IR Calibration basics

1. Introduction to Infrared temperature measurement

This script is meant as a handbook for persons involved in temperature measurement based on infrared emission. The information is part of the knowledge base, on which the JOFRA ETC-400 R infrared temperature calibrator was built. However, most of the information is for general purpose and should therefore be useful for most persons working with any kind of IR systems. We would like to share our knowledge to give you an easy start, better understanding, more accurate measurements, and reliable calibrations. Please note that the material does not cover all details completely, so you need to consult other sources if you are looking for very narrow and specific information. Comments are more than welcome, please mail to ametek@ametek.dk.

The information contained in this paper, has been obtained through interviews with Sønnik Clausen / RISØ Research Centre, Denmark, and from various literature (cf. the literature list). Wherever possible references are made to the source.

2. Thermal radiation

When radiation thermometers are used for temperature measurement, you take advantage of the fact that all objects whatever the material and character radiate (emit) infrared light as soon as their temperature is above the absolute zero point (-273°C). When measuring the intensity of this radiation, you can calculate the temperature of the object.

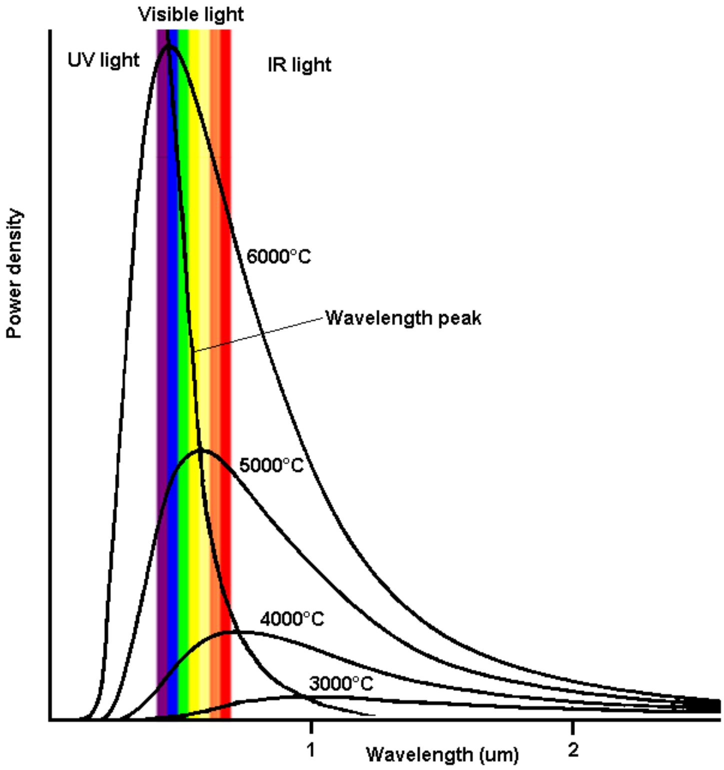
Thermal radiation is light distributed in a wide wavelength band, which is mostly invisible to the human eye. This is due to the fact that the wavelength is too long to be seen of human eyes. The radiation can be felt at our skin - as a sense of heat. At temperatures above 600°C parts of the radiation emitted will start to be visible (glow).

Thermal radiation arises from the atoms of which an object consists as the atom speed raises as a function of increased temperature. Apart from being transmitted into the object itself, this trembling also radiates out of the object, as thermal radiation.

As far as the wavelength concerns there is a tendency that different substances emit thermal radiation in fixed wavelength bands. The bands are actually so characteristic that the material can be decided by identification of the frequency response. Different substances have characteristic frequencies or frequency response, where they have maximum oscillation. The substance of the material is also important when we analyse the frequency response of the thermal radiation. A gas tends to emit in a very narrow band, where radiation from liquids or solid materials are more broadband.

Thermal radiation from solid material is in general emitted in a wide coherent frequency band. The intensity of the radiation will not be flat in the whole wavelength band. The intensity peak of the radiation moves, as a result of the temperature. At low temperatures the peak of the radiation will be placed in the low end of the radiation spectrum (longest wavelength). When heated the peak will move towards a shorter wavelength.

