Optical influences on non-contact temperature measurements

by Albert Book

Non-contact temperature measurements are based on an optical measuring procedure. In this context, the optical properties of a pyrometer have a big and often underestimated influence on the measuring accuracy. Often only electrical errors specified in the data sheet are compared when checking the measurement uncertainty. However, simple or improperly selected or incorrectly adjusted lens systems may cause very grave measurement errors. The following report explains the principles and effects of optical aberrations and specifications of optical parameters of pyrometers. This paper will explain how the users can themselves check the quality of the pyrometer's lens system.

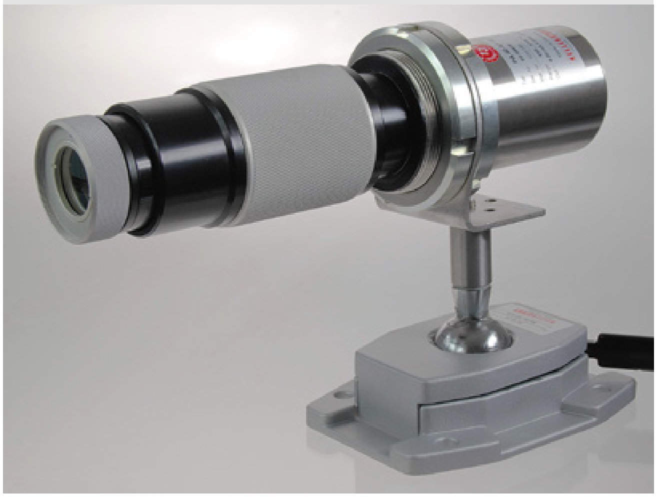

Fig. 1 *CellaTemp PA pyrometer with high-resolution precision lens system.*

Optical aberrations

Spherical aberration (opening error)

Incident light rays close to the edge of a lens are refracted at a shorter distance than incident light rays close to the centre. The result is a slightly blurred image. Spherical aberration in optical systems consisting of several lenses can be reduced by suitably combining multiple lens surfaces.

Chromatic aberration (longitudinal-chromatic-aberration)

The focal distance of a lens also depends on the wavelength. Light or radiation of different wavelengths is focused at different points. The image of an object then appears with coloured rings around the image. Chromatic aberration can be largely reduced by using optical systems that have an integrated correction for two wavelengths (achromat) or three wavelengths (apochromat) (**Fig. 2**). The material of the lenses is selected to mutually compensates the chromatic lens aberrations at two or three wavelengths.

Optical specification of pyrometers

Either the target spot size for a certain distance or the distance ratio, i.e. the ratio of measuring distance to diameter of the measurement area, are indicated to specify the optical system.

The target spot size of pyrometers relates to a fixed percentage of the maximum energy that can be received in a half-space. 100% corresponds to an infinitely large target object. The target spot size typically relates to 90, 95 or 98% of the maximum detectable energy (**Fig. 3**).

