SOLAR-BLIND PYROMETRIC TEMPERATURE MEASUREMENT UNDER CONCENTRATED SOLAR IRRADIATION

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Abstract

The surface temperature distribution of high temperature solar materials is a key parameter in concentrating solar thermal applications. As contact thermometry is often not appropriate in the presence of high-flux solar irradiation, pyrometric techniques can be adopted. However, depending on the optical properties of the sample, special measurement treatments are required to eliminate the bias in the pyrometric measurement resulting from the single and multiple surface reflections of incoming solar radiation. Several pyrometric methodologies for particular applications have been reported in literature. In this paper a more general approach to this technique and its adaptation for the use in high temperature solar receivers is presented. The measurement requirements including the necessity and type of a selective filter are obtained from the analysis of the spectral bi-directional reflectance and the operational range of temperature. According to these conditions a classification of materials encountered in solar receivers is given and adequate measurement methodologies are suggested for each type of receiver and temperature range.

Keywords: concentrated solar radiation, high temperature, pyrometric temperature measurement, solar-blind

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Introduction

In high temperature solar thermal applications, where key components are driven near their limiting temperature, a reliable temperature monitoring is essential for a safe and efficient operation of solar receivers. In the hostile environment of hot, irradiated surfaces, radiation thermometry is a convenient non-contact method for the measurement of surface temperatures. However, besides the characteristic uncertainty in pyrometric temperature measurements due to unknown or variable emissivity of the measurement target, the measurement can be distorted significantly by reflected solar radiation. For ideal diffuse reflectors an in-situ determination of the sample spectral reflectance and the incoming flux enables one to correct the pyrometric measurement errors related to the sample emittance and solar reflections\textsuperscript{1,2}. The distinction between the emitted thermal and the reflected solar radiation becomes complicated for non-diffuse targets. Usually, neither the actual angular distribution of the incoming solar radiation nor the bi-directional reflectance of the measurement object is known accurately enough for a reliable correction. A simple and direct strategy to obviate measurement errors is the measurement in so-called solar-blind spectral measurement ranges, where the contribution of reflected solar radiation to the measured signal can be neglected. Various such solar-blind measurement setups have been reported for specific applications in high-temperature solar thermal applications\textsuperscript{3-7}. The aim of the present paper is to describe the most relevant parameters for the selection of an adequate solar-blind spectral range according to an error budget analysis of pyrometric measurements on high-temperature solar receivers.

Fundamentals

In pyrometry the target temperature is determined by comparing the actual measured radiometric signal $S_{\text{rad}}$ to that of a calibration blackbody. If only thermally emitted light is observed, the radiometric signal of a pyrometer with a narrow spectral measurement range of a half width $\Delta\lambda_{\text{hw}}$ smaller than 5% of the central wavelength $\lambda_{\text{cw}}$ of the spectral filter ($\Delta\lambda_{\text{hw}} \leq 0.05 \cdot \lambda_{\text{cw}}$) can be approximated according to the one-color principle\textsuperscript{8}:

$$S_{\text{rad}}(T_{\text{obj}}) = \gamma_c \cdot \tau_{\text{atm},\lambda_{\text{m}}} \cdot \epsilon_{\text{obj},\lambda_{\text{m}}} \cdot \left[ \exp \left( \frac{c_2}{\lambda_{\text{m}} \cdot T_{\text{obj}}} \right) - 1 \right]^{-1}$$

(1)

where $\lambda_{\text{m}}$ is the mean effective wavelength of the spectral measurement range, $c_1$ and $c_2$ are the first and second radiation constants in Planck’s law, $T_{\text{obj}}$ denotes the target temperature, $\epsilon_{\text{obj},\lambda_{\text{m}}}$ is its emittance and $\tau_{\text{atm},\lambda_{\text{m}}}$ the transmittance of the path between the surface element and the front lens of the pyrometer. The physical output of the sensor as e.g. a photo voltage or a photo current is compared with an internal standard yielding the calibration factor $\gamma_c$ that is usually determined with a gauge measurement on a calibration blackbody. The dimensionless calibration factor incorporates the prefactor $c_1\lambda_{\text{m}}^{-5}$ of Planck’s law and the contributions of the transmittance of the optical train (lenses, optical fibre, filter) and the sensitivity of the light detector.
The relation between a small relative measurement deviation of the radiometric signal and the corresponding relative temperature uncertainty can be estimated according the Gaussian error propagation:

\[
\frac{\Delta T_{\text{obj}}}{T_{\text{obj}}} = C_{\lambda_{m}} \cdot \frac{\Delta S_{\lambda_{m}, \text{rad}}}{S_{\lambda_{m}, \text{rad}}}
\]  

