Precise non-contact temperature measurements of shiny metals

by Albert Book

The measurement of shiny metals at low temperatures is still a challenging measuring task in the field of non-contact temperature measurements due to the very low thermal radiation and the varying radiation properties of metals.

The following article describes the physical principles, different methods of measurement, state-of-the-art technical developments and the basic conditions necessary for a reliable measurement.

Physical principles

A pyrometer captures the heat respectively infrared radiation emitted from the measuring object and determines the temperature from these values using the Planck's law. The radiation level not only depends on the temperature but also to a large extent on the emissivity of the measured object. The emissivity is a relative quantity; it is a result of the ratio of the radiation energy of a real body and of an ideal body or so-called "black body". For non-transparent objects the relation between the emissivity ε and the reflection factor ρ is $\varepsilon + \rho = 1$. Good heat emitters with a high emission capability have a low reflectivity and vice versa. In general, all non-transparent non-metals have a high emissivity of > 80 %. Therefore, non-metallic measuring objects cause less problems when their temperature is measured without contact. Metals, however, have very different emissivities from < 10 % for high polished metals up to > 80 % for oxidised, coated or red-hot metals. The emissivity can also change with the temperature and it is dependent on the wavelength of the radiation. It increases with shorter wavelengths (**Fig. 1**).

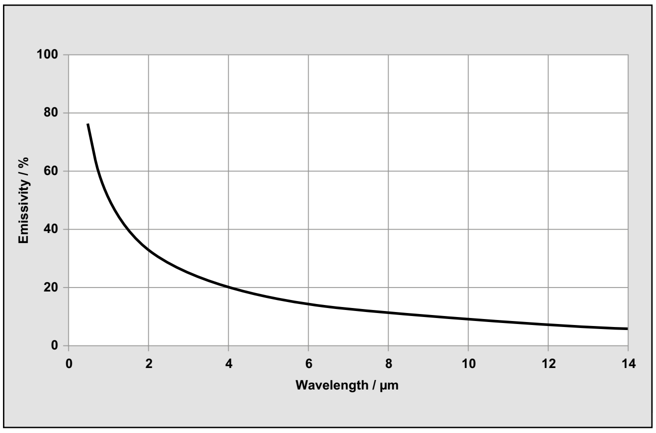

Fig. 1 *The emissivity of metals decreases with an increasing wavelength.*

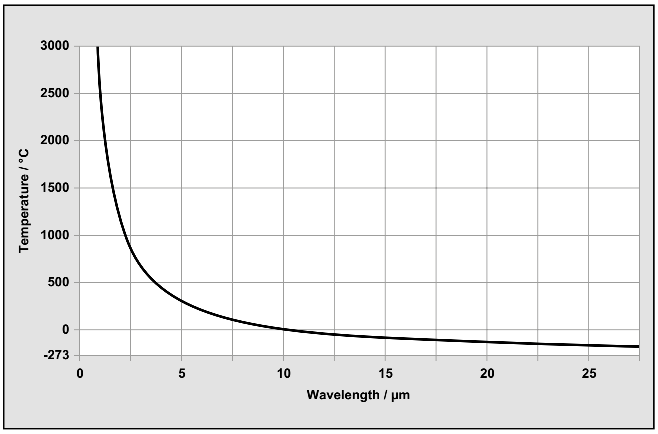

Fig. 2 *Wien's displacement law – relationship between the wavelength and the radiation maximum.*

According to Wien's displacement law, the centroid wavelength where the measured object emits its maximum radiation (**Fig. 2**) changes in relation to the temperature. The lower the temperature, the longer is the wavelength of the maximum radiation. Therefore, longwave pyrometers with a spectral sensitivity of 8 - 14 μm are required to measure temperatures starting at room temperature. Shiny metals, however, are low heat emitters in this wavelength range, as figure 1 shows. Much of the radiation captured by the pyrometer here comes from the background radiation surrounding of the measuring point and reflecting from the measuring object surface. In addition, a longwave pyrometer reacts with large variations of the measured value when the emissivity of the metal surface changes.

To get reliable readings at all from shiny metals, it is necessary to use a pyrometer with a short wavelength where a metallic object emits sufficient heat radiation. For physical reasons, the lowest detectable temperature increases with shorter wavelengths. Analysable measuring signals can be obtained with devices with a wavelength of 2.8 μm, beginning at approximately 50 °C when the radiation detector in the pyrometer is kept at approximately 25 °C.

