilot light is built into the pyrometer and indicates the size or the centre of the measurement spot by means of a light spot. It is usable only if the measured object is not too bright. Generally, it will be visible on an object up to a temperature of 1000 °C. Pilot lights can be a halogen lamp, LED, or laser.

laser pointer

- Depending on its design, the laser pointer will either indicates the centre o the measurement spot, or the measurement spot itself. It is very useful when measuring in dark locations, and for precision measurements. The highly visible laser beam provides for accurate targeting of small and moving objects.

laser pilot light attachment

- This sighting aid is attached to the front-end of the pyrometer. It is available with a single laser beam lying on the optical axis, or with two laser beams intersecting at a defined distance from the lens.

12 Linearization

The relation between the input variable (radiation intensity) and the detector output variable (for example, a change in voltage or resistance) is not a linear one.

However, the output signal of a quality pyrometer must be linear with temperature, as it is used to control peripheral equipment.

Depending on the design, the signal processor of the pyrometer outputs a 0 to 20 m A or 4 to 20 mA signal. The bottom value refers to the beginning of the measuring range, the top value to the upper end of the measuring range.

The linearity with respect to temperature is accomplished by linearization of the input signal. The linearization in a pyrometer is handled by an electronic circuit in analog devices, or by means of mathematical and comparison operations in digital units.

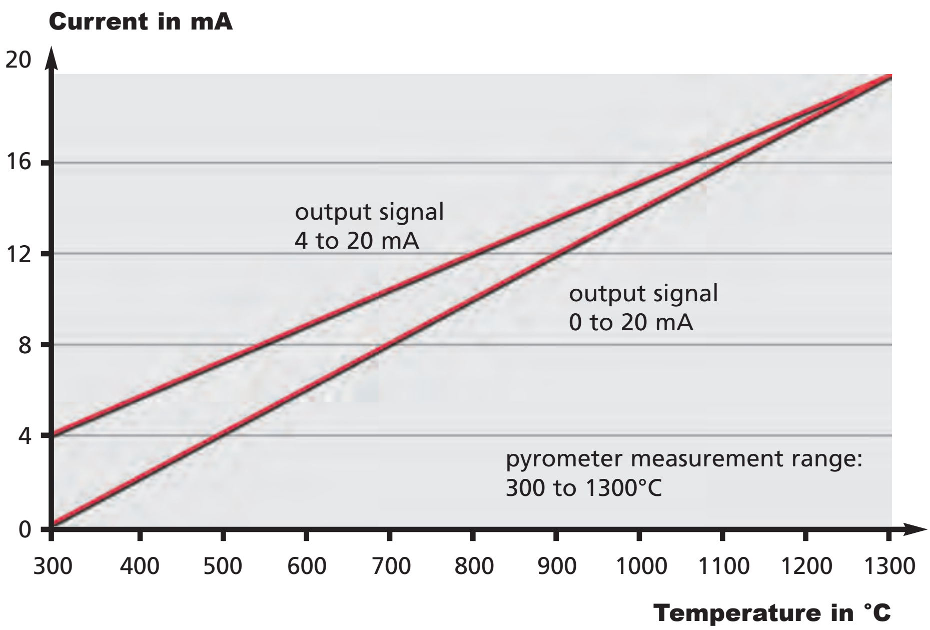


Fig. 26: Output signal

13 Calibration

Every pyrometer is calibrated and checked by its manufacturer before delivery. A certificate to this effect is enclosed with the unit.

More and more final producers, e.g. in the automotive or ship-building industries, require their suppliers to provide fully traceable evidence that manufacturing specifications for outsourced components are complied with. By way of example, the temperatures specified for production of metal components, e.g. during pouring, forging, forming and heat treatment, must be observed and documented for full traceability. This is why pyrometers must be checked at regular intervals during operation and recalibrated in the event of unacceptable deviations.

VDI/VDE guideline 3531 (page 4.2) recommends a checking interval of 2 years. Users of pyrometers should consult the manufacturer as the checking intervals actually required will strongly depend on the application in hand, and in particular on the observation of ambient limit conditions during operation, and also on the pyrometer type. Our past experience with pyrometers fitted with silicon or InGaAs detectors shows that operating periods of up to 10 years without critical accuracy losses are possible.

Page 4.2 of a.m. guideline also includes information on the servicing of pyrometers and the prevention of faults in operation.

Page 4.4 of VDI/VDE guideline 3511 specifies the calibration of pyrometers and their tracking to the International Temperature Scale of 1990 (ITS-90), as well as the calibration procedures to be used. Users have following possibilities to check their instruments:

- inspection and calibration at the manufacturer's or in a laboratory accredited for pyrometers, e.g. a calibration centre of the German calibration service DKD

- inspection and calibration at the user's by the manufacturer's mobile calibration service

- inspection and calibration at the user's with user's own means

Users are able to carry out on-site checks by making comparison measurements with a second pyrometer of the same type or same spectral response and in identical measurement conditions. This second pyrometer should be kept by the Quality Management department as a factory measurement standard, and used only for such checks.

The procurement of own calibrating means is profitable when larger numbers of pyrometers are used, i.e. for bigger companies. The manufacturer offers corresponding calibration sources for sale. They are mostly electrically heated cavity sources as shown in fig. 27.