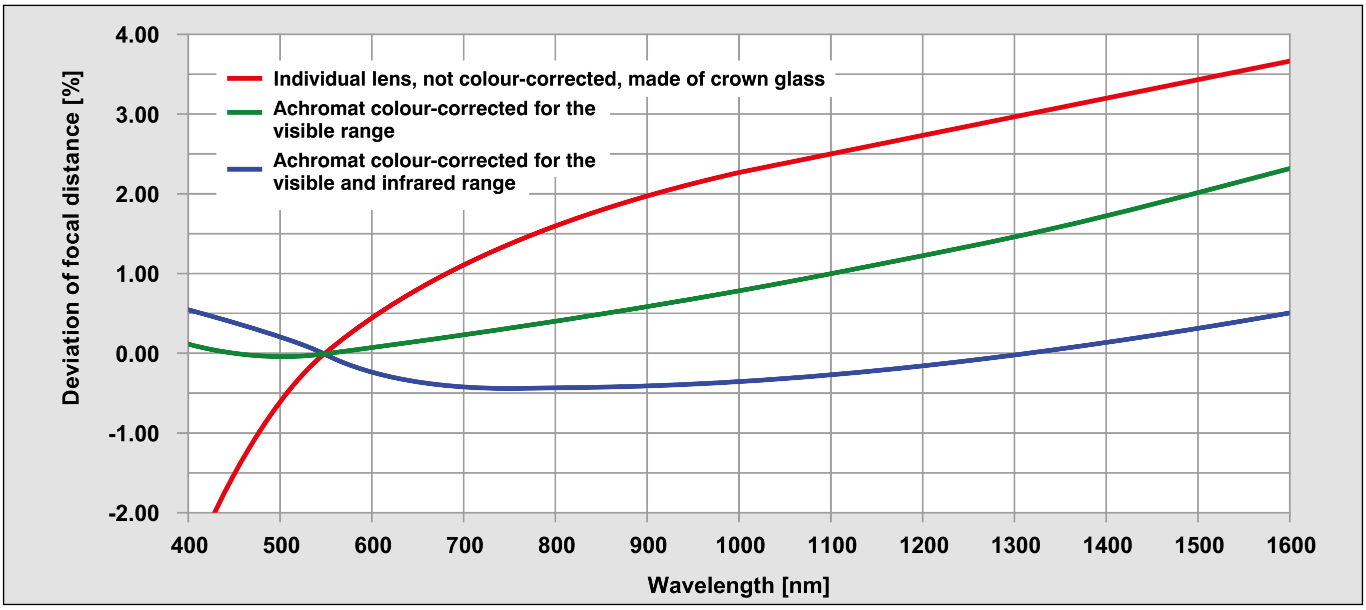

Fig. 2 *Focal deviation due to longitudinal chromatic aberration for uncorrected and colour-corrected lenses.*

The measurement area increases when the proportion of radiation relates to 95 % instead of 90 %. Therefore, data for the size of the measurement area can only be compared when they refer to the same percentage. Some manufacturers do not indicate the amount of radiation in per cent or they define only a lower percentage. By doing so, they simulate a very small measurement area in their data sheets, being fully aware that another definition would result in a significantly higher value. In addition. some manufacturers specify the size of the measurement area without considering lens tolerances.

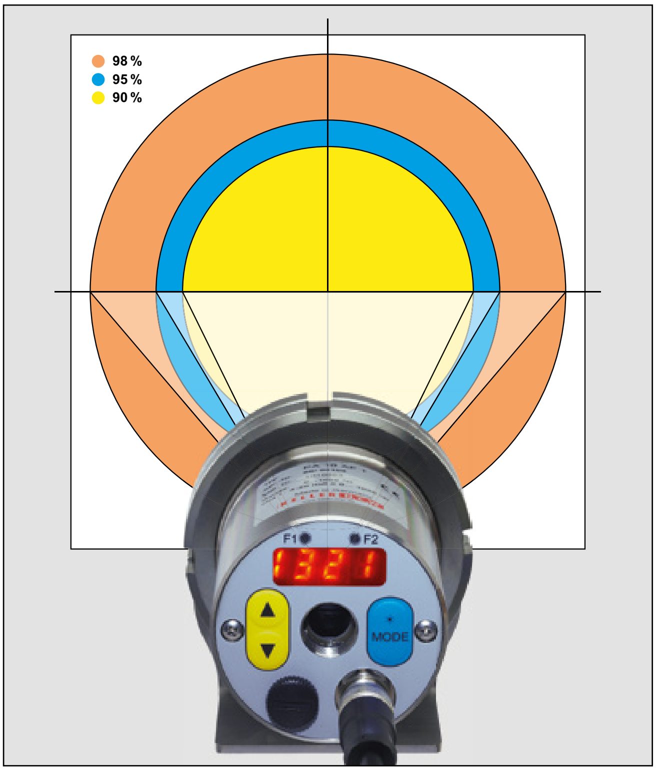

Fig. 3 *Measurement area sizes relating to 90, 95 and 98 % of the maximum receivable energy.*

Effects of optical errors

Pyrometers are distinguished either by a focusable optical system or a fixed focus system. Only the correctly adjusted focal distance provides a sharp picture of the measurement area. A homogeneous distribution of the infrared radiation on the sensor is not guaranteed anymore when the pyrometer is used outside of its focal range (**Fig. 4**).

The radiation received across the measurement area is then unequally detected. Temperature variations have a stronger effect in the centre than at the edge of the measurement area.