Measuring procedure

So far, often pyrometers are equipped with a photoelectric PbS sensor with a short wavelength of 2.4 μ are used for direct measurements of metals at low temperatures. These sensors have a high sensitivity. A disadvantage is that PbS sensors are drifting up to 4 % for each °C of intrinsic temperature change of the sensor. To get a stable measuring signal at all, the sensors have to work according to the in chopped radiation method. This means that a disc is rotating in front of the sensor. The disc has a reflecting surface and an opening. When the disc is rotating, the sensor alternately captures the object radiation through the opening and the reflected internal radiation of a reference surface with a known temperature. When components are continuously rotating in a measuring device the question arises as to the work life and the maintenance that will be necessary, particularly when the devices operate in a rough industrial production area with high ambient temperatures.

Another disadvantage of the chopped radiation method is that the response times of the devices tend to be longer. This sets a limit to the applications where measurements at fast moving objects are required.

Another option for measuring metals at low temperatures is a measuring device with thermopile sensor with a wavelength of 8 – 14 μm which is designed without moving parts (continuous-wave sensor). Thermal radiation detectors, however, have a lower radiation sensitivity compared to photoelectric detectors. Therefore, high signal amplification is necessary which, in turn, requires more time for signal processing to reduce the signal noise sufficiently to get a stable measuring signal. This again restricts its use for measurements at fast moving objects. Due to the low signal, pyrometers with thermopile sensor are more sensitively to short-term variations of the ambient temperature. When, on top of that, the sensor heads are small and have a low mass, sensitive thermal shock behaviour leads to significant overshooting of the displayed measured value, e.g. in production plants where the warm object is periodically detected by a pyrometer. This influence can only be minimised by complex compensation measures.

In order to compensate for ambient temperature influences and to improve the stability of the measuring signal, the chopped radiation method is to some extent used for pyrometers with longwave thermal radiation detectors too. At low radiation intensities, these pyrometers manifest, for physical reasons, a larger noise level than shortwave devices. As a consequence, the measured value may quite vary at the range beginning by up to 20 °C for short measuring time. One certainly cannot call this a precision measuring instrument anymore.

Another often employed method to raise the signal level is to use an optical system with low resolution to increase the measuring area of the heat radiation captured by the sensor. These devices are only of limited use for measurements of small objects or when measuring from a large distance.

A larger lens at the pyrometer would considerably increase the amount of radiation received. However, this would require high-quality precision lenses to keep the optical aberration at a low level. Instead, a number of these devices are equipped with a simple fixed-focus lens operating with a short focal distance. To reduce optical measuring errors, the devices would have to be installed exactly at the specified focal distance f for small targets. Even when the measuring distance only deviates from the focal point by a couple of millimetres, the diameter of the measurement area increases disproportionately. The pyrometer then risks detecting the cool background radiation outside the target object which will display a too low temperature (**Fig. 3**). A pyrometer with a fixed-focus lens therefore limits the flexibility to choose the place of installation and the measuring distance.

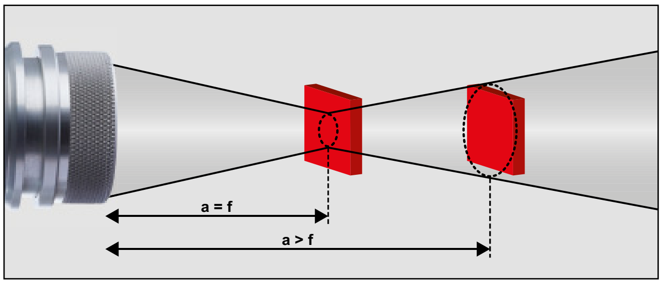

Fig. 3 *The measuring distance a must comply with the focal distance f of the pyrometer to avoid wrong measurements.*

When selecting your pyrometer, special attention should be paid to technical specifications such as response time, measurement method, temperature coefficients, optical resolution, temperature resolution and the NETD (noise equivalent temperature difference) to compare these values in detail. Unfortunately the technical data are not always specified in the manufacturers' documents. It is advisable to ask the manufacture for detailed specifications to avoid unpleasant surprises when the pyrometer is already in use.

Alternative measuring methods

One way, however, to measure the temperature of a coil of metal in a strip coating plant with a longwave pyrometer is to measure the temperature in the gap between the coil and the guiding roller. The multiple reflection of the heat radiation has the same effect as an increase in the emissivity (**Fig. 4**).