An example might be an iron bar. When the temperature rises, the wavelength of radiation becomes shorter a shorter, the intensity top starts moving into the visible field. At first the iron bar will start glowing red, and afterwards it will gradually get a more yellow and eventually it will turn totally white. The radiation is now transmitted in a broad frequency band, white is the colour seen by the human eye, when exposed to broadband light.



If further information is needed, more information is available in the displacement law of Wien's,

and if you want an expression for the total thermal radiation, which is transmitted, you need to get hold of Planck's radiation law.

2.1 Wavelengths
Light is electromagnetic radiation transmitted within the wavelength 0.1-300μm. Visible light is in the interval from approx. 0.4-0.7μm. Radiation wavelength when measuring temperature from –20 to 1700°C will be within the range 1-30μm (Risø-R-862 (DA)). In radiation thermometry the radiation is often referred to as infrared radiation (IR)

2.2 Reflection, absorption and transmission
When light hits the surface of an object, the light can be reflected, transmitted or absorbed. These characteristics can be seen and exploited in different ways together with radiation temperature measurements.

2.2.1 Absorption / Emission
When an object is heated by thermal radiation, the received energy will depend on the level of energy the body absorbs. The so-called thermal "colour" of the body (IAE Thermal Design) decides level of absorption, when the object is exposed to thermal radiation. If all the radiation is absorbed, the body is called absolutely black and referred to as a "blackbody". The surface of such a body has an emission factor of 1. Absolutely black bodies only exist in theory, but it is possible to construct bodies that come very close to "black bodies" by means of colours, surfaces and design. Most surfaces will have an emission factor well below 1.

The term's emission and absorption may be confusing, as they are expressing the same phenomena, just with reverse energy flow direction. To clarify the term "emission factor" just think of a surface, and its ability to absorb incoming light, as this is equal to the ability to emit light.

Emission factor = absorption factor. A rough and dark-coloured surface has a high ability to absorb incoming light and thermal radiation, which means a high emission factor. Oppositely a polished and shiny surface does not absorb light and has a low emissions factor.

2.2.2 Reflection
In principle is it possible to perform radiation temperature measurement using a mirror to redirect the radiation, as thermal radiation to a certain extend behaves like visible light. However you must be aware of the fact that ordinary windows glass absorbs thermal radiation and as a traditional mirror consists of a glass plate with a reflecting back this cannot be used. Instead you need to use a surface mirror, i.e. a mirror where the reflecting surface is placed on the front, or alternatively a traditional mirror where the glass plate used has been made of a glass type that does not absorb infrared light.

2.2.3 Transmission
In connection with glass that does not absorb infrared light, it should be mentioned that it is possible to transmit thermal radiation. This is utilised when it is needed to measure temperature in places that are inaccessible. In these cases, you typically transmit the thermal radiation through mirrors and /or optical fibbers made of suitable material positioned between the source and the detector.

Within astronomy it is utilised that thermal radiation can be transmitted unabatedly in vacuum. This makes it possible to decide the surface temperature of objects far away.

3. Surface structure
When you are performing temperature measurement based on thermal radiation, you must be aware of which kind of surface you are ”looking” at. A surface with a high emission factor will have a higher thermal radiation than one with a low emission factor. This means if you don’t compensate, you will get different temperature readings, even though the surfaces have the same “physical” temperature.
On some radiation thermometers it is possible to compensate for the variation in emission factor, to obtain “true” temperature. Unfortunately is it difficult to predict the emission factor of an unknown material.
The words; emission -coefficient, -degree or -factor is used in technical literature about the same phenomena

3.1 Emission factor of various materials
Emission factors of materials can be found in tables of “material characteristics” or similar. But you must be careful when you use these factors; because they seldom tell you under witch conditions the factors have been obtained.

Generally speaking, you might say that materials with a porous or organic surface have a high emission factor, often above 0.9. The darker the thermal colour of a body, the higher its emission factor. Black surfaces do not necessary have a high emission factor, white-coloured surfaces can easily have the same emission factor as a dark-coloured.

Materials with shiny surfaces such as metals often have a very low emission factor. If you try to measure the temperature of an object with very shiny surface, you may risk to measure the temperature of the environment, witch is reflected in the surface of the test object. This is due to the shiny surface works as a surface mirror.

