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Assessment of Double Modulation Pyrometry as a diagnostic tool for use in concentrated solar facilities

Dimitrios Potamias[a], Ivo Alxneit[a,1], Jean-Louis Sans[c], Emmanuel Guillot[c], Alexander Wokaun[b]

[a] Solar Technology Laboratory, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
[b] Department Energy and Environment, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
[c] PROMES-CNRS, 7 Rue du Four Solaire, F-66120 Font Romeu, France

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ABSTRACT

Double modulation pyrometry (DMP) is a pyrometric method developed to enable radiometric temperature measurements in solar simulators, where solar blind pyrometry cannot be applied due to the continuous spectrum of the artificial light source. Sofar, DMP has been characterized in two solar simulator facilities, but no direct comparison to a reference pyrometer has been performed until now due to the limitations of applying pyrometry in solar simulators. Here, a series of experiments is reported that were conducted in concentrated natural sunlight where reference pyrometers are available. They demonstrate the performance enhancement gained by utilizing the inherent advantages of DMP, i.e. the *in-situ* reflectance measurement and the freedom to select the operation wavelength.

1. Introduction

In a typical experiment conducted under concentrated solar radiation the surface of interest with reflectance ρ is irradiated by a flux I_0 of a few thousand suns (1 sun = 1 kW/m^2). In this situation, non-contact temperature measurement is challenging: The strong reflected component $\rho{\cdot}I_0$ is also detected by the optics of a conventional pyrometer and erroneously attributed to the thermal signal, causing a large error. Solar blind pyrometry (SBP) overcomes the problem by sampling the emitted thermal radiation in a narrow wavelength band where the solar spectrum is attenuated by atmospheric absorption, and thus $\rho{\cdot}I_0$ is minimal. Alternatively, wavelengths where the solar radiation is absorbed by the concentration optics can be used. Application of SBP at $\lambda = 1.39$ μm was demonstrated in Ballestrín et al. (2010), where a sample of high emittance was measured, with a relative bias of ≈ 5% at 1223 K. Usually, the dominant measurement uncertainty in pyrometry results from the unknown emittance ε of the sample, particularly when low ε samples are measured. In Crane (2010), temperature measurements from two SBPs observing the sample over a range of temperatures were combined to estimate ε and T enabling measurements where the emittance is unknown. ε has to be assumed independent of temperature but may be wavelength dependent. To enable satisfactory convergence the method requires measurements spanning a wide range of temperatures.

DMP was developed (Alxneit, 2011) to enable temperature measurement in solar simulators, where SBP cannot be applied due to the continuous spectrum of the xenon-arc light source. While SBP measures in the absence of external radiation, DMP actively tracks and filters out the reflected flux $\rho{\cdot}I_0$ from the radiance observed. Active filtering offers two distinct advantages that were recently assessed in a solar simulator facility (Potamias et al., 2017, 2018). First, accuracy can be improved by an *in-situ* reflectance measurement. Second, the user is no longer limited to operate at one of the few solar-blind compatible wavelengths. Instead, DMP offers flexibility to select any wavelength band within the near-IR region of the spectrum that optimally fits the experimenter's need, in matching sample properties or falling within the range where emittance data is available in case $I_0(t)$ cannot be provided. Hence, these characteristics make DMP an interesting diagnostic tool also for experiments conducted in concentrated natural sunlight.

The objective of this paper is twofold. First, to demonstrate how the free choice of the operation wavelength and the *in-situ* measurement of ρ can improve temperature diagnostics in a solar furnace facility. It will be demonstrated that $\rho(t)$ can be extracted from the on-line measured $\rho{\cdot}I_0$ by utilizing the readily available data of direct normal irradiance (DNI) proportional to $I_0(t)$. Second, to document the direct comparison of DMP against a reference solar blind pyrometer on several samples with different optical and thermal characteristics. DMP will record two

E-mail address: ivo.alxneit@psi.ch (I. Alxneit).
[1] Current address: Bioenergy and Catalysis Laboratory, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland.