To install the devices at a safe distance and still to be able to measure into the narrow coil gap, requires instruments with a high optical resolution and a parallax-free sighting device (laser

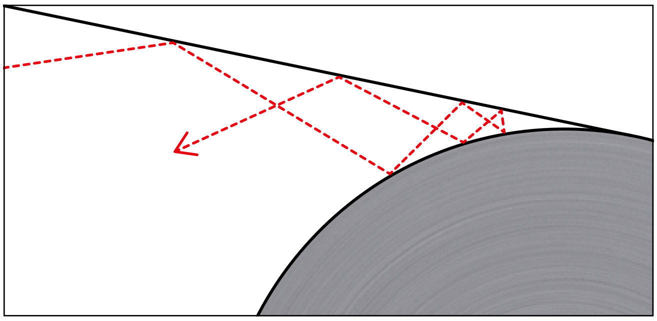

Fig. 4 *Multiple reflection of the radiation between the sheet and the roller.*

spot light, through-the-lens-sighting or video camera) for optimal adjustment. When measuring the coil at the coiler of a strip coating line, the position of the gap varies depending on the diameter of the coil. Accurate readings are obtained with an oscillating mirror in front of the pyrometer which periodically deflects the measurement area (**Fig. 5**). The maximum temperature value is determined for each scan. The gap measuring method is successfully used, however, some efforts are necessary to install the pyrometer and the method is restricted to specific measuring positions in the production plant.

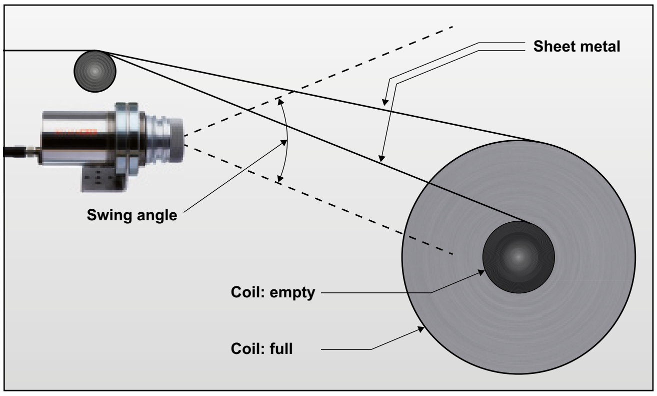

Fig. 5 *Position of the roller gap at the coiler shifts in relation to the coil diameter.*

Another measurement solution uses a hemispherical gold mirror. The position of the mirror is such that the metal coil is situated in the centre of the curvature of the mirror. Here again, the multiple reflection causes a signal increase. This solution, however, has a restriction as the measuring distance to the coil is very low and must therefore be strictly kept. This measuring method also works only in a satisfactory way as long as the mirror remains clean. In addition, the rough industrial conditions may damage the reflecting, usually gold-covered surface. Therefore, the successful use of this method often fails because of its practical feasibility.

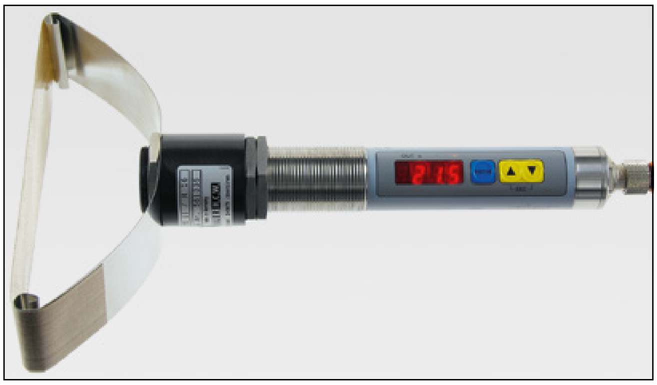

Fig. 6 *Bow with a Teflon tape to measure shiny rollers.*

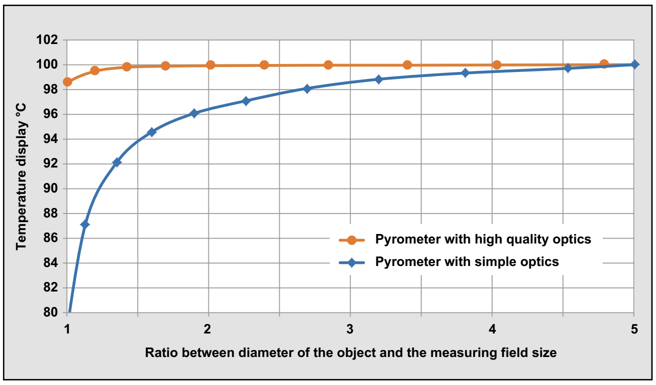

Fig. 7 *Changing temperature readings when the object size changes.*

A further method to measure temperatures of shiny metal rollers is an indirect pyrometric method which uses an emissivity enhancer. For this purpose, a Teflon tape on an elastic bow is mounted in front of the pyrometer (**Fig. 6**). The Teflon tape is pressed on the roller. The pyrometer detects the radiation on the rear side of the tape which has a high emissivity. Disadvantageous is the mechanical complexity of the assembly and the wear of the Teflon tape.

Latest technological developments

It would be preferable to have pyrometers that can be installed easily and without efforts at any place in the production plant and that can read the temperature of the measured object from a safe distance. This however implies that the devices are capable of detecting and evaluating a very low infrared radiation signal.

