An investigation into a calibration scheme for a light pipe based temperature probe

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Abstract

We propose a scheme to ensure traceable calibrations of light pipe based temperature probes. We investigate experimentally and theoretically the properties of a device consisting of a sapphire tube with a tungsten filament at the bottom, filled with an inert gas and sealed to avoid contamination of the filament. The device is used as a contact probe, where the temperature is deduced based on detection and quantification of the Planckian radiation from the filament. The Sakuma–Hattori equation is used to approximate the Planck radiation as a function of temperature, and its parameters are fitted using a small number of calibration points. The impact of a small, temperature dependent emissivity on both the calibration and the interpolation errors is explored, and we find that a dual-band detection scheme is required to reduce the sensitivity to variation in the use conditions.

Keywords: pyrometry, optical thermometry, uncertainty, temperature, traceability, light piping

(Some figures may appear in colour only in the online journal)
relating the light intensity to the Planck law, which can be
deduced from first principles. There are a number of other
mechanisms for light emission, however, and real objects
do not behave as black bodies. An isothermal enclosure
with a small apertures closely approximates a black body, and
pyrometry is in principle a reliable method for temperature
measurement. However, particularly in industrial applications
it is hard to realise isothermal enclosures; indeed, in many
important cases the process relies on temperature differences.
Furthermore, the temperature of interest will in most cases
be the temperature of an object rather than the enclosure as
a whole.

Light pipes have been used in certain industrial processes,
in particular Si production, where the idea is to collect light
from a solid quartz or sapphire rod in close proximity to the
surface of the object of interest. Due to the higher refractive
index the rod will guide light from total internal reflection to
the cold end, where a general purpose pyrometer or a custom
designed device is used to detect the light and convert it to
a temperature reading [12]. The refraction properties of the
rods will also render them immune to light penetrating the
side walls, because any light ray entering the rod must have
an incidence angle small enough to escape through the oppo-
site wall. However, the rods will introduce shadow effects
and heat conduction effects which are sufficient to change the
temperature of the object by several degrees [13].

Růžička et al [14] have previously described a modification
of the light pipe based probe. Rather than just guiding light
from an object of interest a fixed object made from tungsten is
placed inside a hollow tube made from single crystal sapphire.
The Planckian radiation from the tungsten is detected and
converted to temperature using a general purpose pyrometer.
The basic idea is that by using a fixed object as temperature
probe one could overcome the issues encountered with the
traditional light pipe probes, while retaining the advantages
of pyrometric measurements, such as fast response. Since the
properties of the tungsten remain unchanged it would be possi-
bile to calibrate its radiance at a few known temperatures in
a calibration laboratory, and then use the Planck law to inter-
polate between the calibration points in applications without
worrying about the emissivity of the object or other object-
specific properties that might affect the thermal radiation. In
this paper we explore the calibration of such a device in more
detail. Using a well-known 3-parameter approximation to the
Planck law to interpolate between the calibration points, we
discuss the implications of non-perfect emissivity behaviour
of the tungsten filament and the impact on the measurement
precision, and also extend the simple model to a dual-band
 technique which turns out to improve the resilience of the
device to some influences. The scheme is implemented in
the laboratory using a custom built optical setup and tested in a
highly isothermal furnace.