(2)

where the sensitivity coefficient \( C_{\lambda_{m}} \) describes the relation of individual measurement deviations and the uncertainty of the temperature measurement:

\[
C_{\lambda_{m}} = \frac{\lambda_{m} \cdot T_{\text{obj}}}{c_{2} \cdot \left[1 - \exp\left(-\frac{c_{2}}{\lambda_{m} \cdot T_{\text{obj}}}\right)\right]}
\]

(3)

Figure 1. Sensitivity coefficient (solid line) and Planck function (dashed line)

Prerequisites for an accurate pyrometric temperature measurement are a reliable calibration and the knowledge of the atmospheric transmittance and the optical properties of the sample. Measurement deviations may arise due to uncertainties in the calibration factor \( \gamma_{c} \), changing atmospheric conditions, solar reflections, a variation of the sample emittance with wavelength, temperature, direction and surface condition, and in case of cavity receivers, reflected thermal radiation from surrounding hot surface.

Errors due to reflected thermal radiation in a cavity are typically not decisive for the selection of the spectral range. However, if significant, they should be corrected by including the reflected thermal radiation in the measurement equation. Assuming diffusely reflecting and emitting surfaces, a simple approach that approximates the radiance \( L_{i,\lambda_{m}} \) leaving a measurement spot \( i \) with \( N \) hot surface elements in the surroundings is given by:

\[
L_{i,\lambda_{m}} = \varepsilon_{i,\lambda_{m}} \cdot L_{h,\lambda_{m}}(T_{c}) + \left[1 - \varepsilon_{i,\lambda_{m}}\right] \sum_{j=1}^{N} g_{ij} \cdot L_{h,\lambda_{m}}(T_{j})
\]

(4)
where \( L_{b,T_i} \) denotes the blackbody radiance of the corresponding temperatures \( T_i \) and \( T_f \). The configuration factors \( g_{ij} \) are either calculated with numerical formulations or analytical expressions for simple geometries\(^9\). For non-diffuse surfaces the directional properties have to be considered by integrating the bi-directional reflectance and the directional emittance over the solid angle occupied by each surface element. A detailed discussion addressing the problem of cavity reflection errors is beyond the scope of this manuscript and selected references are given for further reading\(^{10-12}\).

For measurements on solar absorbers, the measured radiometric signal must be completed with the signal due to the reflected part of the incident concentrated solar radiation. For a simple solar-blind approach measurement deviations due to reflected solar radiation cannot be corrected and the pyrometric temperature that is still calculated according to equation (1) always tends to be higher than the true temperature. Thus, for the estimation of the overall temperature measurement error, the resulting deviation in the radiometric signal due to reflected solar radiation is included as systematic error, while the uncertainties in the calibration factor \( \sigma_y \), the corrected atmospheric transmittance \( \sigma_f \) and the target emittance \( \sigma_e \) are supposed to be of stochastic nature and statistically uncorrelated. Following the Guide to the Expression of Uncertainty in Measurement GUM\(^{13}\), the expanded uncertainty of the pyrometric temperature measurement can then be approximated as:

\[
\frac{\Delta T_{\text{obj}}}{T_{\text{obj}}} = C_{\lambda_m} \cdot \left[ k \cdot \frac{1}{3} \left( \frac{\sigma_f}{\varepsilon_{\text{obj},\lambda_m}} \right)^2 + \frac{1}{3} \left( \frac{\sigma_f}{\tau_{\text{atm},\lambda_m}} \right)^2 + \frac{1}{3} \left( \frac{\sigma_f}{\gamma_c} \right)^2 + \frac{\Delta S_{T,\lambda_m}}{S_{\text{rad},\lambda_m}} \right] \quad (5)
\]

with \( k = 2 \) being a conservative estimate of the coverage factor with a coverage probability of 95% for an uniform probability distributions of the stochastic uncertainties.

As shown in Figure 1, \( C_{\lambda_m} \) increases with the product of temperature and wavelength. Thus, for a prescribed range of temperatures, the influence of the temperature uncertainty on the errors in the radiometric signal can be reduced by selecting the operating wavelength of the pyrometer as short-wave as possible. However, the practical spectral measurement range has a theoretical limit imposed by the Planck function (see Figure 1), and for \( \lambda_m T_{\text{obj}} \) smaller than approximately 1000 \( \mu\text{mK} \) a low signal-to-noise ratio can result in considerable temperature measurement errors, especially for narrow-band filters.