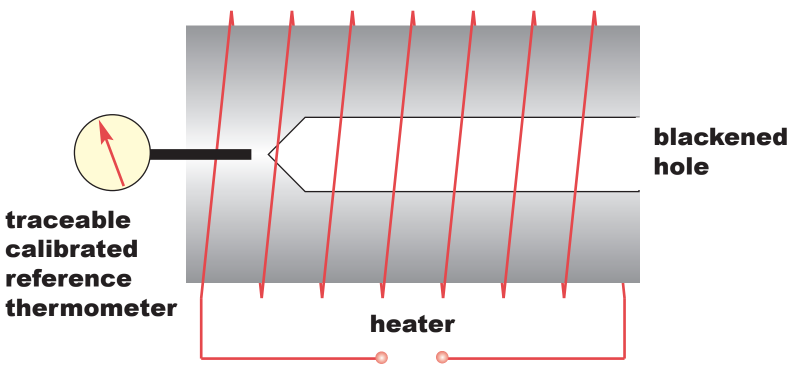


Fig. 27:
Calibration radiator

The cavity is heated to a uniform temperature. Its length is at least six times the opening diameter. With the multiple reflections an emissivity of nearly 1 is obtained. To ensure the traceability of customer's measuring instruments to the International Temperature Scale, the manufacturer offers high-precision standard transfer pyrometers.

14 Optical Units, Lenses and Window Materials

One of the most important components of a pyrometer is its optical system. If lenses are used their material must be adapted to the spectral properties of the detector. The material must be transparent to radiation in the spectral response of the pyrometer, which is determined by the measuring range and the object to be measured.

- Crown glass (BK_7) is used in pyrometers which measure in the short wavelength band (up to 2.7 µm). Crown glass is very stable, resistant to chemicals and easy to clean.

crown glass

- Water-free quartz glass (Infrasil) is also used in short wavelength pyrometers (up to 3 µm).

quartz glass

- Calcium fluoride (CaF_2, fluorite) is used especially where glass is measured. It can be used up to 10 µm and has a high transmission coefficient.

calcium fluoride

- Germanium lenses are useful for pyrometers which measure in the long wavelength band (up to 18 µm). They have a non-reflective surface for the desired region and are opaque to visible light..

germanium

- Plastic lenses are used in simple pyrometers. They are however sensitive to cleaning agents and scratch easily. They also do not tolerate high ambient temperatures.

plastic

The various colours of light have different focal lengths on normal lenses. This divergence of colour is called chromatic dispersion, and the resulting effect is called chromatic error. To eliminate this error an achromat is used. This is a combination of a convex lens and a concave lens with different amounts of dispersion.

chromatic error
achromat

dispersion

They are precisely designed so that the chromatic error is just compensated in the relevant wavelength range.

spherical error

An achromat also reduces the spherical error, i.e. the shorter focal distance of peripheral rays. Achromats are used in ratio pyrometers because they measure in two different colours. Simple lenses would lead to incorrect measurements.

air-spaced achromat

Air-spaced achromats were developed to further reduce chromatic and spherical errors. Unlike in more basic achromats, there is a small air-filled space between the lenses.

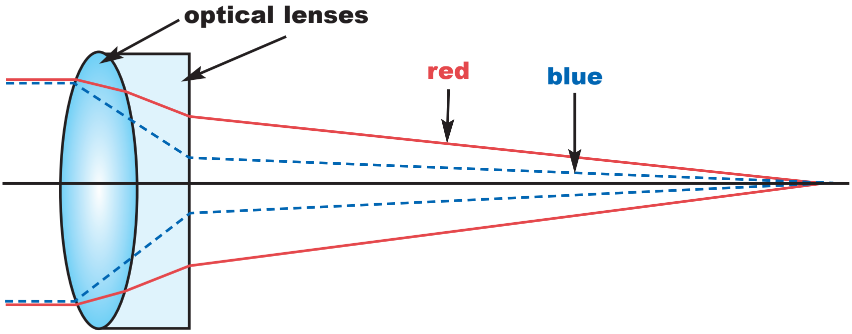


Fig. 28: Schematic diagram of an achromat

The advantage of this design is that it can be also used in higher ambient temperatures. Air-spaced achromats are especially used in the optical heads of fibre optic pyrometers.

Window Materials

Pyrometers permit the non-contact temperature measurement of materials in furnaces or other enclosures. Of course, this requires special openings through which the pyrometer can "see" the surface of the object to be measured. In many cases these openings must be sealed by means of windows (for instance, in vacuum chambers, in pressurized enclosures, when dealing with gases, liquids or viscous masses). The correct window material must be chosen as a function of the temperature range and spectral response of the pyrometer. Table 2 (see page 63) gives an overview of the most commonly used materials and their technical characteristics. The transmission range must be chosen so that it will not conflict with the pyrometer's spectral response, which is determined by the temperature and material of the object to be measured. Other requisite properties are mechanical strength, resistance to moisture and chemical attack, and the ability to withstand thermal shocks.