2. Device description

A sketch of the setup is shown in figure 1. A small tungsten
filament is inserted into the sapphire tube, carefully positioned
at the bottom. The tube is filled with Ar gas and sealed by
gluing a quartz window onto the opening. The inner diam-
eter of the sapphire is 4 mm with a wall thickness of 1.5 mm.
The tube length can be adapted to the application, but 600 mm
was used in the present work. The tube is attached to a simple
optical system, which acts as a spatial filter. The objective lens
images light from the filament onto a screen, with a carefully
placed aperture to let light from the filament through to the
collimation lens behind. Behind the collimation lens a beam-
splitter ensures that two detectors, with appropriate spectral
filters, are illuminated at the same time. The first detector is a
Si detector with a 0.95 μm spectral filter in front, the second
detector is a cooled InGaAs detector with a 1.51 μm spectral
filter. According to the specifications from the manufacturer
the filters are narrowband with a FWHM of 10 and 12 nm,
respectively. The detectors are bundled with integrated pream-
plifiers, which outputs a robust and stable voltage signal pro-
portional to the light intensity. A manual shutter (not shown)
is inserted before the beamsplitter to enable blocking of the
light path, which is used to record the dark current. The entire
unit is then used as a contact thermometer by inserting the tip
of the sapphire tube into the region of interest. After a brief
equilibration time the thermal radiation from the filament is
stable and can be used as the temperature response signal.

The signal at the detectors is generated by light from three
sources: (i) the thermal radiation from the filament; (ii) light
originating elsewhere and reflecting from the surface of the
filament; and (iii) light transmitted through the sapphire, or
scattered at surface imperfections, and reaching the detectors
directly. For a spectral response $r(\lambda)$, and assuming that we
can describe the light propagation with a simple 1D model,
the signal at the detector can be written as

$$S(\lambda, T) = \int \varepsilon L(\lambda, T_W) r(\lambda) d\lambda + \int (1 - \varepsilon) S_{th}(\lambda, T_{bck}) r(\lambda) d\lambda + S_{sc}. \quad (1)$$

The first term describes the radiation from the filament. The
Planck law $L(\lambda, T_W)$ is a function of wavelength $\lambda$ and
filament temperature $T_W$, moderated by an emissivity $\varepsilon$. The
second term describes the reflected radiation. The reflected
radiation is mainly thermal radiation from the surroundings,$S_{th}$, which depends on a temperature $T_{bck}$, which in general is
different from the filament temperature. There is also a small
component from self-radiation in the sapphire: sapphire has
a small, but finite absorption, which in general is temper-
ature dependent [15]. The final term is stray light reaching the
detector directly. It may be transmitted through the sapphire
wall from somewhere behind the filament, or it may be light
scattered from the sapphire surface.

With a careful characterisation of the spectral response, the
emissivity and the properties of the sapphire, one could use
equation (1) directly to convert a measured signal to a temper-
ature. However, it is simpler to calibrate the signal response
at a few reference temperatures and fit a sensible response
model. A commonly used approximation to the Planck law is
the Sakuma–Hattori equation ([16–20]):
Figure 1. (Left) A sketch of the sapphire tube thermometer. The tungsten filament, shown in black, is located at the bottom of the tube (light blue). The tube is filled with inert Ar gas and the opening sealed with a quartz window. The path of two sample rays from the furnace wall, through the sapphire wall and to the filament are shown as lines. (Right) The light detection system is a spatial filter with an objective lens (O) with focal length 150 mm, an aperture (A) with diameter 300 μm in the image plane of the tungsten filament, and a collimation lens (C) with focal length 100 mm. A beamsplitter (B) ensures that the two detectors (PD1 and PD2, Si and InGaAs based, respectively) are irradiated simultaneously by light which has passed through appropriate filters (F1 and F2, at 0.95 μm and 1.51 μm, respectively).

\[ S(T) = \frac{a_1}{\exp[c_2/(a_2 T + a_3)] - 1]. \]  

The equation contains three fitting parameters, \(a_1\), \(a_2\) and \(a_3\), the blackbody temperature \(T\), and the second radiation constant \(c_2 = 0.01488 \text{ K} \cdot \mu\text{m}\). The equation is a very convenient approximation as it is simple to invert analytically while tracking the thermal radiation closely, and it only requires three calibration measurements. It can be shown that for blackbody radiation and a narrow band spectral response \(c_2\) in equation 1 can be related to the central wavelength and its width \([21]\), with \(a_2\) being quite close to the center wavelength.