This again requires a complex optical system to detect sufficient energy radiated from the measured objet and to transmit it to the sensor. The larger the entrance aperture of the optical system, the more radiant energy will be gathered. Nevertheless, with an increasing diameter of the optical components it is becoming more complex to reduce optical aberrations. High-quality lenses and a complex mechanical structure of the optical system is necessary to minimise aberration errors respectively minimize the dependence of the readings from the measuring distance and from the size of the measured object. This dependence is called size-of-source effect (SSE). The graph (**Fig. 7**) shows the SSE curves for two devices with optics differing in quality and their readings in relation to the object size and the size of the measurement area. The device with a simple optical system needs a measuring object that is more than 2.5 times greater than the measurement area of the pyrometer to keep the measurement error under 2 %.

A highly luminous optical system with a large entrance aperture is again associated with lower field depth. To avoid reading errors caused by a blurred image it is imperative to keep the exact focal distance during installation. The best option would be devices with a focusable optical system. Compared to pyrometers with a fixed focus they are flexible and easily adaptable to the existing assembly conditions.

Fig. 8
Continuous-wave sensor pyrometers to measure temperatures from 75 °C upwards.

A quite elaborate electronic evaluation unit is needed to amplify and interpret the small measuring signals and to compensate for environmental temperature influences. Low noise amplifiers, high-resolution A/D converters, high-capacity processors for signal processing and complex mathematical algorithms for linearization and compensation of the ambient temperature are necessary to achieve stable and reliable measuring results from 75 °C upwards (**Fig. 8**) with modern short-wave continuous-wave sensor devices The devices measure within milliseconds and are therefore also suitable for fast-moving objects. A high optical resolution facilitates measurements from a far distance or of objects as small as 2 mm, e.g. in the field of inductive heat treatment or wire manufacturing.

Not only stationary pyrometers are offered with this technology but also portable pyrometers with a main wavelength of 2.4 μm for easy and fast temperature checks at various measuring points are available.

General requirements for measuring low temperatures at metallic objects

A direct measurement underlies the restriction that the object temperature must be at least 25 °C above the internal device temperature to obtain an interpretable radiation value. A rising ambient temperature and a lower emissivity increase the minimum temperature needed for measurements (**Fig. 9**). Some of the manufacturers refer to a black body with 100 % emissivity when defining the range beginning; others do not state the general conditions at all. When measuring real objects with a low emissivity, the minimum measurable temperature then lies distinctly above the specified value. As an example figure 9 shows that the range beginning increases to 125 °C for an object with an emissivity of 10 % and an ambient temperature of 50 °C.

Nevertheless, for a reliable measurement of low temperatures at bright metals it is necessary that the measuring point is shadowed from any external radiation. Compared to the low heat radiation of the measured object, normal daylight already emits a percentage of interfering radiation in the infrared range of the pyrometer. Very often it is therefore unavoidable to use a sight tube. However, a simple sight tube is only suitable to a limited degree as the tube itself can act as a radiation source. The sight tube must be cooler than the measuring object and it must consist of a low-radiating material such as stainless steel or aluminium. The diameter of the tube must be at least 6 times larger than the distance from the tube end to the measuring object to reach sufficient shadowing.

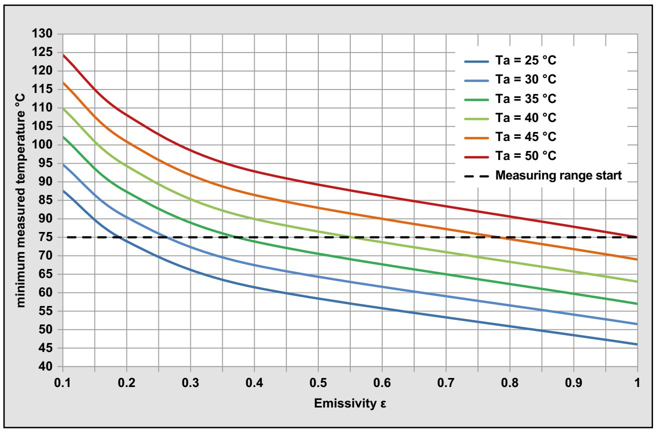

Fig. 9 *Minimum measuring temperature in relation to ambient temperature Ta and emissivity.*

Conclusion

A stable and maintenance-free measurement of low temperatures of metals is possible with modern continuous-wave sensor pyrometers possessing a high luminously intense lens, a modern sensor and electronic unit. However, this only works in a satisfactory manner when considering the basic conditions for the selection of the measuring point and the mounting accessories. In the end, however, the stability of the measurement reading is determined by the physical properties of the measuring surface.

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