selection and spectral range

Following formula is used to calculate the minimum window thickness (t_{min}) to ensure proper resistance to pressure:

mechanical strength

$$t_{min} = r \cdot \sqrt{\frac{S \cdot c \cdot \Delta p}{M_r}}$$

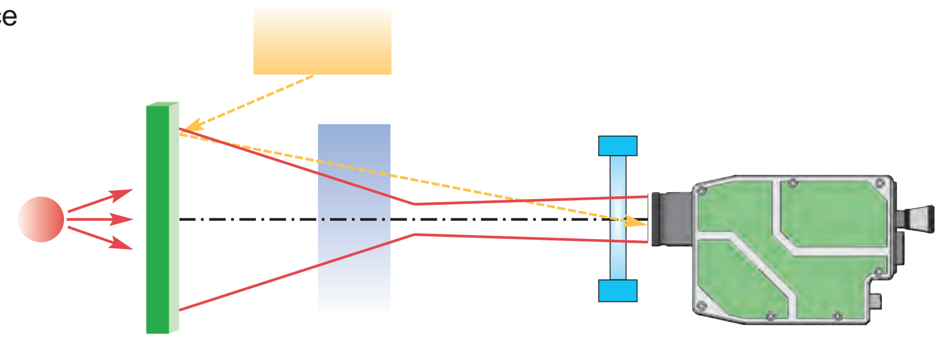
r **- radius of the windowpane**
S **- safety factor (≥4)**
c **- method of window attachment (for instance c=1.1 for loose placement)**
Δp **- pressure difference**
M_r **- modulus of rupture (material constant, see table 2)**

Glass and quartz windows are inexpensive solutions (suitable for high-temperature measurements), as are silicon and fluorite windows (suitable for lower temperatures).

15 Sources of Interference

In nearly all applications there is a risk of having temperature measurement errors caused by interfering radiation and other sources of interference.

Fig. 29: Sources of interference



However, once the most common sources of error are known, they can be avoided by simple means in most cases. The following list shows the most common sources of interference and possible remedies.

hot equipment components

- Extraneous infrared radiation, e.g. from hot equipment components located close by, may be reflected off the surface of the object to be measured (see fig. 21-A).

transparent materials

- When measuring objects which are transparent to radiation, hot objects behind the measured object will interfere with the measurement (fig. 21-B).

dust, vapour, smoke, window

- Infrared radiation can be attenuated by dust, water vapour, smoke, or viewing windows (see fig. 21-C/D).

field of view

- The object of measurement doesn't completely fill the measurement spot.

Remedies

daylight and artificial ligh

Extraneous infrared radiation such as from daylight, indoor lighting or another infrared radiation source can be blocked by means of optical filters because of their predominantly short-wave nature. Quality pyrometers with silicon, germanium or InGaAs detectors are equipped with daylight filters so that daylight or artificial light have no adverse effect on the measurement. Exceptions are pyrometers with InGaAs detectors whose temperature range begins at under 300 °C. In these cases a shade has to be used to prevent measurement errors.

IR radiators

Interference from extraneous infrared radiation sources (with wavelengths up to approx. 4 µm), for example in continuous furnaces, can be avoided by using pyrometers which work in the long-wave infrared spectral range (for example in the wavelength band between 8 and 14 µm.

hot furnace walls

The radiation emitted by a furnace wall or a hot machine enclosure has the same wavelength range as the radiation coming from the object of the measurement, and cannot be eliminated by optical filters. It must be blocked out by mechanical means, or masked. Alternatively, the measurement result can be corrected mathematically. So long as the temperature of these other hot objects is constant, the input of a certain temperature value into the equation will suffice. However, if it is subject to uncontrollable changes, it must be measured with an additional sensor. These values are then processed in the signal processor together with the pyrometer signal for the measured object.

viewing window

When the measurement is done through a window, the emissivity must be adjusted on the pyrometer to compensate for the degree by which the radiation has been attenuated. The influence of dirty viewing windows (due to smoke, material deposits or vapours) can be eliminated by using an optical unit monitoring device in conjunction with a ratio pyrometer[9].

9) see pages 54 and 59

H_2O, CO_2

The interference caused by water vapours and carbon dioxide contained in the air can be eliminated by choosing the correct spectral response of the pyrometer.

dust, smoke

Sources of interference which are variable over time, such as dust, smoke and vapour, call for the use of a ratio pyrometer.

transparent objects

Objects that are transparent to radiation must be measured by pyrometers working in the wavelength range in which the measured object is opaque. When the background behind the measured object is significantly cooler than the object itself, the transparency of the object can be taken into account by correcting the emissivity.

measurement spot not filled

If the measurement spot is not completely filled you must change the location of the pyrometer to remedy this[9]. If this is not possible a different optical unit must be used.

A ratio pyrometer will allow you to measure the temperature with an insufficiently filled measurement spot so long as the background is cold.

