Optical metrological errors in non-contact temperature measurement applications

by Albert Book

Radiation thermometry uses optical measurements for a non-contact determination of object temperatures. Error analyses for this measuring method must therefore also take optical measuring errors into consideration. It is often the optical system that makes the difference between radiation thermometers. The specifications given in the manufacturers' data sheets are often insufficient and difficult for users to compare. The following article explains the basics, specifications and practical effects of optical aberrations. Methods are presented how the user himself can check the quality of the optical system of the selected radiation thermometer.

Definition of measurement uncertainty with radiation thermometers

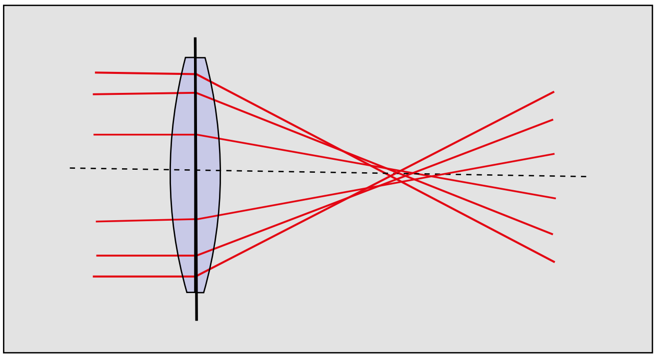
When speaking of measuring errors we are referring to a deviation from a reference value. The technical standards use the term "measuring uncertainty" to state a measuring error. The measuring uncertainty is a parameter that indicates the quality of the measurement. This parameter is indicated together with the measuring range. The measuring uncertainty is an unsigned value. The very common term "measuring certainty" is a qualitative value and defines the approximation of the measurement reading to the true value. Therefore, this term should not be used with figures.

The measuring uncertainty is given as a relative value in relation to the reference value. When measuring temperatures, a difference is correctly specified in Kelvin [K] and not in degrees Celsius [°C]. An indication such as ± 5 K or Δ 5 K would perhaps be easier to understand, but would not be correct according to the applied standard. Some manufacturers indicate the reference temperature in Kelvin instead of degrees Celsius to show a smaller value for the measuring uncertainty. An indication such as "1% of the measured reading in K", for example, results in a measuring uncertainty of 3.73 K at a temperature of 100 °C. The conversion from degrees Celsius to Kelvin requires the addition of a value of 273 (1 % of (100 + 273)K = 3.73 K). Putting this measuring uncertainty in relation to degrees Celsius, however, will result in a value of "3.73 % of the measurement reading in °C".

One advantage of non-contact temperature measurements is the potentially short measuring time in the millisecond range. Even so, depending on the device used, the measuring time is often not a constant. At low temperatures, that is at low heat radiation, the measuring time can be several times longer than at higher temperatures. Some manufacturers therefore relate the measurement uncertainty to a long measuring time to be able to show a better value.

Basics of optical measuring errors

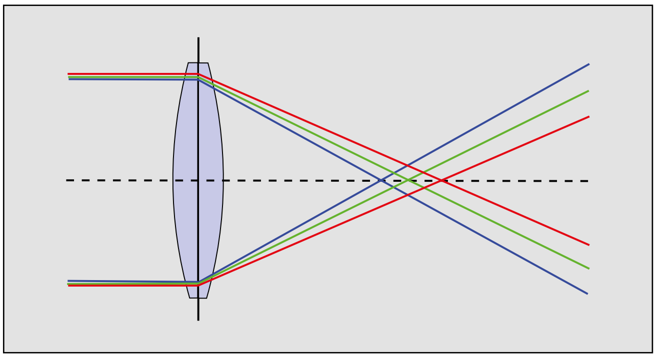
In optics, the term “aberration” is used to describe the imperfections of lenses which produce a distorted image. Aberrations on the optical axis are mainly spherical aberrations and chromatic aberrations. In addition, the size-of-source effect and transmission properties of the lens are to be considered for optical error analysis.



Picture 1 *The rays at the edge are refracted more, thus the focal point of simple lenses is shorter.*

Spherical aberration

Incident light rays or infrared rays at the edge of a convex lens parallel to the optical axis are refracted at a shorter distance than incident light rays close to the optical axis (**picture 1**), i.e., the focal distance is slightly different. The result is a blurred image. Spherical aberration can be significantly reduced by combining several lenses with different radii and by using glass types with a high refractive index.