An initial inspection of the geometry in figure 1 would suggest that the effective emissivity of the tungsten is very close to 1. The surface of the tungsten filament is usually inserted deep into a hot cavity, where multiple reflections of light inside the cavity enhance absorption at the tungsten surface, and by conservation of energy enhances the emissivity. The example in figure 1 is a case where the sapphire tube is inserted into a cylindrical cavity with a large aspect ratio: furnace cavities of diameter 40 mm and length 300 mm, which are common dimensions in laboratory furnaces, would give a length-to-radius ratio of 15 for a fully inserted tube. Such a high aspect ratio would give an effective emissivity very close to 1 (see e.g. [22]). However, the presence of the sapphire between the tungsten filament and the cavity walls significantly affects the radiation transfer. With reference to the geometry of figure 1, an aspect ratio \(L/R\) of 5 leads to an incidence angle of almost 80° at the sapphire surface of waves originating at the furnace wall. By the Fresnel relations (see e.g. [23]), taking into account multiple reflections in the tube wall and using a refractive index of 1.7 for the sapphire, this amounts to a reflection coefficient of around 0.5. Clearly such a strong impendiment to the light transfer reduces the background irradiation on the filament, resulting in a non-isotropic background even if the sapphire tube were immersed in a completely isothermal enclosure, akin to the shadow effect pointed out by Qu et al [13]. Hence we must expect that the effective emissivity of the filament is significantly lower than 1 even when the sapphire tube is inserted deep into a hot cavity.

A further complication that follows from a low effective emissivity is related to thermal behaviour. The emissivity of real surfaces is in general temperature and wavelength dependent: indeed, Brodru et al [24] found that the hemispherical emissivity in a band covering the wavelengths of interest here depended on temperature, increasing from 0.3 to 0.5 between 1000 K and 1900 K. The behaviour was complex, however, depending on surface finish and heat treatment. An increased temperature dependence was seen after exposing the filament to much higher temperatures, up to 2500 K, and in some cases even a drop in emissivity with increasing temperature was observed.

These considerations raise the question of how well the Sakuma–Hattori equation can track the full behaviour encompassed by equation (1). The temperature dependence of the emissivity and possibly the background is different from the Planck law, and the received light intensity at the detector follows a different curve from the expected \((\exp(T^{-1}) - 1)^{-1}\) behaviour. We have investigated this numerically by integrating equation (1) to obtain theoretical signals and fitting those to equation (2) using a small number of calibration points (3–5). The spectral response \(r(\lambda)\) in equation (1) was modelled with gaussian profiles, whose center wavelength and width were taken from the manufacturer specification of the peak and FWHM for the interference filters. The background irradiation on the tungsten was not modelled in detail, but assumed to result from an integrated thermal radiation over a cylindrical enclosure around the sapphire tube. The axial temperature profile resembled the measured profile in the laboratory furnace used in section 3, and reflection at the sapphire surfaces was taken into account. The self-radiation from the sapphire is related to its intrinsic absorption, which is also temperature dependent [15], but this radiation replaces absorbed background and we do not expect a strong net effect; for this reason, absorption was not considered. Incidentally, the interpolation error is not strongly dependent on the intensity of the background.

The effective emissivity of the tungsten is harder to address, as it depends on the geometry and hence should be computed separately in each use case. However, the primary concern for assessing the fidelity of the Sakuma–Hattori approximation is
the linear dependence. The effective emissivity was modelled with a linear temperature dependence:

\[ \varepsilon(T) = (1 - f)A + f. \]  