10) see pages 54 and 59

16 Accessories

Manufacturers offer special accessories to meet the specific needs of various industries. They help solve many measurement-related problems and have been developed with specific difficult applications in mind.

air purge attachment

- An **air purge attachment** protects the optical unit from dust and other suspended particles, as well as from condensation. It is designed as a ring-shaped blow nozzle which creates a conical air curtain forcing dirt away from the lens, so that no dust can settle on it. With an air purge system it is important to use dry and oil-free compressed air. In normal conditions a pressure of 0.2 bar will be sufficient.

cooling systems

- A **radiation shield** is used when most of the heat radiation comes from the front.
- A **cooling plate** is a water-cooled plate. It diminishes the radiation from the front without heating up itself. It allows pyrometers to be used in ambient temperatures exceeding their maximum rated operating temperature by 10 to 20 °C.
- **Cooled enclosures** come with cooling coils or as fully jacketed cooling systems.
  Cooling coils allow pyrometers to be operated in high ambient temperatures.
  Fully jacketed cooling systems permit pyrometers to be used in ambient temperatures of up to 100 °C with air cooling, and up to 250 °C with water cooling.

mounting fixtures

- Pyrometers are fixed in place by means of **mounting brackets**.
- **Adjustable mounts** are used to provide for adjustable alignment (in 2 axes).
- **Flange systems** allow pyrometers to be mounted to furnaces, vessels or pipes.
- With a **mounting tube**, pyrometers can be attached to various containers (asphalt mixing plants, painting lines).
- A **ball and socket mount** is used for pyrometers requiring quick position adjustments.

ceramic tubes

- **Ceramic tubes** are available as open or closed types. A closed ceramic tube is used to measure the average interior temperature of a furnace or the temperature of molten materials (e.g. glass).
  Open ceramic tubes are used to measure the surface temperatures of objects inside furnaces.

scanning assembly

- **Scanning optics** allow the measurement spot to be moved back and forth across the object to be measured by means of a mirror oscillating around its centre position.This enables you to measure temperatures on drifting or moving objects, for example in wire production. The scanning assembly should always be used in conjunction with a peak picker (maximum value storage) function. A peak picker stores the highest temperature reading off the object during each scan (provided that the ambient temperature is lower than that of the object to be measured). Scanning assemblies may either be integral or attached to the front of the optical unit. With an output that indicates the position of the mirror a pyrometer with scanning unit can be used as a line scanner.

emissivity enhancer

- The **emissivity enhancer**, whose core is a gold-coated concave mirror, attaches to the front-end of a pyrometer. It is used for very shiny measurement objects having extremely low emissivities. Together with the pyrometer it will be mounted as close as possible to the object of the measurement.
  The ensuing multiple reflections between mirror and measurement object amplify the radiation incident on the pyrometer. This results in a much higher effective emissivity. This enhancer enables temperature measurements to be implemented which would not be feasible with conventional methods. In addition, it shields the measurement object from extraneous radiation, which also contributes to significantly improving the results of temperature measurements close to ambient temperature.

optical unit monitoring system

- Dirt on the optical unit or an a viewing window in front of the measured object is the single most common cause of measurement errors with pyrometers. To prevent such problems, manufacturers offer **optical unit monitoring systems** in connection with ratio pyrometers. Even though ratio pyrometers have a high tolerance for dirt, there are limits. The monitoring system outputs a warning when dirt accumulation exceeds a set limit. An interface allows users to set two warning levels: pre-alarm and main alarm, which prompts the user to clean the optical unit or viewing window. This add-on feature is already integrated in some pyrometer types.

indicators

- **Indicators** are used to display the temperature readings. They can be integrated into the pyrometer but they are also available as external units for remote temperature indication, e.g. in a control room or on a switchgear cabinet. Indicators can be analog or digital, some have built-in maximum peak pickers and limit contacts (for open- or closed-loop control of heating systems etc.).

gateways

- **Gateways** enable RS 485 signals to be coupled to various bus systems such as Profibus-DP.

recorders and printers

- **Recorders** and **printers** provide graphic logging of the measured temperature.

calibrators

- **Calibration equipment** is used to calibrate and check the accuracy of pyrometers. These black-body radiators serve as reference radiation source.

maximum value storage

- Where there are swings in temperature, **maximum value storage**, also known as **peak picking**, allows the highest temperature value to be recorded and stored. Peak pickers have very fast response times so that even the most rapid temperature changes are registered. These units have proven invaluable in metal processing applications (rolling, forging etc.). When scale develops, temperature variations occur on the surface being measured. With a maximum value storage feature the highest measured value is memorized as it corresponds to the temperature of the measured object. By using a double storage memory you obtain a quasi-continuous reading. This feature is mostly used in combination with scanning optics and limit contacts.

limit contacts

• **Limit contacts** output a switching signal when temperature falls below or exceeds user-definable limit values.

converters

• The **converter** changes the output signal of 2-wire sensors from 4-20 mA to 0-20 mA.

digital converters

• **Digital converters** change an RS 485 signal into an RS 232 signal, or vice versa.

averaging unit

• In the presence of temperature fluctuations, the **averaging unit** calculates the mean value and supplies a stable output signal which is easy to feed to controllers etc.