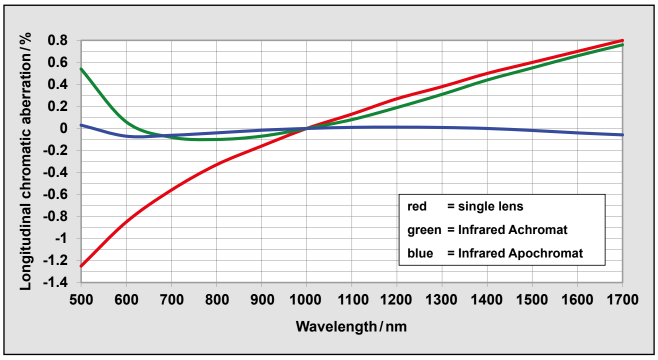


Picture 2 *Short-wave rays are refracted more, thus the focal point is shorter.*

Chromatic aberration

The focal distance of a lens also depends on the wavelength. Short-wave rays are refracted more and have a shorter focal point than long-wave rays (**picture 2**). The image of such an object appears with a rainbow-coloured halo.

Chromatic aberration can be largely reduced by using optical systems that are already corrected for two wavelengths (achromat) or three wavelengths (apochromat). The material for the lenses is selected to mutually compensate for chromatic aberrations of the lenses for two or three wavelengths (**picture 3**).



Picture 3 *Comparison of a chromatic aberration of lenses with different corrections.*

Size-of-Source-Effect

The output signal of a radiation thermometer also depends on the size of the target. This influence is known as size-of-source-effect (SSE).

The SSE is caused by stray light reflected from the optical components, by radiation reflected from the enclosure surrounding the optical path and by diffraction at the diaphragm apertures. Aberrations of the optical system also have an impact on the SSE. The SSE describes how much radiation reaches the sensor from outside the target spot. The complete optical assembly, consisting of the objective lens and the diaphragms, is crucial for the magnitude of the size-of-source effect on a radiation thermometer.

The radiation thermometer is placed in front of a thermally stable furnace to determine the SSE curve. The diameter of the furnace opening must be distinctly larger than the target spot of the radiation thermometer (**picture 4**).

Picture 4 *Determining the optical properties of a radiation thermometer.*

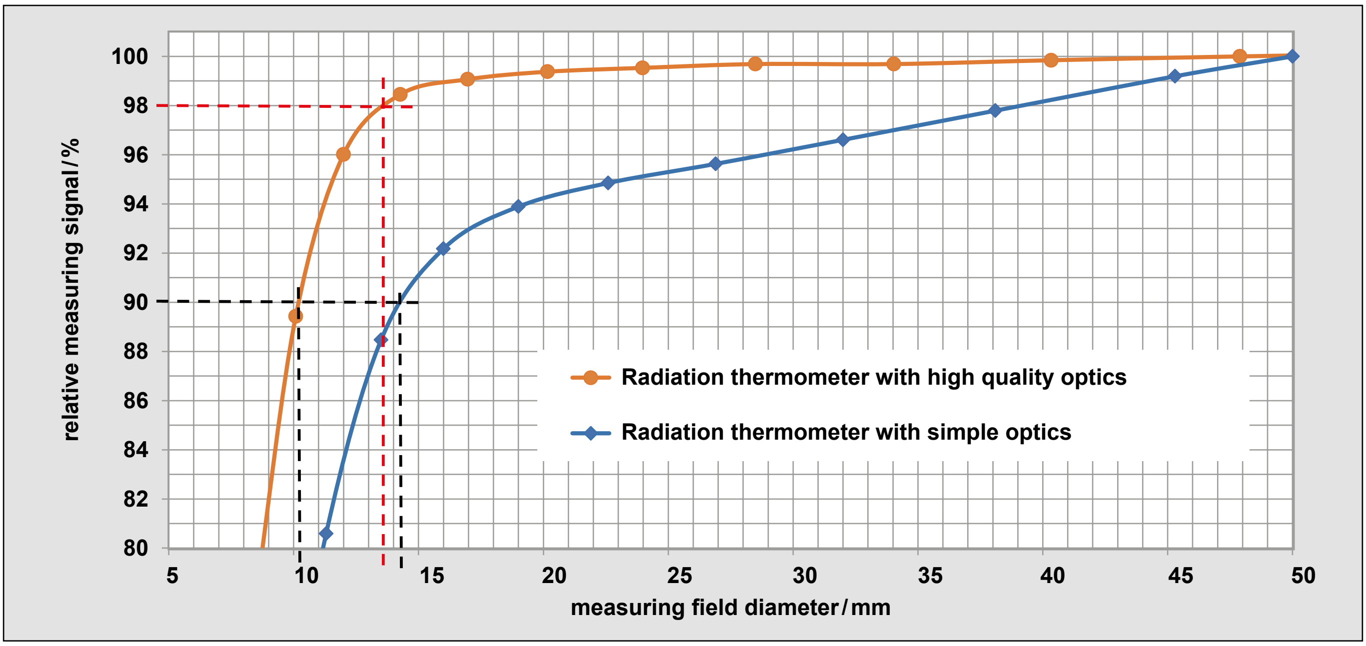
Place an open iris diaphragm with variable aperture between furnace and thermometer, spaced at the thermometer's focal distance. Increase the aperture diameter and determine the signal received from the radiation thermometer. In order to show a curve independent of the furnace temperature, the signal strength is indicated as a relative magnitude in relation to the maximum receivable energy.