Two sets of coefficients \( A \) and \( B \) were used, both of which were determined based on emissivity values from Brodut et al [24]. The first set uses an increasing emissivity with temperature with \( \varepsilon(1000 \, K) = 0.33 \) and \( \varepsilon(1900 \, K) = 0.5 \), giving \( A = 0.186 \cdot 10^{-3} \, K^{-1} \) and \( B = 0.198 \). The other set models a decrease in emissivity with increasing temperature, which were observed after exposure to high temperatures, with \( A = -0.186 \cdot 10^{-3} \, K^{-1} \) and \( B = 0.672 \). \( T \) is the temperature (in K), and the factor \( f \) is a number between 0 and 1 which increases the effective emissivity depending on the actual geometry. If \( f = 1 \) the effective emissivity is 1 for all temperatures and corresponds to an ideal situation where the tungsten is immersed in a completely isothermal and isotropic cavity; if it is 0 the effective emissivity is identical to the values from [24] and corresponds to a completely open hemisphere around the filament. The above discussion makes it clear that the presence of the sapphire tube renders \( f = 1 \) unattainable, however it is also clear that the actual value and behaviour would depend on the specific use scenario. For the case of a cylindrical furnace chamber the value of \( f \) is a monotonously increasing, but non-linear, function of the immersion: \( f = 0 \) corresponds to the filament inserted just inside the hot zone.

The interpolation error \( E_{\text{int}} \) was computed as the difference between the outputs of equations (1) and (2) at the same temperature \( T \). \( E_{\text{int}} = S_{\text{theory}}(T) - S_{\text{sh}}(T) \). It is a 3rd order polynomial which increases fast beyond the calibration range [25], but its absolute value has a local maximum within this range. The value of this maximum depends on the range spanned by the calibration points, the wavelength used, and the number of calibration points. The dependence is shown in figure 2 for two specific cases with a narrow (830 °C–1000 °C) and a wide (800 °C–1500 °C) calibration temperature range. In the former case the interpolation error remains below 15 mK. For the wider calibration range the interpolation error is appreciable and it is necessary to ensure \( f > 0.5 \) if the error is to remain below 400 mK in all cases.

As explained above these results were obtained assuming a thermal background, i.e. one with a distinct signal-versus-temperature spectral profile. While the interpolation errors do not depend strongly on the intensity of the background, its temperature and spectral dependence would have an influence. Strong, localized, sources at high temperature could disrupt the spectral contents of the background. Scattering on surface imperfections in the sapphire may also be wavelength dependent and similarly affect the spectral characteristics. There are, in other words, reasons to be cautious about the spectral content and temperature dependence of the reflected light.

3. Calibration and characterisation

A prototype device was constructed according to the sketch in figure 1, and calibrated using equation (2) at the temperatures 830 °C, 920 °C, 980 °C and 1000 °C. The photosignals were recorded using external voltmeters connected to a computer for automated data acquisition. The furnace was a tube furnace lined with a Na heatpipe, with a cylindrical central cavity of approximately 350 mm length and 40 mm diameter. Alumina insulation bricks were placed behind and in front of the furnace liner. The back was completely sealed, while in front there was a 40 mm opening to accomodate the thermometers. The setup provides a very uniform temperature across more than 200 mm along the axis. The reference temperature was measured using a calibrated type S thermocouple with its weld displaced laterally no more than 15 mm, and axially no more than 3 mm, from the tungsten filament.

After obtaining the calibration curves the device was retracted from the chamber in small steps while the optical signals and thermocouple outputs were recorded simultaneously. The calibration curves were used to convert optical signals to temperature, and subsequently the difference between the thermocouple data and the optically deduced temperature was computed. The immersion curves produced this way are shown in figure 3.

Each of the bands are highly sensitive to the immersion. There does not seem to be any sign of a saturation behaviour: the trend is linear to the depth of the furnace. In the 200 mm where the thermocouple indicates that the temperature is stable the optically obtained indications drops by approximately 4 °C and 8 °C for the band centered on 0.95 µm and 1.51 µm, respectively.
The interpolation uncertainty for equation (2), given a set of calibration points \( \{ T_i, S_i \} \), is to fit the Sakuma–Hattori equations, and sample the resulting curve at desired points. By repeating the procedure a large number of times one can extract information about the statistical distribution of function values at the sample temperatures.