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Table 1: Emissivities of Various Materials

Material	Spectral range 0.7 ... 1.15 µm	Spectral range 1.4 ... 1.8 µm	Spectral range 2 ... 2.5 µm	Spectral range 4.9 ... 5.5 µm	Spectral range 8 ... 14 µm
Steel, bright	0.40 ... 0.45	0.30 ... 0.40	0.20 ... 0.35	0.10 ... 0.30	0.10 ... 0.30
Steel, rolled	0.45 ... 0.55	0.35 ... 0.50	0.25 ... 0.40	0.20 ... 0.30	0.20 ... 0.30
Steel, annealed	0.70 ... 0.80	0.70 ... 0.85	0.45 ... 0.70	0.30 ... 0.60	0.30 ... 0.60
Steel, oxidized	0.80 ... 0.90	0.80 ... 0.90	0.75 ... 0.85	0.70 ... 0.90	0.60 ... 0.80
Copper, bright	0.06 ... 0.20	0.06 ... 0.20	0.06 ... 0.10	0.05 ... 0.10	0.03 ... 0.10
Copper, oxidised	0.50 ... 0.80	0.40 ... 0.80	0.40 ... 0.80	0.20 ... 0.70	0.20 ... 0.70
Aluminium, bright	0.05 ... 0.25	0.05 ... 0.25	0.04 ... 0.20	0.03 ... 0.15	0.02 ... 0.15
Aluminium, anodized	0.20 ... 0.40	0.10 ... 0.40	0.10 ... 0.40	0.10 ... 0.40	0.95
NiCr, bright	0.20 ... 0.40	0.20 ... 0.40	0.20 ... 0.40	0.20 ... 0.40	0.10 ... 0.30
NiCr, oxidized	0.65 ... 0.90	0.65 ... 0,80	0.65 ... 0.80	0.65 ... 0.80	0.50 ... 0.80
Carbon, graphite	0.70 ... 0.95	0.70 ... 0.95	0.70 ... 0.95	0.70 ... 0.95	0.70 ... 0.95
Stone, soil, ceramics	0.40 ... 0.70	0.40 ... 0.70	0.40 ... 0.70	0.50 ... 0.80	0.60 ... 0.95
Varnish, paint	---	---	---	0.60 ... 0.90	0.70 ... 0.95
Wood, plastics, paper	---	---	---	0.60 ... 0.90	0.80 ... 0.95
Textile	---	0.70 ... 0.85	0.60 ... 0.85	0.70 ... 0.90	0.75 ... 0.95
Thin glass	0.05 ... 0.10	0.05 ... 0.20	0.60 ... 0.85	0.70 ... 0.90	0.75 ... 0.95
Water, snow, ice	---	---	---	---	0.90 ... 0.95

Table 2: Window Materials

Window material	Trans-mission range µm	Average trans-mission %	Melting point °C	Modulus of rupture MN/m²	Solubility in water g/l H_2O	Properties	
						Pros	Cons
KRS-5	0.8 ... 45	70	414	25.9	0.2	extremely resistant, uniform transmission profile across a wide spectral range	soft, toxic components
CaF_2	0.13 ... 9	90	1380	36.5	0.017	high transmission, inexpensive	
ZnSe	0.5 ... 18	70	1526	55	0.01	constant transmission across wide spectral range, chemically resistant (except against strong acids)	not scratch resistant, toxic components
Quarz	0.15 ... 4	90	1470-1700		0.01	little thermal expansion, insensitive to large temperature fluctuations	
BK_7	0.4 ... 2	92			not soluble	high transmission high chemical resistance, inexpensive	can only be used up to the transformation temperature (BK_7 = 560°C)
Ge	2 ... 18	45	936		not soluble	scratch resistant, higher transmission with antiglare coating in measuring range	expensive, transmission rapidly deteriorates with rising ambient temperature
Sapphire Al_2O_3	0.2 ... 4	90	2040		not soluble	very high thermal and mechanical resistance, chemically resistant, high transmission	expensive

Table 3: Selection Table

	Temperature [°C]	Spectral response [µm]		Other measures comments	Applications
		Partial radiation	Ratio		
		pyrometer			
Bright metals (not oxidized	> 5	3…5		ε- enhancer	
	>50 (>100)	2…2.6 (2.8)		ε- enhancer	metal processing
	> 300		1.28…1.7		
	> 600		0.8..1.1		
Aluminium	>350 (200)	special	(special)		
Silicon	>350	special			extrusion
Molten metals	>750		0.8..1.1	line-shaped field of view, optical fibre	semiconductor industry pouring beam, continuous casting
	>1100	0.676			
Oxidized metals	>5	3…5			Sforging, hardening, rolling, wire drawing
	>50 (>100)	2…2.6 (2.8)			
	> 300	1.45…1.8			
	> 600	0.7…1.1			
Glass	>0	8…14		penetration depth 0.04 mm	
	>100 (250)	5.14			glass surface
	>650	0.7…1.1		penetration depth 0.7 mm penetration depth 90…300 mm	glass surface
Transparent plastics	>50	3.43		material gauges >10 µm	molten glass PE and PP films
Non-metals	>-40	8..14			foodstuffs, textiles, paper, plastics
	>550	0.7…1.1			
Objects behind flames	>300 (>75)	3.9			metal parts in direct
Luminous flames		0.7…1.1	0.8…1.1		fuel-fired furnaces
Non-luminous flames	>400	Hot CO_2 - Bands			combustion systems waste incineration

Table 3: Temperature Errors Caused By 1% Emissivity Change at Different Spectral Ranges