3.2 Form factor
Knowing the emission factor of a material is not sufficient, the shape or the processing of an object might also impact the emission factor. It might be difficult to state how the processing will impact on the emission factor. But as a rule of thumps you may say that rugged, rough or porous surfaces gives higher values to be added to the emission factor.

Generally speaking, when you need to compensate a radiation thermometer for the emission factor, the form factor is part of the total emission factor.

To avoid varying additions from the form factor to disturb the temperature measurements, perform the temperature measurements on the same spot on the object, when comparable measurements are needed over time.

4. Measuring equipment
Radiation thermometers are often named pyrometers. ”Pyro” is Greek and means fire.

There are several types of equipment for measuring thermal radiation. Normally divided in narrow-band and wide-band pyrometers. It is important to know which kind of instrument you are working with as two instruments might show different temperature reading, although they are set in the same way and exposed to the same thermal radiation, if you are not aware of the bandwidth differences.

The different temperature reading is due to the fact that objects at same temperature might have different emission factors depending on witch wavelengths your instrument are measuring, this is primary difference between various radiation thermometers, and a major source of the difference between IR thermometers.

4.1 Narrow-band pyrometers
Narrow-band pyrometers are the most common type. They typically have their ”measurement window” between 8 to 14μm. However, there are pyrometers with bands that are even narrower.

When only measuring in this band (8 to 14μm), one of the benefits is that there are not many disturbing elements in this range. For example water vapour might be very disturbing to measurements at wavelengths around 5-8μm and CO_2 will cause disturbances around 4,3μm. These vapours absorb large parts of the thermal radiation. In test environments with atmospheric air these vapours will be present in large quantities. In test environments with many vapours you must in advance control if there are any gases that might disturb your measurements.

An optical filter in front of the thermometer obtains the limited bandwidth. This filter only allows radiation in a selected wavelength interval to be measured by the narrow-band pyrometer. These filters and the optics mounted on radiation thermometers have a large impact on the price of the thermometer. Radiation thermometers with “zoom” lenses with a narrow well-defined measurement area, will normally be more expensive than radiation thermometers with a broader more diffuse monument area.

4.2 Wide-band pyrometers
Opposite to narrow-band pyrometers, wide-band pyrometers or total radiation thermometers have a very broad measurement bandwidth. This means that care have to be taken, and compensating for e.g. atmospherics distortions such as water vapour, CO_2 and other gasses is necessary.

4.3 Measuring detector
The most used detector for measurement of thermal radiation is stacked thermocouples. The detector is based on semiconductor technology, which means that the individual thermocouples have a very small mass and subsequently react very quickly on changes when exposed to varying thermal radiation.

To read temperature from a thermocouple there is a need to make cold junction compensation. On some radiation thermometers this may constitute a source of error, if the compensation not has been made properly. Therefore try to avoid positioning the radiation thermometer close to the source of heat as the heating of the thermometer might disturb the measurements. For additional information about the extent of this source of error, please see the user manual for the radiation thermometer in use.

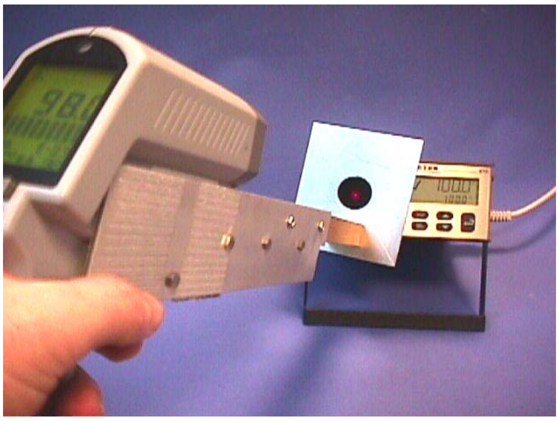
5. Potential sources of measurement errors
As previously implied there are a lot of factors that might impact on the quality of a temperature measurement based on radiation. In the following paragraphs will go through the most common sources of errors.