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temperatures: $\tilde{T}_{\mathrm{dmp}}$ where the on-line measured ε is used and T_{dmp} using constant emittance measured on the samples before the experiments. Such a direct comparison between DMP and a reference pyrometer has not been possible in solar simulators, as no reference method insensitive to the intense reflected radiation exists. So far, only measurements on a thin platinum sample that was assumed isothermal, where DMP observed the irradiated surface, while a conventional pyrometer observed the back side of the sample were reported (Potamias et al., 2017).

In the following, the methodology of DMP will be presented and the use of DNI data to determine *in-situ* the reflectance of the samples will be discussed. Then, the experimental setup will be introduced as well as the calibration and measurement procedures. Finally, temperature and reflectance measurements from experiments conducted on two metallic samples (copper, stainless steel 310S) and three oxide ceramics (Al_2TiO_5, ZrO_2, CeO_2) will be presented and the relative performance of DMP will be discussed.

2. Theory

2.1. Double modulation pyrometer

Fig. 1 shows DMP installed in a vertical solar furnace at PROMES-CNRS: Quasi-parallel radiation from the heliostat passes through a shutter regulating its intensity I_0. A fraction of the radiation is then intercepted by the rotating blade that modulates the flux I_0 at a frequency of ω_1. A paraboloidal reflector focuses the radiation onto the target's surface, where it is in parts absorbed and reflected. Both, the reflected component ($\rho \cdot I_0$) and the thermal self-emission ($\varepsilon \cdot I_{\mathrm{th}}$) leave the hot surface. The fraction of the radiance within the narrow cone subtended by the DMP optics is collected, chopped at ω_2 and detected. The detector output $D(t)$ is fed in parallel to two lock-in amplifiers (LIA) that are phase-locked to ω_1 and ω_2, thereby extracting respectively,

$$\begin{aligned} \mathrm{LIA}_1(t) &\propto M_1 \cdot \rho(t) I_0(t) \\ \mathrm{LIA}_2(t) &\propto M_2 \cdot (\varepsilon(t) I_{\mathrm{th}}(t) + \rho(t) I_0(t)), \end{aligned} \tag{1}$$

where M_1 and M_2 are the modulation functions that remain constant for a given instrument configuration. More details about the DMP hardware and its operation principle can be found in Alxneit (2011) and Potamias et al. (2017). Note, that in the specific setup realized at PROMES-CNRS, M_1 increases as shutter transmittance () is decreased because the rotating blade is positioned parallel to the shutter blades and is not shaded until the shutter closes substantially. Thus, as the shutter initially closes I_0 decreases but the absolute amount of radiation blocked by the rotating blade remains constant. Therefore, the blocked fraction of the solar flux, therefore also the amplitude of M_1, both increase as the shutter closes. Constant quantities such as the reflectance of the paraboloid, geometry factors related to the collection optics, and the detector gain are contained in the proportionality factor of Eq. (1). The thermal signal $S(t)$ is obtained as the difference if both $\mathrm{LIA}_1(t)$ and $\mathrm{LIA}_2(t)$ are properly scaled. The scaling factors g are obtained from the observation of a cold reference ($I_{\mathrm{th}} \to 0$) where both LIAs only detect the reflected radiation allowing the thermal emission of a hot sample to be determined as

$$S(t) = \mathrm{LIA}_2 - g \cdot \mathrm{LIA}_1. \tag{2}$$

$\rho(t)$ can be obtained from $\mathrm{LIA}_1(t)$ (Eq. (1)) if the incident flux is either constant or can be measured independently. In the present case a relative measure of $I_0(t)$ is readily available as the product of the measured DNI and of

$$I_0(t) \propto \mathrm{DNI}(t) \cdot \tau_{\mathrm{shutter}}(t). \tag{3}$$

$\mathrm{DNI}(t)$ is available from a pyrheliometer, while $\tau_{\mathrm{shutter}} \in [0, 1]$ is obtained from the shutter control system. In the following, Lambertian and opaque samples are assumed where $\varepsilon = 1 - \rho$ is a good approximation of the directional spectral emittance.