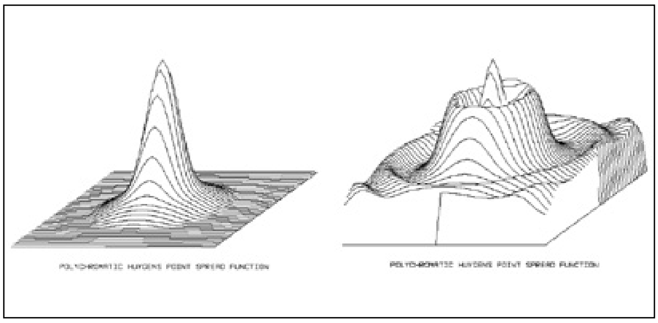

Fig. 4 *Comparison of the intensity distribution with correct and incorrect focal adjustment.*

This affects in particular the calibration of the pyrometer in front of a "black body". The opening of the furnace must be several times larger than the measurement area of the pyrometer. Devices with basic-quality lens systems and a large measurement area must use an extremely large-scale radiation body as a calibration source to reduce the measurement errors that may arise during calibration. This is one of the fundamental sources and rather high measurement uncertainty of low-cost, low quality devices.

A wrong focal adjustment may lead to serious measuring errors especially with small objects that are only slightly larger than the measurement area of the pyrometer. Although the pyrometer looks through openings, inspection glasses, kiln walls or sighing tubes on the target, a poorly adapted lens system or a wrong focal adjustment may well lead to a constricted cone of vision and thus to wrong measurements. When measuring targets that are significantly larger than the measurement area of the pyrometer, devices with a basic-quality lens system will change the displayed temperature when the target size or the distance to the target changes. **Fig. 5** compares the lower reading for a high-quality and a basic-quality lens system in relation to the target diameter. The reading significantly drops with the basic-quality lens system when the target size is changing. The same effect arises when the distancesor the target size change. This means that devices with a basic-quality lens system show other readings when the distance to the target varies. This source of error must be taken into consideration especially with small hand-held devices which are often used at various distances. This effect is called Size-of-Source Effect (SSE) and is a more or less relevant source of errors with all pyrometers. The causes are optical aberrations, stray light and reflections at optical components and parts of the casing as well as diffractions by the wave character of light. The size-of-source effect is reduced as the measurement wavelength gets shorter. This effect can be minimised by carefully correcting the optical aberrations or by using non-reflecting optical components and by avoiding stray light or by avoiding reflections within the device. In practical applications, the user can minimise this error by an exact focal adjustment to the correct measuring distance.

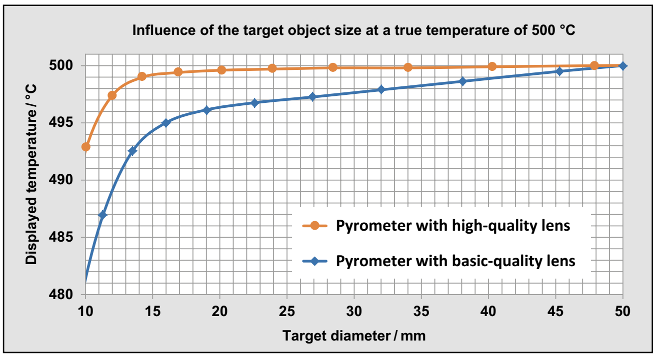

Fig. 5 *Comparison of low readings for a high-quality and a basic-quality lens system.*

Depending on the temperature, the infrared radiation emitted by a target lies within the range of wavelengths from 0.6 to 20 μm, which is in most cases above the visible light. First of all, this means that the lens systems have to be corrected with reference to the used wavelength range of the pyrometer. When the user wants to set the focal range visually or when the devices are equipped with a video camera as a sighting aid, the optical systems have to be designed to provide an equal correction of the optical aberration both for the visible and for the infrared wavelength range. Simple devices use lenses without colour correction or correction only for one wavelength. In this case, the focal points of the infrared and the visible radiation do not match (**Fig. 2**). If the pyrometer is correctly and sharply adjusted using the sighing aid, it is not optimally adjusted for infrared radiation.

The laser spot indicates the focus point the visible spectrum. For basic-quality lens systems, this position does not match with the focus point in the infrared spectrum.

Only optically elaborate achromat lenses or apochromat lenses eliminate these errors to a large extent. The pyrometers of the CellaTemp® PA series, for example, are equipped with a high-quality precision broadband and non-reflecting lens system.

This system even lets you correctly capture the temperature of wires with a diameter of only 0.3 mm.

Checking the imaging qualities

The size of the radiation surface should be several times larger than the measurement area of the pyrometer. Now an opened iris diaphragm in the focal distance (a) of the pyrometer is positioned in front of the radiation source and the pyrometer determines the temperature at an emissivity setting of ε = 1 (**Fig. 6**). A measurement near the range end is recommended, as optical reading errors become more visible at higher temperatures. Now set the emissivity on the pyrometer to 0.98 which leads to an increase of the temperature display.

