

Improved algorithm for true temperature measurement using dual-wavelength thermography

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Abstract

The following paper deals with quantitative dual-wavelength thermography, which hinges on precise, contactless temperature measurement. The success of this measurement depends on emissivity, influenced by material surface, wavelength, temperature, and observation angle. Small uncertainties in emissivity can lead to large temperature deviations. In a previous paper first simulations showed that within certain limits true temperature measurement is possible. Here, we will look at it in a more theoretical, mathematically resilient way. Assuming the absence of measurement errors, the algorithm can identify precise temperature in two iterations. The accuracy is contingent on the device's limitations

1. Introduction

Thermal radiation is a heat transport phenomenon that requires no medium. In 1879, Josef Stefan discovered that the total radiation power of a black body is proportional to the fourth power of its absolute temperature T , with Ludwig Boltzmann providing the theoretical proof. Planck's law, formulated later, accurately described the black body radiation spectrum, confirmed by Lord Rayleigh's work in wave theory. [1]

Devices that make use of thermal radiation, namely pyrometers, are essential in applications where physical contact is impractical, such as rotating machinery or environments requiring material purity like semiconductor manufacturing. Pyrometers typically operate from the visible spectrum to the mid-infrared range as a consequence of available detectors and temperatures ranges in demand covering typical temperatures from just above room temperature to 3000°C.

Planck's Radiation Law, expressed as:

$$M_{bb}^{\lambda} = \frac{8\pi hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1} \quad (1)$$

with speed of light c ; Planck's constant h and Stefan-Boltzmann constant k_B relates an object's temperature T to its thermal radiance M as a function of wavelength λ [2]. Eq. (1) is valid for ideal black bodies (bb), but real objects require adjustments to include emissivity ε as a proportionality factor for accurate temperature readings. When an object's emissivity is less than one but constant across the spectrum, it is considered "grey.", "coloured" otherwise. The knowledge on emissivity is crucial for any kind of pyrometry as the emissivity changes the thermal radiance M linearly, while this changes temperature exponentially at the same time (cf. Eq. (1)).

Dual-wavelength pyrometers measure temperature by comparing thermal radiation at two wavelengths, maintaining a constant ratio even with uniform background interference, allowing accurate temperature assessments without direct emissivity measurements if and only if this ratio remains constant throughout the measurement [3-4]. This constant ratio, however, cannot be held anymore for a change in background or surface properties just to name two examples. In addition, this pronounced ratio is often unknown and even more sensitive to changes than the individual emissivities that make up the ratio as explained earlier.

Advanced techniques necessitate assumptions about temperature-emissivity relationships or models relating emissivity with wavelength. Various methods for accurate temperature measurement using pyrometry without detailed emissivity knowledge include reflectometry, which determines emissivity through radiation conservation, and dual-wavelength pyrometry, supplemented with material property data from literature. [5-6] Here, we are going to present an approach that works without those kind of assumptions.

2. Theory

In analyzing thermal processes, it is essential to consider the *interplay* between emissivity, *temperature and spectral radiance* as described by Planck's Radiation Law (cf. Eq. (1)). The theoretical framework posits that for any two wavelength positions in Planck's Radiation Spectrum, it is always possible to identify two emissivities, $\varepsilon_1(\lambda_1)$ and $\varepsilon_2(\lambda_2)$, to match any

desired temperature, given that emissivity is an irrational number between 0 and 1. However, all subsequent measurements will narrow that list down to just one possible combination of emissivities ε_1 and ε_2 .

To simplify this derivation, consider a thermal process with constant material properties, i.e. unchanged emissivities, but varying temperatures. This scenario reflects real processes as temperature is never a constant physical state. If I chose any two wavelength positions in Planck's Radiation Spectrum, then it is possible to find these two emissivities ε_1 and ε_2 that give a perfect fit for a any temperature T . These emissivities will change with temperature but they will always match the measured radiance. The true temperature keeps hidden within. So far one is left with a continuous range of possible temperatures for an ideal measurement with accuracy and reproducibility of 0 K.

However, as $M_{bb}^{\lambda_1}/M_{bb}^{\lambda_2}$ is a bijective strictly monotone decreasing function $f(T)$ of temperature, i.e. $T_1 < T_2 \Leftrightarrow f_1(T) > f_2(T)$ for $\lambda_1 < \lambda_2$, the assignment of emissivities ε_1 and ε_2 to $f(T)$ is unique. Combining Eq. (1) with this ratio leaves us to:

$$\varepsilon_2/\varepsilon_1 F_{Ratio}^{1,2}(T) = M_{bb}^{\lambda_1}(T) / M_{bb}^{\lambda_2}(T) \quad (2)$$

with emissivities ε_1 and ε_2 which correspond to the two single-wavelength-channels at λ_1 and λ_2 , with the respective real spectral radiances $M_1(T)$ and $M_2(T)$, their ratio $F_{Ratio}^{1,2}(T)$ as well as their black body equivalents $M_{bb}^{\lambda_1}(T)$ and $M_{bb}^{\lambda_2}(T)$.