Effective Wavelength [µm]	0.65	0.9	1.64	2.3	3.43	3.86	4.5	5.0	7.9	10.6	0.78-1.06
Target Temperature [°C]	Errors [°C]										
-30.0									1.0	0.8	
-20.0									0.7	0.6	
-10.0									0.5	0.4	
0.0									0.3	0.3	
10.0									0.2	0.2	
20.0									0.0	0.0	
30.0					0.0	0.0	0.0	0.0	0.0	0.0	
40.0					0.1	0.1	0.1	0.1	0.1	0.1	
50.0				0.1	0.2	0.2	0.2	0.2	0.2	0.2	
60.0				0.2	0.2	0.2	0.2	0.2	0.3	0.3	
70.0				0.2	0.2	0.3	0.3	0.3	0.4	0.4	
80.0				0.2	0.3	0.3	0.3	0.3	0.4	0.5	
90.0				0.2	0.3	0.3	0.3	0.4	0.5	0.5	
100.0			0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	
120.0			0.2	0.3	0.4	0.4	0.4	0.5	0.6	0.7	
140.0			0.2	0.3	0.4	0.4	0.5	0.5	0.8	0.9	
160.0			0.2	0.3	0.4	0.5	0.6	0.6	0.9	1.0	
180.0			0.2	0.3	0.5	0.5	0.6	0.7	1.0	1.1	
200.0			0.3	0.4	0.5	0.6	0.7	0.8	1.1	1.2	
220.0			0.3	0.4	0.6	0.7	0.7	0.8	1.2	1.4	
240.0			0.3	0.4	0.6	0.7	0.8	0.9	1.3	1.5	
260.0			0.3	0.5	0.7	0.8	0.9	1.0	1.4	1.6	
280.0			0.4	0.5	0.7	0.8	0.9	1.0	1.5	1.8	
300.0			0.4	0.5	0.8	0.9	1.0	1.1	1.6	1.9	
320.0			0.4	0.6	0.8	0.9	1.1	1.2	1.8	2.0	
340.0			0.4	0.6	0.9	1.0	1.2	1.3	1.9	2.2	
360.0			0.5	0.7	1.0	1.1	1.2	1.4	2.0	2.3	
380.0			0.5	0.7	1.0	1.1	1.3	1.4	2.1	2.4	
400.0		0.3	0.5	0.7	1.1	1.2	1.4	1.5	2.2	2.6	
420.0		0.3	0.5	0.8	1.2	1.3	1.5	1.6	2.4	2.7	
440.0		0.4	0.6	0.8	1.2	1.4	1.6	1.7	2.5	2.9	
460.0		0.4	0.6	0.9	1.3	1.4	1.7	1.8	2.6	3.0	
480.0		0.4	0.6	0.9	1.4	1.5	1.7	1.9	2.8	3.2	
500.0		0.4	0.7	1.0	1.4	1.6	1.8	2.0	2.9	3.3	
550.0		0.5	0.7	1.1	1.6	1.8	2.1	2.3	3.2	3.7	
600.0		0.5	0.8	1.2	1.8	2.0	2.3	2.5	3.6	4.1	10.6
650.0		0.6	0.9	1.4	2.0	2.3	2.6	2.8	4.0	4.5	11.2
700.0		0.6	1.0	1.5	2.2	2.5	2.8	3.1	4.3	4.9	11.7
750.0		0.7	1.1	1.7	2.5	2.8	3.1	3.4	4.7	5.3	12.2
800.0	0.5	0.8	1.2	1.8	2.7	3.0	3.4	3.7	5.1	5.7	12.8
850.0	0.6	0.8	1.3	2.0	3.0	3.3	3.7	4.0	5.5	6.1	13.4
900.0	0.6	0.9	1.4	2.2	3.2	3.5	4.0	4.3	5.9	6.5	14.0
950.0	0.7	1.0	1.5	2.4	3.5	3.8	4.3	4.7	6.3	6.9	14.6
1000.0	0.7	1.1	1.7	2.5	3.7	4.1	4.6	5.0	6.7	7.4	15.3
1100.0	0.9	1.3	1.9	2.9	4.3	4.7	5.3	5.7	7.5	8.2	16.7
1200.0	1.0	1.4	2.2	3.4	4.9	5.4	6.0	6.4	8.4	9.1	18.1
1300.0	1.1	1.6	2.4	3.8	5.5	6.0	6.7	7.2	9.2	10.0	19.7
1400.0	1.3	1.8	2.7	4.3	6.2	6.7	7.4	7.9	10.1	10.9	21.3
1500.0	1.4	2.0	3.0	4.8	6.8	7.4	8.1	8.7	11.0	11.9	23.1
1600.0	1.6	2.3	3.4	5.3	7.5	8.1	8.9	9.5	11.9	12.7	24.9
1700.0	1.8	2.5	3.7	5.8	8.2	8.9	9.7	10.3	12.8	13.7	26.8
1800.0	1.9	2.8	4.0	6.4	8.9	9.6	10.5	11.1	13.7	14.6	28.8
1900.0	2.1	3.0	4.4	7.0	9.6	10.4	11.3	12.0	14.6	15.5	30.9
2000.0	2.3	3.3	4.8	7.6	10.4	11.2	12.1	12.8	15.5	16.5	33.1
2100.0	2.5	3.6	5.2	8.2	11.2	12.0	12.9	13.6	16.4	17.4	35.4
2200.0	2.8	3.9	5.6	8.8	12.0	12.7	13.8	14.5	17.3	18.3	37.8
2300.0	3.0	4.2	6.0	9.5	12.7	13.6	14.6	15.3	18.3	19.3	40.2
2400.0	3.2	4.5	6.4	10.1	13.5	14.4	15.5	16.2	19.2	20.3	42.7
2500.0	3.5	4.9	6.9	10.8	14.3	15.2	16.3	17.1	20.2	21.2	45.4
2600.0	3.7	5.2	7.3	11.5	15.1	16.1	17.2	18.0	21.1	22.2	48.1
2700.0	4.0	5.6	7.8	12.2	15.9	16.9	18.1	18.9	22.1	23.1	50.9
2800.0	4.2	5.9	8.3	12.8	16.8	17.8	19.0	19.8	23.0	24.1	53.8
2900.0	4.5	6.3	8.8	13.6	17.6	18.6	19.9	20.7	24.0	25.1	56.8
3000.0	4.8	6.7	9.3	14.3	18.4	19.5	20.7	21.6	24.9	26.0	59.9