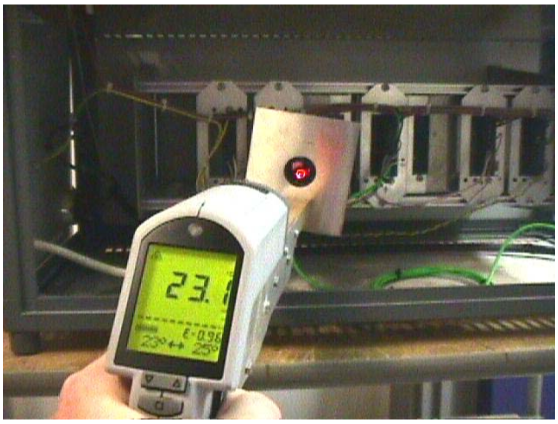
5.1 Edge effect
On most radiation thermometers it will be described either direct on the instruments or in the manuals the size of their measurement area. For example it could be specified that the measures area be within a circle with a diameter of 100 mm in a distance of 50 cm from the thermometer. A circle of laser spots might mark the measurement area.

Unfortunately it is not always correct. It is not unusual that the thermometers have a high “edge effect”, which means that they include radiation outside the field that is described. Problems with the edge effect are due to limitations in the optics.

Special care has to be taken when measurements are performed on small objects. If you are not sure whether there is a problem with the edge effect it might be an idea to make a physical shielding of the test area. If the thermometer changes reading, with and without shielding, you need to take into account at future measurements. Either by placing the shielding in a fixed distance from the thermometer at future measurements or by only performing temperature measurements on objects of such a large physical size that you avoid the problem with the edge effect.

By adding a shielding you obtain the possibility of performing temperature measurements on area of the same size each time.





5.2 Instrument bandwidth

As most surfaces have a varying emission depending on the bandwidth used when measuring, you may risk to get varying temperature measurements if measurements are performed by using different radiation thermometers. To avoid this use the same (type) thermometer to examine the same surface currently.

5.3 Correction of emission factor

The most significant source of error in radiation thermometry is an emission factor that has been set to the wrong factor. It may be difficult to obtain the correct factor, as it is impacted by several factors and often total unknown.

If there are variations in the structure of the surface that you are measuring on, you will have to change the emission factor. If there is a little variation in the distance between the thermometer and the surface it might have an impact, etc.

Besides, as you only rarely have the possibility of correcting the emission factor with a resolution better than 1% (0.xx) you will generally have to accept with some uncertainty in your temperature measurements.

As a consequence of these factors it is often not possible to perform very precise or absolute temperature measurements with IR thermometers, unless it concerns very high temperatures where the form factor is less important.

5.4 Instrument heating

There might be a risk of a measurement error if the radiation thermometer is positioned too close to a strong heating source. The problem is that the sensor of the radiation thermometer is built as a thermocouple. Temperature reading from thermocouple is only possible when the temperature of the connecting point is known (cold junction), wrong temperature reading are obtained if the instrument has not been designed properly.

This may place the user in a dilemma regarding the distance to the test surface, short distance to avoid the edge effect and still so far away from the surface, that heating of the radiation thermometer can be avoided.

6. Sources of error in measuring environment

The measuring environment might contain factors disturbing the measurements, and the most common are mentioned in the following.

6.1 Dirt, dust and gasses

There might be several completely or partly invisible elements in the test environment, which may disturb the measurements. Among these can be mentioned dirty lens, dust, radiation absorbing gasses or smoke between the thermometer and the test object.

If you want to clean the lens of the thermometer you need to do it before calibration, or even better make an as found / as left calibration before / after cleaning. Just doing it afterwards might make the calibration worthless. When cleaning the instrument lens be very gentle to avoid damaging the lens and the coating, this might destroy the thermometer entirely.

Gasses, dust and smoke might block the thermal radiation to such an extent that it will make the measurements very inaccurate. You need to control if there are gasses in the test environment that might disturb the measurements.

6.2 Gradients in the surface of the measuring object

Somewhere between a hot object and a cooler ambient environment there will be temperature gradient. Therefore you must be cautious when concluding the temperature of the object has the same temperature inside as the surface temperature, which you measure by using a radiation thermometer.

If the object has a high thermal conductivity you can to a certain extent expect that there is a great resemblance between the internal and the external temperatures. On the opposite side the surface temperature of an object or a surface with low conductivity, perhaps exposed to draught will not tell much about the internal temperature of the object.