If a second measurement is undertaken given that there is no change in effective emissivity, say by surroundings or material properties, again it will be possible to find a set of emissivities $\varepsilon_1(\lambda_1)$ and $\varepsilon_2(\lambda_2)$ for any temperature, but this time there will only be one temperature which has been deduced by exactly the same set of emissivities as in the measurement before. Therefore, for ideal conditions devoid of measurement uncertainties, only one combination of emissivities can reproduce both measurements, however close others may come. This leads to accurate emissivity determination and true temperature measurement. It should be added, that the mentioned change does not need to be excluded. Moreover, it ought to happen on a timescale that is long in comparison to the measurement frequency of the pyrometer. Further, this algorithm holds for true measurements, but then it requires more than just two iterations as it had already been demonstrated in a previous paper [6].

3. Proof of Concept

Taking the example of hot rolling in a rolling mill, the steel, cast into slabs, needs to be brought to the austenitic phase typically between 1070K and 1470K to be ductile and plastic, facilitating the rolling process. Therefore, temperature monitoring is very important in this regime. After the rolling process the steel slabs are usually rapidly cooled, namely quenched, to take them into the martensite state, a hard, but brittle structure formed by diffusionless transformation. [10]

During hot rolling, the steel typically cools continuously as it passes through the rolling mill by both natural convection and contact with the rolling stands. However, efforts are made to maintain the temperature within a specific range to ensure the desired material properties and formability for milling. Sometimes intermittent heating is used to bring the steel to the desired temperature and compensate for heat losses, ensuring formability and consistent material properties. [10]

Yet, the importance of reliable temperature monitoring goes beyond. The temperatures during hot rolling promote recrystallization, resulting in a fine-grained microstructure and improved mechanical properties. Temperature control thus ensures a uniform structure and composition of the steel, enhancing the quality of the final product. [11] After hot rolling, the cooling rate of the steel must be controlled to achieve the desired mechanical properties, either through air cooling or quenching baths. Typical cooling rates during hot rolling range from 1K to 10K per second, depending on material thickness, rolling speed, ambient temperature, cooling methods, and material composition. [10]

Therefore, the following simulation has chosen different time frames within the cooling process, may it be naturally while rolling or deliberately afterwards. Time intervals are not constant and are chosen such that the drop in temperatures increases to show the strength of the algorithm for large, but also small changes between the above described two measurement iterations. Further, the taken emissivities do not resemble the material steel, but are arbitrarily chosen. For a fictional measurement at 1420K device accuracy and repeatability are included to highlight the crucial part of device quality for the proposed algorithm.

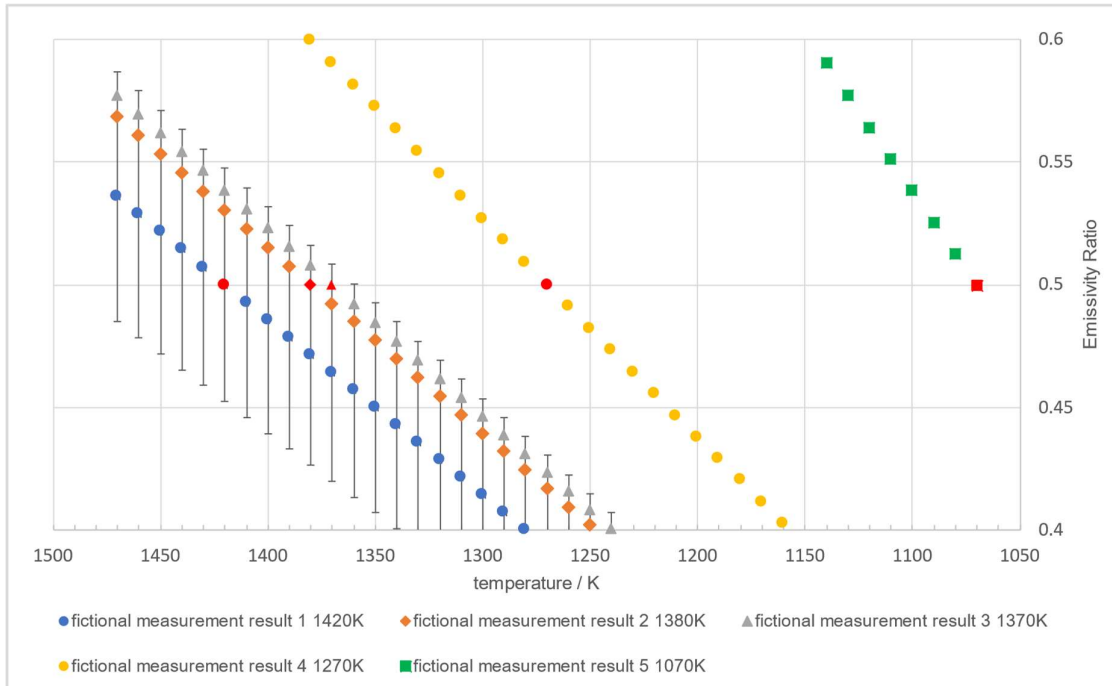


Fig. 1. Simulation of emissivity ratio $\varepsilon_2/\varepsilon_1$ during cooling at different time frames and thus temperatures.