In order to avoid solar reflection errors one is further limited to spectral regions where the emitted thermal radiation exceeds the reflected solar radiation by a multiple. As can be seen in Figure 2, the influence of solar reflections increases in the short-wave spectral range, limiting solar-blind spectral measurement ranges to windows where the atmosphere absorbs the incoming solar radiation sufficiently.
The reflectance $\rho_{hel,\lambda}$ of a typical solar concentrator displayed in Figure 2 has been analysed for a 3 mm glass layer with a silver coating on its backside using the optical constants of low-iron soda lime glass\textsuperscript{14} and silver\textsuperscript{15}. It can be seen clearly that the reflectance of the backside coated mirrors drops at around 2.7 µm resulting in a significant attenuation of the spectral irradiance of the concentrated solar radiation. In solar furnaces, apart from heliostats a secondary concentrator is usually used, which might even enhance the resulting filter effect of backside coated solar concentrators\textsuperscript{5}.

Influence of reflected solar radiation

For ideal diffusely-reflecting solar absorbers, the relative deviation in the measured signal caused by reflected solar radiation can be estimated by the ratio of reflected solar irradiance $(1 - \varepsilon_{obj,\lambda_n}) \cdot E_{ksol,\lambda_n}$ and emitted radiant exitance $\varepsilon_{obj,\lambda_n} \cdot M_{b,\lambda_n}$:

$$
\frac{\Delta S_{rad,\lambda_n}}{S_{rad,\lambda_n,\text{diff}}} = \left(1 - \varepsilon_{obj,\lambda_n}\right) \cdot \frac{E_{ksol,\lambda_n}}{\varepsilon_{obj,\lambda_n} \cdot M_{b,\lambda_n}(T_{obj})}
$$

(6)

To simplify the notation, a wavelength-independent Lambertian emission is assumed, which holds for most surfaces for narrow-band spectral measurement ranges and emission angles smaller than 30°. Following the one-colour principle, the contribution of the concentrated solar radiation $E_{ksol,\lambda_n}$ can be calculated as:

$$
E_{ksol,\lambda_n} = c \cdot \int_{\lambda_n} R_{\lambda} \cdot \rho_{hel,\lambda} \cdot E_{sol,\lambda} d\lambda
$$

(7)

with $R_{\lambda}$ the sensor spectral responsivity that incorporates the transmittance of the optical train (lenses, optical fibre, filter) and the sensitivity of the light detector, $c$ the concentration factor of the solar concentrator and $E_{sol,\lambda_n}$ the spectral irradiance of the solar spectrum.
A similar expression can be derived for specularly reflecting targets. In this case, the impact of the error by reflected solar radiation is determined by the ratio between the reflected and emitted radiance. The comparison of the ratio of the reflected and emitted irradiance and radiance reveals the influence of the bi-directional reflectance on the estimation of measurement deviations due to reflected solar radiation. It can be shown that measurement deviations due to ideal specular reflections equal measurement deviations on diffuse reflecting targets with a solar concentration factor $c$ that is determined by the thermodynamic limit of light concentration divided by $\pi$. Thus, the relationship between solar reflection errors due to the diffuse and specular reflections can be found as:

$$\left( \frac{\Delta S_{\text{r},\lambda_n}}{S_{\text{rad},\lambda_n}} \right)_{\text{spec}} = \frac{1}{c \cdot \pi \cdot \sin^2 \theta_s} \left( \frac{\Delta S_{\text{r},\lambda_n}}{S_{\text{rad},\lambda_n}} \right)_{\text{diff}} \approx \frac{15000}{c} \left( \frac{\Delta S_{\text{r},\lambda_n}}{S_{\text{rad},\lambda_n}} \right)_{\text{diff}}$$

(8)

where $\theta_s$ is the half-cone angle of the sun’s disk.