Picture 5 shows two typical SSE curves of radiation thermometers with different optical properties.

Based on a relative measurement signal of 90%, the curves show a target spot diameter of 10.2 mm for the high-quality lens and 14.4 mm for the basic quality lens. If the target spot were specified for 98% for the device with the high-quality lens, the target spot diameter would have to be 13.5 mm. Data sheets based on different reference values suggest a nearly identical good optical resolution for the two devices. Data sheet specifications for optical systems are therefore not directly comparable in all aspects. The reference values may differ or are not even specified. Manufacturers of devices with poor optical properties use reference values that make the values in the data sheet apparently comparable to the high-quality devices.

For several years now, the VDI/VDE Society of Measurement and Automatic Control's technical committee FA 2.51 "radiation thermometry" is seeking a uniform definition and reference value for optical specifications by including the SSE curve in its preparation of the German guideline VDI 3511 Page 4.1. The VDI 3511 guideline page 4.3 describes test methods for checking basic specifications of radiation thermometers. Since 2008, the international guideline IEC/TS 62942-1 for the specification of radiation thermometers applies, which originated from the VDI 3511. It would be desirable if all manufacturers regarded this directive as a common basis. Finally, the optical properties of the devices would be comparable.

The VDI/VDE guideline 3511 sheet 4.1 recommends, on the basis of the SSE curve, specifying the target spot diameter where the signal has dropped to a defined part of its maximum



Picture 5 *Comparison of SSE curves of two optical systems with different properties.*

value. Common values are 90 %, 95 % or 98 %. The maximum value is the reading produced by a hemispherical radiation source (half-space).

Influence of size and transmission of the lens

Another quality factor is the amount of infrared radiation coming through the lens to the sensor. The transmitted radiation energy increases with the square of the free lens diameter.

The larger the amount of radiation received, the better the temperature resolution, i.e. the noise equivalent temperature difference NETD. It indicates the contribution to measuring uncertainty in Kelvin that is due to instrument noise.

A large and effective lens diameter is necessary to transmit sufficient energy to the sensor for an adequate signal evaluation especially for low temperatures, small measuring objects and large measuring distances. This sets high expectations for an optical system, as the spherical aberration increases with the lens diameter. Such a device with a small SSE can only be manufactured using elaborately corrected lenses and several diaphragms.

Material and coating of the lens also are a decisive factor for the amount of infrared radiation reaching the sensor. Low-cost devices are equipped with simple pressed plastic lenses without coating. Conversely, a high-quality glass lens with a special anti-reflective coating has significantly reduced transmission losses.

It is certainly interesting when manufacturers advertise that they have the world's smallest sensor head. Small sensor heads with simple lenses, however, transmit a significantly lower signal to the sensor. This has an adverse effect on the temperature resolution. To compensate for this, the target spot must become distinctly larger which, in return, results in a lower optical resolution.

Simple two-component devices with a separate small electronic sensor head very often suffer from changing temperature readings when moving the connecting cable between the sensor head and the electronic part because their signal exploitation is very poor at low object temperatures.

All these optical influences together ultimately show that the measured temperature is more or less dependent on the target size and the distance to the target. This can easily be verified. The radiation thermometer has to be placed in front of a homogeneous hot target, spaced at its focal distance. The distance to the target is then reduced or increased and the displayed temperature was checked.