Table 1 summarises the uncertainty contributions taken into account here. The reference temperature uncertainty budget takes into account calibration of the thermocouple sensor, calibration and resolution of the voltmeter used to read the thermovoltage, and inhomogeneity of the thermocouple wires. It also contains a term to take into account the temperature gradients within the furnace chamber. This term will in general depend on the position in the furnace chamber. The uncertainty estimate stated in the table is based on the measured temperature profile in the stable region, where the gradient is smaller than 2 \( ^\circ \text{C} \text{ m}^{-1} \), and scaled with the approximate axial distance between the sapphire tip and the reference sensor (less than 5 mm). We assume that the temperature uniformity in cross sections of the furnace chamber is much better. The uncertainty assigned from the resolution of the voltmeter is scaled with the sensitivity of the thermocouple, and hence depends on temperature.

The signal values used in the computations are the dark current compensated voltages from observations. The estimate of the dark current is therefore 0, but the uncertainty is not. The dark current is determined by closing the light path using a shutter inserted just before the beamsplitter (see figure 1). The dark signal is recorded for a couple of minutes before opening the shutter and starting the measurements. The average reading is subtracted from all subsequent measurements. The uncertainty assigned to this correction is Normally distributed with a standard deviation taken from the dark current sequence. In each iteration of the MCM the same realisation of the dark current compensation for all four calibration points.

The evaluation proceeds by drawing pseudo-random numbers used to realise each calibration point \( \{ T_i, S_i \} \), fit the Sakuma–Hattori equations, and sample the resulting curve at desired points. By repeating the procedure a large number of times one can extract information about the statistical distribution of function values at the sample temperatures.

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Each iteration in the MCM process then draws four values for temperature, four values for corresponding optical signal from the Si detector, a single value for the dark current for the Si detector, four values for the InGaAs optical signals corresponding to the calibration temperatures, and a single value for its dark current. The same realisations of the temperature values are used in both detectors. This procedure ensures that the correlation between the calibrations in the two bands is properly accounted for. The final stage is to fit equation (2) to the 0.95 μm and 1.51 μm observations separately, and the process is repeated 10^6 times.

The output of the computation is shown in figure 4 for each of the three cases (a single narrow band centered on 0.95 μm, a single narrow band centered on 1.51 μm, and the ratio).

5. Discussion

For narrow band pyrometry the rule of thumb is that a shorter wavelength provides a smaller uncertainty. There are usually other reasons for selecting long wavelengths, such as signal strength or molecular absorption lines in the medium between the target and the detector. The interpolation uncertainty in our case is similar for the two wavelengths used, which is partly due to the different nature of the detection systems (the voltmeters used, and the detector and preamplifier hardware). It is clear that in terms of a calibration uncertainty, however, either is better than the ratio model.

The observed immersion depth dependence in figure 3 implies that the behaviour of the tungsten filament cannot be adequately described by a simple blackbody radiation model. It is clear that a small calibration uncertainty is not necessarily the optimal criterion for the ultimate performance of the device. In the present case a dual-band ratio detection scheme is more robust to immersion than using a single band detection. A likely explanation for this is the relatively low effective emissivity of the tungsten surface caused by the screening effect of the sapphire tube wall. One of the main attractions of the ratio scheme is that it reduces the influence of emissivity and object size [30]; if the emissivity at the wavelengths $\lambda_1$ and $\lambda_2$ are $\varepsilon_1$ and $\varepsilon_2$, respectively, the ratio of the thermal signal at the two wavelengths is completely determined by the temperature of the object and the Planck curve:

$$\frac{\varepsilon_1 L(T, \lambda_1)}{\varepsilon_2 L(T, \lambda_2)}$$

The prefactor $\varepsilon_1/\varepsilon_2$ is constant at all temperatures, and can be determined in a calibration. For this method to work properly in general purpose pyrometry it is necessary to assume (i) that the wavelength dependence of emissivity is the same in calibration and application, and (ii) that the background irradiation is negligible. In our case the former assumption is probably true since we use the same object in calibration and application. The background irradiance is considerable, but its intensity increases with temperature in a way that resembles the radiance from the furnace. To a first approximation the reflected background increases the radiance from the tungsten. To a first approximation the reflected background increases the radiance from the filament somewhat and just increases the effective emissivities $\varepsilon_1$ and $\varepsilon_2$ while maintaining the ratio between them. However, if the background irradiation originates from an inhomogeneous temperature background the spectral characteristics of the reflected radiation could change, which clearly has an impact on a dual-band detection scheme. This is a plausible explanation for the observation in figure 3 that, despite the improvements, the ratio scheme also produces a temperature offset compared with the reference thermocouple. The magnitude of the offset remains smaller than the either of the wavelength channels separately. On the other hand, the test case here is a very uniform environment, and ensures that the reflected light behaves in a predictable and consistent way. If powerful background sources are present, such as exposed furnace heating elements, the dual band ratio technique may prove less efficient.
The uncertainty rises sharply. The model always has a higher uncertainty. Beyond the calibration range the temperature calibration limits the useful temperature calibration range in any single calibration. To extend the usable temperature range it will be necessary to calibrate the device in subranges and use different calibration curves in each subrange.

The choice of wavelengths for the dual-band detection scheme has not been optimised for a maximum sensitivity [31], but chosen mostly to match the sensitivity of the individual detectors used. The impact of such an optimisation could be pursued elsewhere. Nevertheless, the main observations of a larger calibration uncertainty with the ratio model, but better resilience to changes in the experimental conditions (e.g. immersion), is likely to remain regardless of wavelength choices.

The tungsten filament is also subjected to a non-uniform heat load. The front surface experience a net loss of heat, which is balanced by slightly larger heat gain through the other surfaces. This induces a temperature gradient inside the filament. We have not explored whether this could affect the calibration. However, since the filament is small compared to any reasonable hot zone the device can be used in, we expect the thermal profile inside the filament to be deterministic and very similar in calibration and use scenarios. It is of course conceivable that a strong radiation source could irradiate the front face and modify the temperature gradients inside the filament, but the presence of such a light source would cause other complications, for instance a much stronger reflected signal. The immersion profiles from figure 3 suggests that care is needed if the sapphire tube device is used in highly non-uniform environments.

The in-use uncertainty is dominated by three main contributions: (i) the interpolation uncertainty from calibration, (ii) the interpolation error, primarily due to the temperature evolution of the emissivity, and (iii) the effective immersion depth during usage. Using the narrow calibration range from from 830 °C to 1000 °C the uncertainty is dominated by the immersion behaviour, with expanded uncertainty of 2.1 °C, 3.9 °C and 1.2 °C for the 0.95 μm, 1.51 μm and ratio model, respectively. The figures are computed as the quadrature sum of the three contributions with values taken from the figures 2–4. One crucially important choice is the calibration range. The calculations of the interpolation errors (figure 2) shows that rather than covering a wide range, e.g. from 800 °C to 1500 °C one should strive to use narrower calibration ranges. A practical tradeoff between small interpolation error and an economical number of calibration points might be to use a sequence of adjacent ranges spanning 300 °C–400 °C.

6. Conclusion

We have explored a calibration scheme for a light pipe based temperature probe. The probe consists of a sealed sapphire tube filled with inert gas, with a tungsten filament positioned at the bottom. A number of influences must be taken into account. Because of a strong immersion dependence, probably caused by an impaired optical radiation transfer between the surroundings and the tungsten filament, the optimal scheme requires independent detection of two wavelengths to reduce the sensitivity to background irradiation and temperature induced changes in the filament surface properties.

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