Glossary of Terms

absolute zero
-273.15 °C, lowest possible temperature where molecular motion ceases.

absorption
Transfer of energy to a material by means of wave radiation or particle radiation.
Assimilation of energy (light, heat), gases or liquids by substances or tissues.

absorption bands
Spectral regions where materials absorb radiation and where they are not very transparent to this radiation.

absorption coefficient
Ratio of absorbed radiation to total incident radiation

achromat
Combination of lenses made of crown glass with low refractive index and flint glass with high refractive index to alleviate chromatic errors

aiming device
Accessory for accurate adjustment of the measurement spot of a pyrometer

air purge unit
Accessory to keep dust off the optics

air-spaced achromat
Special achromat design which reduces both chromatic and spherical error

aperture
Lens opening of an objectiv

atmospheric windows
Spectral regions in which air transmits radiant energy well

averaging unit
Accessory which forms the average value of the signal for an adjustable period of time

black body (radiator)
An ideal body that absorbs all incident radiation at all wavelengths. Its emissivity is 1.

blackbody furnace
Cavity radiation source needed for calibration and checking purposes. It is designed in such a way that its opening approximates a blackbody radiation source.

calibration
The checking and correction of a measuring instrument to a standard of known accuracy

calibration certificate
A certificate that verifies the accuracy of an instrument (this can be in a format that is traceable to National Standards)

calibration source
A blackbody radiation source used for calibration of pyrometers

carbon dioxide
A colourless, incombustible gas (CO_2) having a faint sour taste

cavity-type black-body source
Equivalent to a black-body source, used to calibrate pyrometers

chromatic error
Colour aberration. Individual lenses have different focal distances for different wavelengths.

compensation for ambient temperature
Changes in the temperature of the instrument caused by extraneous influences are compensated for automatically

contact thermometer
Temperature measuring device which measures the temperature of an object by direct contact, for example thermocouples or resistance thermometers (e.g.Pt100)

cooling system
Accessory which allows pyrometers to be used in high ambient temperatures

data storage unit
Device used to store measured values for later read-out and analysis

detector
A sensor that converts incident thermal radiation into an electrical signal

disappearing filament pyrometer
Optical pyrometer where the brightness of the measured object is compared to the brightness of the built-in filament

dispersion
Refraction of light into various colours

emissivity
The ratio of the energy emitted by an object to the energy emitted by a black body at the same temperature

emissivity control — A control on the pyrometer that allows you to adjust it to the emissivity of the measured object

fibre optic pyrometer — Pyrometer whose separate optical head is connected to the detector by means of an optical fibre

field of view — The angle over which the pyrometer is sensitive to incoming radiation. The field of view is determined by the optics and distance to target (see also measurement spot).

field-of-view diagram — Specifies the size of the measurement spot as a function of measuring distance

filter — A device for absorption or transmission of radiation of a given wavelength, in pyrometry a component used to limit the spectral response

fixed optics — Fixed-focus optics without focus adjustment feature

flame pyrometer — Pyrometer used to measure the temperatures of flames

four-colour pyrometer — Pyrometer which simultaneously measures in four different spectral ranges and then calculates the true temperature mathematically from the received signals

grey body — A body whose emissivity can be considered constant within the spectral region of interest

infrared — The region of the electromagnetic spectrum where the majority of thermal radiation occurs (0.78 to 1000 µm)

intensity — Power of radiation

interface — RS 232, RS 485, digital output for communication of a pyrometer with a computer or field bus

laser pointer — Accessory using a laser light source for precise targeting of the measuring instrument

limit contact — Accessory which trips when the temperature falls below or exceeds user-defined limit values

linearization
Part of the signal processing in a pyrometer where the input signal is converted into an output signal proportional to, and linear with, temperature

maximum value storage
Also referred to as peak picker, an accessory which memorizes the highest temperature value occurring within a specified, user-definable time interval

measurement spot
Surface on the measured object where the pyrometer receives the major portion (mostly 90%) of the signal (see also field of view)

measurement uncertainty
Maximum deviation between temperature reading and true temperature

measuring range, lower limit
Lower limit of the measuring range (lowest temperature that can be measured by the pyrometer)

measuring range, upper limit
Upper limit of the measuring range (highest temperature that can be measured by the pyrometer)

measuring distance
Distance between the object of the measurement and the front of the lens of the pyrometer

multi-wavelength pyrometer
Pyrometer which measures in several spectral ranges and calculates the true temperature of the measured object by combining the different incoming signals (for example, a ratio pyrometer).