Then slowly close the aperture of the iris diaphragm until the displayed temperature is again equal to the originally displayed

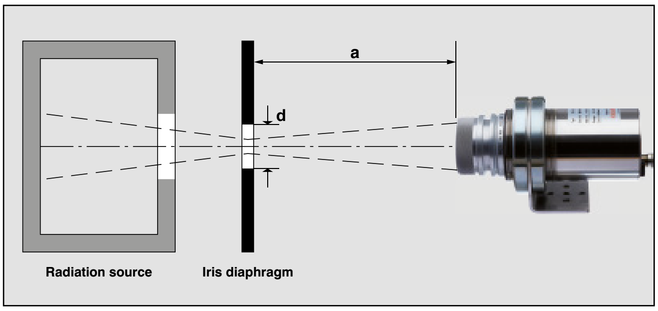

Fig. 6 *Arrangement to check optical properties.*

value. The aperture diameter of the iris diaphragm then corresponds to the size of the measurement area based on 98 % of the radiation energy. The ratio to the measuring distance results in the distance ratio $D = \frac{a}{d}$. This measurement has to be repeated for a measurement area size of 95 % and 90 %. The result can be compared with the indications in the data sheets of pyrometer manufacturers.

This is a very simple way to check and to compare the real optical imaging properties including the effects of lens errors for various devices.

Fig. 7, for example, shows the target diameters for 90 % and 95 % of the radiation energy. With reference to 90 %, the differences in the measurement area sizes are still relatively small with Ø 14 mm for the basic-quality lens system and Ø 10.2 for the high-quality one. But with 95 % (Ø 24 mm for the basic-quality and Ø 11.5 mm for the high-quality lens system) the indications are already quite different. To be able state a better (smaller) value for the measurement area diameter, some manufacturers prefer to specify the value for a lower radiation reference value (e.g. 90 %). This makes the basic-quality lens apparently better than it is in reality.

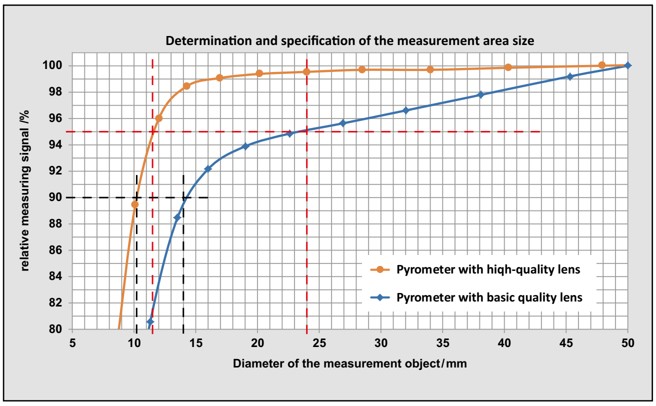

Fig. 7 *Comparision of the target diameters for 90 % and 95 % of the radiation energy for a high-quality and for a basic-quality lens system.*

Making the test with pyrometers with spot light, video camera or through-the-lens-sighting reveals at the same time whether the distance of focal point to target area and from the field of view is identical and whether the target marker actually matches with the position and size of the measurement area of the pyrometer.

Conclusion

It is recommendable to especially check and compare the optical characteristics and not only the measurement parameters when selecting pyrometers. Unfortunately, as the specifications in the data sheets of some manufacturers are insufficient, it is advisable to ask for detailed information on how the measurement area was determined and whether lens errors and alignment tolerances were taken into consideration for the specifications. Only identical optical indications and reference values enable the user to really compare different pyrometers. In case of doubt, the user should check the quality and specifications given in the data sheets himself using the methods described above. After all, what is the point of buying a pyrometer with a specified electric measuring uncertainty of far below 1 % when basic-quality lenses and a simple lens arrangement lead to significantly larger reading errors.

Author

Dipl.-Ing. Albert Book
KELLER HCW GmbH · Germany
Infrared Thermometer Solutions
Phone +49 54 51 85 320
albert.book@keller-msr.de
www.keller-msr.com/pyrometer

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Keller HCW GmbH
Infrared Temperature Solutions (ITS)
Carl-Keller-Straße 2 - 10
49479 Ibbenbüren-Laggenbeck
Germany

www.keller.de/its
Tel. +49 (0) 5451 850
Fax +49 (0) 5451 85412
its@keller.de

Distributor

KROHNE INOR

INOR Transmitter Oy
Unikkotie 13
FI-01300 Vantaa
Puhelin +358 10 4217900
Faksi +358 10 4217901
myynti@inor.fi