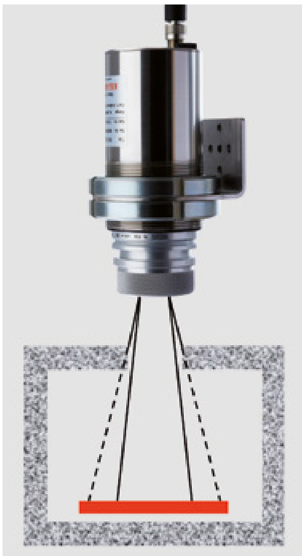
A laboratory test determined the deviation of two devices at a furnace temperature of 280 °C. When increasing the distance to the target from 150 mm to 300 mm, the temperature reading of a high-quality device only changed by 2 K. The temperature reading displayed on the low-cost device dropped by 38 °C.

Practical effects of optical measurement errors

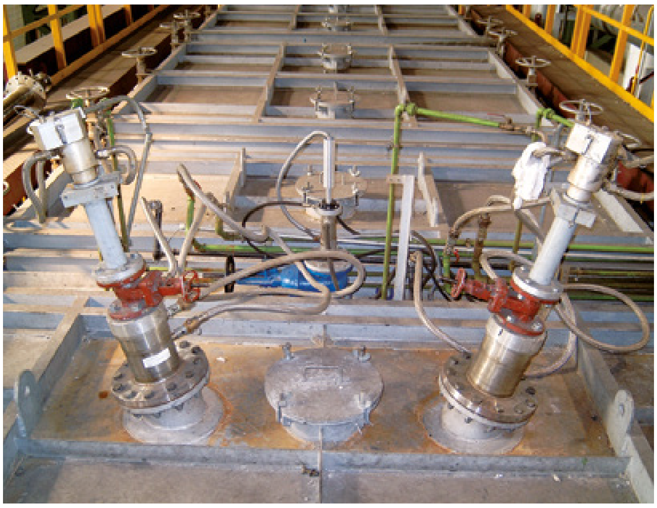
Under real conditions it often occurs that the focal distance of radiation thermometers is not correctly adjusted. The focal distance of simple devices is fixed and cannot be adjusted. On the other hand, the design of the machine or plant to be measured dictates the distance to the target. It is often observed during service operations that, even with focusable devices, the distance to the target was incorrectly set. A wrong focal distance can lead to significant measurement errors.

Radiation thermometers are used in numerous applications to capture targets within a furnace. The radiation thermometer then measures the target object through a furnace aperture. Devices with a poor optical resolution or a poor SSE then may have a cone of vision constricted by the furnace aperture (**picture 6**).

When measuring through with thick-walled furnace openings it is crucial to choose the correct focal distance and to ensure that the cone of vision of the radiation thermometer is distinctly smaller than the minimum aperture diameter. Otherwise, the device is very difficult to adjust and it might happen that the radiation thermometer captures a part of the colder furnace wall. A spectral pyrometer then always displays a too low temperature.



Picture 6 *Constricted cone of vision when the optical resolution is poor.*



Picture 7 *Though measuring the same target, the devices showed large temperature differences due to wrong focal adjustment.*

Picture 7 shows that, although the two radiation thermometers measure the same spot of the strip through a water-cooled sighting tube, a falsely adjusted focal distance resulted in a reading difference of 23 °C at a strip temperature of 850 °C.