7. IR temperature calibrator

As number of radiation thermometers and their applications increase, the need of calibration also increase. As it is expensive and time-consuming to get your IR thermometers calibrated by an external calibration laboratory the interest of performing in-house calibrations has increased significantly.

The advantages of having your own calibration equipment are that you are able to calibrate and control your thermometers more often and in the actual temperature range you need to measure. Especially the last reason is very important, because the temperature deviation at one temperature does not necessarily apply at another temperature. IR thermometers show a certain degree of non-linearity.

If you have several IR thermometers there are even more advantages in having a calibrator. Instead of sending all thermometers for calibration it is now enough to send one calibrators for calibration and compare the others with the calibrated instrument. Furthermore it is possible for you to perform comparable relative measurements, which is in fact the “true” nature of the radiation thermometer.

7.1 IR calibration

When calibrating a radiation thermometer, you need to know the emission factor and the surface temperature of the target with a high degree of precision. Both parameters are difficult to determine precisely and set a high level of demands for the calibrator manufacture.

The “true” surface temperature is hard to obtain, as the temperature are inclined to change during the measuring process when using traditional thermometers. When measuring the temperature deeper inside a body instead of in the surface itself, you may forget to include the temperature gradients, which always are present in the surface.

Also the emission factor of the surface is hard to find, as the precise temperature of the surface, at the moment you are establishing the emission factor has to be known. To avoid impacts from draught, convection and gradients you will inevitably be tempted to shield the test surface. However, you need to take care as you risk destroying the test surface.

Calibration of radiation thermometers are often done by using blackbodies. They are constructed as cavities or holes where the relation between the opening diameter and the depth often are less than 1 to 8. They have a stable emission factor very close to 1. More reliable temperatures are found in cavities than on flat surfaces, cavities are excellent reference/calibration instruments.

As the design of a blackbody is not representative for the surfaces on which you measure temperature in the “real word”, other types of reference instruments are often used, i.e. the grey body.

The grey body is remarkable for having a known stable emission factor, which always is lower than 1. The grey body will often be designed as a special designed surface retained on a known temperature block.

7.2 JOFRA ETC-400 R

The JOFRA ETC-400 R is constructed as an optimum between size and performance. The best instrument for calibration of a radiation thermometer is a “blackbody”, as it is the most reliable as regards the emission factor. But to save space this has not been possible, as “black bodies” are often rather voluminous. At the same time there has been a demand for a small quick instrument and JOFRA therefore aimed at the second best, the ”grey body”.

As it appears from the definition of a “grey body”, it has a constant emission factor through a broad bandwidth. We have constructed the emission factor itself to be very close to 0.96.

Internally the instrument contains a precise and traceable calibrated thermometer and we urge the user to get the thermometer calibrated regularly. With a calibrated internal thermometer the calibrator will be able to produce a precise temperature in the test field of the instrument. This means that the user has all necessary information to perform a precise calibration of IR thermometers, known emissions factor and known temperature.

7.2.1 Use of JOFRA ETC-400 R

Set the test temperature required and wait until the temperature has stabilised. When this happens the display will visually indicate that the temperature is stable by the following sign: (√). Furthermore the instrument will indicate that it is ready for use by a clear “beep”.

If possible, set the emission factor of the test surface (0.96) on the thermometer that need to be calibrated. By comparing the reading of the radiation thermometer with the temperature set on the calibrator, you can determine deviations.

If deviation is recorded, adjust the thermometer accordingly to make the deviation disappear (if possible). After adjustment you need to recalibrate the IR thermometer to control that the adjustment has been successfully carried out. On thermometers where it is not possible to adjust the temperature reading you must record the deviation, to apply correction for the deviation during measurements.

Apart from calibrating your IR thermometer in the temperature points where the instrument is used it is also recommended to check minimum and maximum temperatures due to non-linearity in radiation thermometers.

If there is found deviation on the thermometer when it has been set to an emissions factor of 0,96, this deviation will also apply when the thermometer is used on surfaces with other emissions factors at the same temperature.