Real surfaces normally exhibit a glossy reflection behaviour of diffuse and directional components, which complicates the estimation of the solar reflection errors. A realistic modelling of the reflected solar radiation is usually not feasible because of the uncertainty in the bi-directional reflectance and the directional properties of the incoming solar radiation. A simple approach to check for a possible interference of the reflected solar radiation on the pyrometrically measured temperature is to replace the diffuse reflectance in equation (6) with the maximum of the bi-directional reflectance. A further simplification is achieved with the approximation of the bi-directional reflectance by two independent functions of angle and wavelength. Thus, for radiation sources with small beam divergence the relation between the normal-hemispherical reflectance $\rho_{\lambda}^{n,h}$ and the normal-normal reflectance $\rho_{\lambda}^{n,n}$ can be expressed as:

$$\rho_{\lambda}^{n,h} \approx \rho_{\lambda}^{n,n} \cdot \eta_d$$

(9)

with the diffusivity factor $\eta_d$ defined as the integral of the bidirectional reflectance $\rho^*$ over the hemisphere$^{16}$:

$$\eta_d = \int_\omega \rho^* \cdot \cos(\theta) \, d\omega$$

(10)

For ideal diffuse reflectors the diffusivity factor equals $\pi$ while for specular reflectors it tends to zero. Using the normal-normal reflectance as approximation for the maximum of the bi-directional reflectance for near-normal incidence directions, an estimation of the error influence caused by reflected solar radiation results as:

$$\left( \frac{\Delta S_{\text{r},\lambda_n}}{S_{\text{rad},\lambda_n}} \right)_{\text{glos}} < \frac{\pi}{\eta_d} \left( \frac{\Delta S_{\text{r},\lambda_n}}{S_{\text{rad},\lambda_n}} \right)_{\text{diff}}$$

(11)
Note that equation (11) is a rough and conservative measure to verify the effect of the reflected solar radiation on the pyrometric temperature measurement. It is not appropriate for any corrections of the measurements.

As a result of the wavelength-independent approximation of the angular distribution of the reflected radiation, the diffusivity factor can be assigned equally to possible spectral measurement ranges in the near- and mid-infrared spectral region (1-12µm). This assumption may not be valid for many real surfaces, because the angular distribution of the bi-directional reflectance is in general a function of wavelength. However, the approximation is appropriate for an analysis of absorber materials in order to select an adequate solar-blind spectral measurement range. Figure 3 indicates the factor $\pi/\eta_{\lambda\nu}$ and the emittance in wavelength and temperature ranges significant for pyrometric temperature measurements on high-temperature solar absorbers. The diffusivity factor $\eta_{\lambda\nu}$ was determined based on estimations of the bi-directional reflectance in the near infrared (0.830 µm) with an optical fibre reflectometer.

![Figure 3. Emission and reflection behaviour of some materials commonly used in high-temperature solar applications](image)

The optical properties of solar absorbers are strongly dependent upon material and surface conditions. Figure 3 indicates that optically smooth surfaces like the selective parabolic trough absorber coating tend to show a marked directional peak. This in turn might lead to elevated errors of the temperature measurements in the direct solar reflection cone. In contrast, porous materials with a random facet orientation like the SiC foam absorber matrix do not differ significantly from the ideal diffuse reflection behaviour. While polished and blank metallic surfaces are usually characterised by a high directional component, oxidised metal surfaces often show almost perfect diffuse reflection behaviour. In case of NiCrFe alloys shown in Figure 3, the operation at high temperatures leads to the formation of a spinel oxide film of a mixture of NiF$_2$O$_4$ and FeCr$_2$O$_4$ that covers the metallic absorber surface. For normal and near-normal incident directions, the rough oxidised metal surfaces reflect radiation in an almost ideal diffuse way, similar to that of Al$_2$O$_3$ coatings used as a reflection target in solar flux density measurement systems.
Spectral measurement range considerations

Quasi-diffusely reflecting targets
Depending on reflectance and temperature of the measurement object, for the quasi-diffuse reflection properties of porous ceramic absorber materials and rough oxidised metal surfaces the filter effect of the concentrating mirrors might already be sufficient to reduce the influence of reflected solar radiation to a tolerable limit. In order to reduce the influence of measurement uncertainties due to unknown or variable emittance of the measurement object, the shortest possible operating wavelength should be selected. An operating wavelength in the atmospheric window between 4.3 µm (CO₂) and 6.3 µm (H₂O) already halves the sensitivity on emittance uncertainties as compared to the sensitivity range of 8-12 µm, typical for the standard LWIR cameras (see Figure 1). For elevated temperatures, a further reduction of sensitivity coefficient with an operating wavelength in the narrow absorption bands in the near infrared at 1.86 µm and 1.38 µm can be advantageous. However, care must be taken because of the narrow bandwidth of the absorption bands and a possible overlap of the wings of the spectral filter transmittance with the solar spectrum. The resulting temperature measurement errors due to reflected solar radiation depend on the solar concentration, the target emittance, temperature and the spectral distribution of the solar spectrum influenced by air mass, precipitable water, and the elevation above sea level of the experimental setup. Depending on the exact filter transmittance curve, the solar concentration, and the emittance of a target, the 1.86µm spectral measurement range seems to be favourable for temperatures above approximately 1000°C and the 1.38 µm for temperatures higher than approximately 1200°C. At short measurement distances (<1 m), the atmospheric absorption in these weak absorption bands can be neglected. At larger measurement distances corrections of the atmospheric absorption might be necessary.