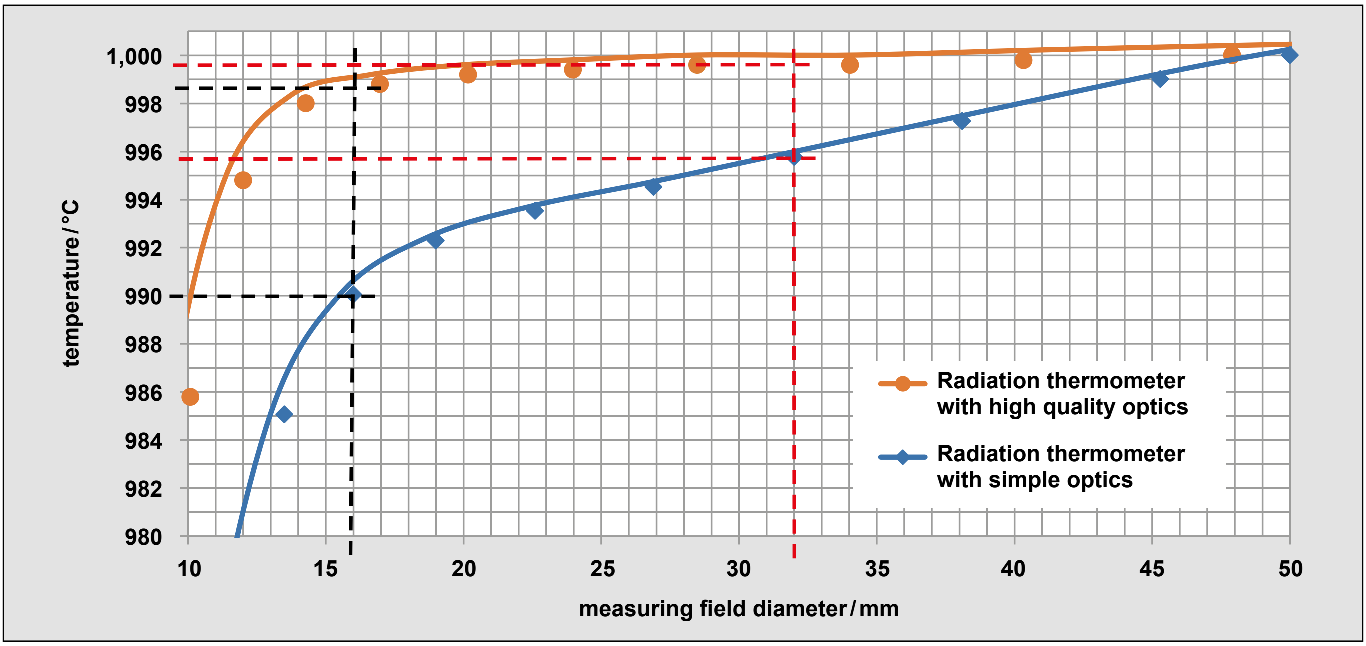
An erroneous measurement is often not even noticed in furnace applications when not using a parallax-free through-the-lens sighting device or a video camera showing the exact focal adjustment and target size.

It is particularly precarious to use fixed focus radiation thermometers for furnace measurements where several devices are needed and where the furnace geometry dictates different distances to the target. The devices show identical readings in a calibration laboratory in front of a “black body”. Under industrial furnace conditions devices susceptible to a large size-of-source-effect may show considerable temperature differences in relation to each other, not permitting a kiln control program working with narrow temperature spans. Exchanging the thermometers under thermally stable operating conditions and comparing the temperature readings is a practical method to verify if the devices work correctly.

There are also numerous applications, e.g. in induction heating systems where the target is small or the field of view of the pyrometer is only slightly larger than the target. Important metrological errors may arise when using thermometers susceptible to a large size-of-source effect or when the focal distance is incorrectly set. An extremely critical situation may develop when differently sized goods are produced within one plant.

The graph (**picture 8**) the SSE curves for two thermometers (high-quality and basic quality) at a reference temperature of 1000 °C.

The curves illustrate the effects on the temperature when the target size changes. If, for example, the target diameter is doubled in size from 16 mm to 32 mm, the temperature reading



Picture 8 *Effects of a changing target size on the temperature.*

of a thermometer with a high-quality optical system changes from 998.7 °C to 999.7 °C; i.e a rise of only 0.9 K, whereas the radiation thermometer with a simple optical system shows an increase from 990 °C to 995.9 °C, i.e. 6 K.

In relation to the true temperature of 1000 °C and with a target diameter of 16 mm, the high-quality thermometer produces a metrological error of 1.2 °C. The device with a simple optical system deviates from the true temperature by 10 °C. That means that the SSE alone produces a measuring uncertainty of 1 % for the basic device.

Conclusion

From a practical perspective, the difference in quality and the measuring uncertainty of radiation thermometers is far less determined by the electric measuring uncertainty but to a greater extent by the quality of the optical system. It is therefore recommendable to especially check and compare the optical characteristics when selecting radiation thermometers. As the manufacturers' data sheets often provide little information in this respect, it is advisable to ask for additional information in the form of a size-of-source effect curve. Owing to the size-of-source effect, low-cost handheld devices with a plastic lens cannot be expected to produce sophisticated measuring accuracies. Stationary instruments with a small sensor head have physical limits to their measuring accuracy owing to poor signal exploitation. When selecting radiation thermometers, the user should very carefully consider which measuring uncertainty he wants to accept. In case of doubt, the user should check the radiation thermometers using the methods described above to get a true picture of their quality before initial setup of the devices.

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