7.2.2 Calibration of JOFRA ETC-400 R

To enable you to calibrate the internal thermometer of the calibrator, a hole for a 3 mm reference sensor has been made 1 mm under the surface. The surface coating itself has a thickness of approx. 50μ, making the difference between the temperature measured by the reference thermometer in the heating block and the temperature of the surface negligible. However, please note that the best calibration result is obtained by using the reference sensor manufactured by AMETEK Denmark A/S as it has been specifically produced to calibrate of this instrument.

This sensor has been designed to the short insertion depth of the “reference hole”. Due to the short insertion depth, most other sensors would show wrong temperature.

In connection with calibration and adjustment of the ETC-400 R it is recommendable to use an accredited laboratory, as they are able to perform a traceable calibration.

8. Mathematics

In the following paragraph you will find some interesting equations with reference to radiation thermometry. In other literature you will find equations and demonstrations to calculate multiple conditions regarding thermal radiation. Below only small extract is shown.

8.1 Equation for establishment of emission factor

If you want to find the emission factor of a surface, you need to use a calibrated radiation thermometer as well as a calibrated surface thermometer.

With the thermometer you monitor the surface temperature of the object that you want to test. The temperature that you find is called t_s. In the radiation thermometer you set the emission factor at 1 and perform a temperature measurement of the object t_m.

T_m = t_m+273 temperature measured with radiation thermometer in Kelvin
T_s = t_s+273 temperature measured with surface thermometer in Kelvin
λ = Mean value of wavelength within the visual field" of the radiation thermometer, e.g. 8- 14μm $\approx$ 10μm
C_2 = Constant =1.4388*10^{-2}
ε = Emission factor

Total radiation thermometer Narrow-band thermometer (Risø-R-862(DA) #[9][10])

$$\varepsilon = \frac{T_m^4}{T_s^4} \qquad \varepsilon = e^{\left[C_2\left(\left(\frac{1}{T_s\cdot\lambda}\right)\cdot\left(\frac{1}{T_m\cdot\lambda}\right)\right)\right]}$$

This equation applies for narrow-band radiation thermometers and is a transcription of a formula used in (Risø-R-862(DA)) [formula #10].

8.2 True temperature

T_m = t_m+273 temperature measured with radiation thermometer in Kelvin
T_s = t_s+273 temperature measured with surface thermometer in Kelvin
λ = Means value of wavelength within the "visual field" of the radiation thermometer, e.g. 8-14μm $\approx$ 10μm
C_2 = Constant =1.4388*10^{-2}
ε = Emission factor

Total radiation thermometer Narrow-band thermometer (Risø-R-862(DA) #[9][10])

$$T_s = \sqrt[4]{\frac{1}{\varepsilon}}\cdot T_m \quad T_s = \frac{T_m\cdot C_2}{C_2 + \ln(\varepsilon_\lambda)\cdot\lambda\cdot T_m}$$

8.3 Total radiation from a blackbody

Without going into the calculation, you may find the total thermal radiation from a blackbody at a given temperature by using a equation described in the Stefan-Bolzmann Law.

M_{bb} = Total thermal radiation at a given temperature of a blackbody
T = Absolute temperature [Kelvin]
σ = Bolzmann constant = $5{,}67 \cdot 10^{-8} \left[W/_{m^2} - K^4 \right]$

$$M_{bb} = \sigma \cdot T^4 \qquad \text{(Pedrotti 2-14)}$$

All objects have a total radiation lower than the one that applies to a blackbody, and to make the measurements comparable a co-efficient has been introduced to equalise this difference, i.e. the emission co-efficient. It is defined as:

M = Total thermal radiation from a body at a given temperature
ε(T) = Emission factor

$$\varepsilon(T) = \frac{M}{M_{bb}}$$

If an object has an emission factor at a given temperature that does not vary according to the wavelength this is referred to as “grey body”.

9. Literature references

Text abbreviations:	**Title of book:**
(Pedrotti)	"Introduction To Optics" Frank L. Pedrotti, S.J. Leno S. Pedrotti
(Risø-R-862(DA))	"Infrarød temperaturmåling" (Infrared Temperature Measurement) Sønnik Clausen
(IAE Termisk Design)	"Termisk Design" (Thermal Design) Jørgen Møltoft Lars Rimestad