Selecting the ultraviolet spectral region 280-292 nm for absorber temperatures above 1500°C leads to temperature measurements that are almost unaffected by variation in the target emittance due to the low sensitivity function. However, the low radiance emitted by the measurement object in the UV-B spectral range requires a very sensitive and low noise measurement system. This can be achieved by using photo multiplier tubes with a wide dynamic range to handle the exponential increase of the radiometric signal with temperature.

Specular and glossy reflecting targets
A common example for pyrometric temperature measurements under the influence of specular solar reflections are absorbers that are installed behind a glass cover. Besides specular reflective properties of windows the possible spectral measurement range is limited to the transmittance range of the window material. The measurement through quartz might be possible up to 3.5-4 µm, depending on the specific properties of the quartz used, while for technical glasses usually water related absorption in the glass hinders from measuring the absorber temperature beyond 2.7 µm.
For some applications it is possible to align the pyrometric setup to measure outside the direct solar reflection cone. In this case the selection of the spectral measurement range depends on the diffuse component of the bi-directional reflectance and the temperature of the solar absorber as described in the previous section. For conditions where direct reflections in the sensor direction cannot be ruled out, a measurement in the 2.7 µm water absorption band shows a sufficient suppression of the solar radiation to be able to avoid misinterpretations of hotspots due to solar reflections. For a temperature range above 400°C a narrow-band spectral filter at 2.63 µm was found to enable solar-blind pyrometric temperature measurements through quartz and through usual technical glasses. Concerning the strong absorption in the 2.7 µm atmospheric water absorption band the measurement distance has to be minimised and already at short measurement distances atmospheric absorption corrections are necessary to account for varying atmospheric conditions. Atmospheric corrections with line-by-line calculations based on spectrometric databases like HITRAN have been proven to be able to reduce the uncertainty in the transmittance corrections to magnitudes of around 2 %, similar to usual uncertainties in the emittance of the measurement object.

Another strategy to avoid solar reflections for both diffuse and specular reflecting targets is to choose the spectral measurement range at the so-called Christiansen wavelength, where the sample approximates blackbody behaviour. In the case of measurements of temperatures on glass covers the high emittance values in the opaque spectral region and the filter effect of the concentrator allow a solar-blind measurement for temperatures above 400°C, despite the specular reflection properties of the glass window. To avoid atmospheric absorption effects due to the 6.3 µm atmospheric absorption band and because of the smear out of absorption edges of glasses at high temperatures, the recommended measurement range reduces to approximately 5-5.5µm.

**Conclusions**

In order to avoid errors caused by the reflected solar radiation, the operational wavelength of pyrometric measurements in concentrating solar thermal applications has to be selected in a spectral interval in which the concentrated solar irradiance is negligible. Possible spectral measurement ranges are the gaps due to strong atmospheric absorption bands in the short-wave infrared (1-3 µm) or intervals with high attenuation of backside coated mirrors. The concentration level, the target temperature and the optical properties of the solar receiver, in particular the bi-directional reflectance, determine the influence of solar reflections and thus the required selectivity of the spectral measurement range. For diffuse and quasi-diffuse reflecting targets the filter effect of the concentrator mirrors might be already sufficient to avoid solar reflection errors. To reduce the sensitivity of the pyrometric temperature measurement, at high temperatures the narrow absorption bands in the short-wave infrared can be used. Solar-blind ranges for diffusely reflecting targets and various target temperatures and specific boundary conditions were found for operational wavelength of 5.2 µm and 4.56 µm, in the weak absorption bands at 1.86 µm and 1.38 µm, and in the UV-B spectral interval for temperatures above 1500°C. In case of targets with unavoidable directional reflections, the atmospheric water absorption band at 2.7 µm is suitable to obtain reasonable accuracy of the pyrometric temperature measurements.
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References and Notes