The measured signal S combined with the measured ε is converted to a true temperature by the algebraic Sakuma-Hattori equation (Bakker et al., 1973; Saunders et al., 2008; Saunders, 2011)

$$T = \frac{c_2}{k_2 \cdot \log\left(k_1 \cdot \left(\frac{S}{\varepsilon}\right)^{-1} + 1\right)} - \frac{k_3}{k_2} = f_{\mathbf{k}}(S, \varepsilon), \tag{4}$$

where $\mathbf{k}$ is a three-element vector that holds the calibration coefficients (Bakker et al., 1973).

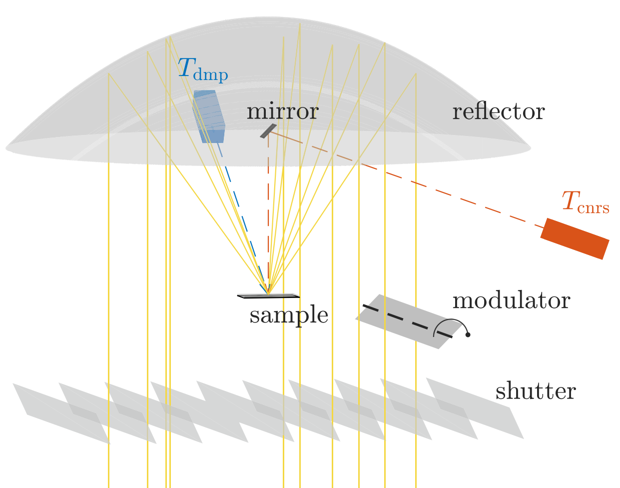

Fig. 1. Experimental setup: Solar radiation from the heliostat passes a shutter where its total flux I_0 is controlled. A paraboloidal reflector focuses the radiation onto the sample. A rotating blade is mounted below the sample and imprints a modulation of a few % at $\omega_1 = 7$ Hz onto the solar flux. DMP observes the sample at an angle while the CNRS pyrometer measures normal to the sample's surface (via a small mirror).

3. Experimental

Setup: The experiments were conducted at the vertical-axis solar furnace facility in Odeillo, France. The experimental setup is shown in Fig. 1. A heliostat at the base of the facility deflects radiation onto a 1.5 m diameter parabolic reflector. The system can deliver up to 800 W over an area of about 1 cm^2 giving rise to a peak concentration of 15 MW/m^2 under nominal conditions of 1000 W/m^2 direct normal irradiance as measured with calorimetric and camera based flux measurement techniques. Guillot et al. (2014) DNI measurements are provided by a pyrheliometer. The flux I_0 to the sample is regulated a computer-controlled shutter system.

Samples: Disk shaped samples of copper, stainless steel 310S, and Al_2TiO_5 (15 × 5 mm^2, d × h) as well as reticulate porous ZrO_2 and CeO_2 (65 × 25 mm^2, d × h) were used. Their thermal conductance and reflectance at $\lambda = 5.5\,\mu m$ were determined before. The hemispherical emittance at high temperatures was measured using the MEDIASE (Sani et al., 2014) setup (Moyen d'Essai et de Diagnostic en Ambiance Spatiale Extreme) of the PROMES-CNRS Megawatt Solar Furnace (MWSF).

Double modulation pyrometer: A lens that picks up radiation coming from the sample was mounted inside the parabolic concentrator. The radiation was fed to the detection unit located outside the solar furnace by a fiber optical cable. The rotating blade modulator was located between the sample and the shutter. Details on the detection and analysis components used in the DMP can be found in Alxneit (2011), Potamias et al. (2017, 2018).

Solar blind pyrometer: Installed at the facility was a radiometer (Heitronics KT19) that operates at 5.5 µm and has an effective observation angle of $\theta = 0°$. It observed the sample via a tilted mirror above the focal plane. The radiometer used as pyrometer had been calibrated in this configuration against a black body reference. Values