Fictional measurements were undertaken at five distinct temperature values. The red marks indicate the position of the actual temperature during the cooling with the true emissivity ratio of 0.5. For a fictional measurement at 1420K device accuracy and repeatability are included at a total impact of 5%. The calculation used Eq. (1) at $0.9\mu\text{m}$ and $1.1\mu\text{m}$.

At its core, the algorithm returns emissivity ratios that can be converted into temperatures readings for a fictional user. Here, this last step is omitted as it does not add additional value to the proof. The simulation assumes a ratio of 0.5. For each fictional measurement, a table of emissivity ratios as a function of temperature was calculated using Eq. (1) to indicate the unique relationship explained above in the theory section. But only a second iteration (here: 5 in total) reveals which one of them actually matches the material properties. The red marks indicate the position of the actual temperature during the cooling and the true emissivity ratio of 0.5 is returned each time.

The algorithm shows clearly that only for the correct fictional temperatures (simulation input) one distinct emissivity ratio (simulation output, here: 0.5) is returned. The included measurement uncertainties for a fictional measurement at 1420K, however, show that this algorithm can produce the same true or false temperature value that a user would obtain knowing the exact emissivity ratio. Accuracy and reproducibility of the devices cannot be compromised. Figure 1 shows the error indication assuming 5 % total uncertainty for measurements at a wavelength of $(0.09 \text{ and } 1.10) \mu\text{m}$ which in this case returns a misreading in temperature of more than 50 K which cannot be avoided. Due to Planck's Radiation Law this mismatch gets more pronounced with increasing central wavelength.

4. Analysis of Results

The results underscore what has been intuitively understood: precise temperature measurement is intrinsically linked to the quality of the pyrometer measurements. The accuracy and reproducibility of these measurements set the limitations.

Larger errors can be attributed to the behaviour of Planck's Law of Thermal Radiation at longer wavelengths. As Planck's Radiation Law tells us in case that the (detection) wavelength as a function of the temperatures to measure sits on the flat low-energy tail of the Planck curve a given temperature difference is harder to distinguish as for the high-energy fast-rising tail of the curve. This leads to the circumstance that even a small error in assumed emissivity can lead to significant temperature reading errors, and vice versa, as emissivity is the one parameter that introduces a degree of freedom to for Planck's Radiation Law despite the unique mathematical relationship set out in Eq. (1). Likewise for a given fractional mismatch in emissivity the resulting mismatch in temperature is larger for smaller emissivities. This is a direct consequence of the exponential relationship between thermal radiation and temperature. Therefore, the results align with the implications of Planck's Radiation Law (cf. Eq. (1)). However, these implications only hold true when considering the

measurement uncertainties of the pyrometer. In other words, the higher the quality of the measurement, the smaller the impact of Planck's Radiation Law on the results.

Still, from a mathematical point of view a perfect match in true and calculated / measured temperature can be found by this algorithm. The practical implication is significant for industries relying on precise temperature monitoring, such as metallurgy and semiconductor manufacturing, where accurate thermal readings are critical for process control and product quality.

5. Closing Discussion and Outlook

This paper presents a profound mathematical proof and simulation-supported validation, demonstrating that true temperature measurement is possible with the constraints defined solely by the accuracy and repeatability of the pyrometer. Dual-wavelength pyrometers measure temperature by comparing thermal radiation at two wavelengths, maintaining a constant ratio even with uniform background interference, allowing accurate temperature assessments by themselves without direct emissivity measurements if and only if this ratio remains constant throughout the measurement. However, this is not the case, neither with respect to material surface changes throughout heat treatment nor with respect to surrounding measurement conditions.

Notably, the proposed method distinguishes itself by negating the necessity for prior knowledge of the material's emissivity and surroundings. This characteristic significantly simplifies the measurement process, making it more versatile and less dependent on specific material properties. Furthermore, the algorithm is designed to adapt automatically to changes in effective emissivity and variations in the measurement environment. This adaptive capability ensures that the method remains reliable and accurate even under varying operational conditions.

The robustness and adaptability of this approach make it highly suitable for practical, in-field applications. Whether used in industrial settings, research environments, or other scenarios requiring precise temperature measurements, the algorithm provides a dependable solution that can handle real-world variability and complexities. Though on-field verification is still pending this paper as well as prior attempts have already shown what is to be expected in real measurement environments. [9]

The conclusion of this paper has to be the question whether a true temperature measurement can really happen outside the laboratory. It needs to be asked whether the error in temperature is in fact lower than ensuring best in place measurement conditions and take a general assumption on the material's emissivity which may be outranged by 10 % or even 20 %. This question surely cannot be answered on paper without an application to consider. The algorithm being tested in field which will undermine its power in either way.

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