objective
Optical system consisting of one or several lenses or mirrors and which projects the measured object onto the detector in the pyrometer

optical head
Objective of a pyrometer that is connected by optical fibre to the converter unit. It can be mounted close to the object of the measurement in harsh conditions and withstands high ambient temperatures.

optical fibre
Glass fibre in which light propagates according to the principle of total internal reflection

partial radiation
Pyrometer which uses only a portion of the radiation emitted by an object to measure the object's

pyrometer temperature. Depending on the range of the spectrum used, one distinguishes between spectral pyrometers and narrow-band radiation pyrometers.

peak picker See maximum value storage

pilot light Accessory used as sighting device simulating the measurement spot by means of a halogen lamp, LED, or laser light source

Planck's law of radiation Planck's law of radiation describes intensity emitted in the wavelength interval dλ, (i.e. between λ and λ+dλ)

$$dM = C_1 \frac{1}{\lambda^5} \cdot \frac{1}{e^{C_2/\lambda T} - 1} \, d\lambda$$

C_1, C_s radiation constants

$C_1 = 3{,}74 \cdot 10^{-16}\ Wm^2$ $C_2 = 1{,}44 \cdot 10^{-2}\ mK$

pyrometer An instrument used to measure temperatures without making contact with the object to be measured (radiation thermometer)

ratio pyrometer See two-colour or four colour pyrometer

reflection Return of radiation from the interface between two media, reflection may be specular or diffuse

reflectivity The ratio of reflected radiation to total incident radiation

repeatability The capability of a measuring instrument to repeat the same reading in identical conditions

scale Oxidised layer which is created on the surface of steel during the heating process. This layer has a lower temperature than the steel itself.

scanning assembly Device used to move the sight path of a pyrometer along a line perpendicular to its optical axis to scan the surface of the object of the measurement. The scanner moves the measurement spot over the object.
A device to increase or decrease the aperture of an

shutter
objective, an adjustable device to limit the amount of light entering the lens system

soot
Black powder of carbon particles formed by the in-complete combustion of organic substances (and having a very high emissivity)

spectral pyrometer
Spectral pyrometers have only a narrow spectral response. This is why they can be assigned a wavelength λ which is independent of the temperature.

spectrum
All the wavelengths produced by electro-magnetic radiation

spectral response
The region of the spectrum which is used by the pyrometer

spectrometer
Measuring device which determines the radiation intensity in relation to the wavelength

spot size
see measurement spot, field of view

Stefan-Boltzmann law
Describes how the intensity emitted in the total wavelength range (0 to ∞) depends on temperature

$M = \sigma \cdot T^4 \qquad \sigma = 5{,}67 \cdot 10^{-8} \frac{W}{m^{-2} \cdot K^{-4}}$

σ: Boltzmann constant T: absolute temperature

temperature
The heat capacity of a material (solid, liquid or gas), measured in absolute Kelvin, °Celsius, °Fahrenheit, or °Reaumur

Conversion: K = °C + 273.15°
°C = 0.555 (°F - 32) = 1.25 °R
°F = 1.8 °C + 32 = 2.25 °R + 32
°R = 0.8 °C = 0.444 (°F - 32)

test certificate
Certificate of the measurement uncertainty of a measuring device

thermal capacity
A physical property of a material describing its ability to store heat

thermal conductivity
A physical property of a material describing its ability to conduct heat

thermocouple a temperature sensor that consists of two wires connected together and made from different metals (e.g. Ni-NiCr) or alloys, which produces an electrical voltage that is dependent on temperature

through-lens sighting accessory for precise targeting of measurement object

total reflection complete reflection of light at the boundary between a more dense optical medium and a less dense optical medium.

traceable calibration official calibration by an authorised calibration laboratory

transmission the passing of radiation through a solid substance, a liquid or a gas

transfer pyrometer a transfer pyrometer, also referred to as transfer standard pyrometer, having a very high accuracy and long-term stability. It is used to exactly measure the temperature of calibration sources. It helps users ensure calibration of their measuring equipment to the International Temperature Scale.

transmissivity ratio between the intensity of radiation that has passed through and incident radiation

two-colour pyrometer two-colour pyrometer A pyrometer which measures in two neighbouring wavebands and internally calculates the ratio of the output signals

variable-focus optics Optical unit with focus adjustment feature

viewing window A windowpane that transmits radiant energy well and that is used to seal a viewing port through which a pyrometer measures a target

wavelength Describes the length of a wave between two points characterized by the same phase

Wien's distribution law Describes the relation between the wavelength at which the maximum radiation occurs, and temperature

$$\lambda_{max} = \frac{C_3}{T} \qquad C_3 = 2{,}898 \cdot 10^{-3}\ \mathrm{mK}$$

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Non-contact Thermometry

Pyrometry, being a highly specialised field of thermometry, has developed a certain mysterious aura about it. This mystery stems from the false perception that the technology is difficult to master, whereas in truth pyro-meters are easy to use in industrial applications so long as some basic principles are known and observed.

Unfortunately, in the past these principles were not always fully taken into account, especially when low-cost pyrometers and infrared sensors were offered for sale by mail order. As a consequence, pyrometers were often used incorrectly, so that the reputation of this really very reliable measuring method suffered tremendously.

This handbook was created with the intention of reassuring users and giving them an idea of what can be measured using pyrometry.

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