Development and Validation of an Algorithm for Emissivity-Corrected Pyrometry Independent of Material Properties

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Abstract. True contactless temperature measurement or pyrometry is closely connected to the knowledge of the material's emissivity which is generally a function of the material surface, wavelength, temperature and angle. The present paper will show how this indispensable parameter for contactless thermography can be deduced from real temperature data without any knowledge of and any demands on the material's chemical or physical structure. An algorithm was developed to deduce the unknown emissivity value by an iterative process involving random data taken with a virtual ratio or two-colour pyrometer within a temperature regime of 1100 K +/- 100 K. Possible influences on the simulation, namely level of true emissivity, emissivity ratio, measurement uncertainty and detection wavelength, were studied to find an increasing mismatch between the simulated and true emissivity for larger uncertainties and wavelengths which had been expected following Planck's Law of Thermal Radiation. An increased error has also been found for larger values of the true emissivity whereas no significant influence could be shown for the emissivity ratio of the two channels of a ratio pyrometer. The simulation was considered to be completed for results corresponding to a maximum deviation of 8 K from a given true temperature of 1100 K.

Keywords: Pyrometry, Thermography, Temperature Measurement, Emissivity, Algorithm, Ratio Pyrometry, Two-colour Pyrometry

1 Introduction

1.1 Importance of Emissivity for Pyrometry

Sensors for contactless temperature measurement are indispensable for applications that do not allow for direct contact due to surrounding circumstances, e.g. rotation bodies, or due to purity requirements of the material, e.g. semiconductors for microelectronic use. For this reason measuring devices (here: pyrometers) are needed which are able to detect thermal radiation from a distance.

Each body emits thermal radiation due to its own temperature and pyrometers measure this radiation in different spectral regimes (spectral pyrometers) or across the entire spectrum (broadband pyrometers). The detection regime, however, usually only stretches from the visual to the mid-infrared regime due to typical temperatures between 0 °C and 3000 °C. Planck's Radiation Law [1]

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

connects the object's temperature T to the detected thermal radiance M as a function of the detection wavelength λ. h and k_B denote the Planck and Boltzmann constant, respectively. However, this only holds for black bodies (here denoted by *bb*), i.e. objects that absorb and – according to Kirchhoff's Law [2] – emit 100 % of the incident radiation ($\varepsilon = 1$). Generally speaking, Kirchoff's Law states that the spectral and directional absorptivity $\alpha_{s,d}$ equals $\varepsilon_{s,d}$ at thermal equilibrium:

$$\alpha_{s,d}\,(\lambda,\gamma)_T = \varepsilon_{s,d}\,(\lambda,\gamma)_T \quad (2)$$

This is true for all objects, but hypothetical black bodies show a constant emissivity over wavelength and angle. Real bodies, however, are so called "coloured", which means that their absorption and thus emission actually differs as a function of wavelength (cf. (2)). For those bodies (1) is incomplete, it needs to be expanded by the emissivity ε. This is a very crucial parameter as it determines a true temperature measurement which makes it the most desired material parameter for pyrometry. In addition to the variables named in (2) ε also depends on the sample surface. Due to diffuse reflection which leads to an increased probability that incoming radiation is absorbed and thus to a greater absorptivity emissivity is larger for rough than for smooth surfaces. Moreover, emissivity may be a function of temperature itself. Further, dust or smoke may change the effective emissivity for the pyrometer. This shows the importance of the emissivity for temperature determination beyond its existence as a material parameter. Without the knowledge of an effective emissivity for the measurement pyrometry is rather radiometry of thermal radiation.

1.2 Ratio Pyrometry or Two-Colour Pyrometry

If an object's emissivity is smaller than *one* and constant independently of the spectral position, the object is said to be "grey". However, this reduction in emittance may also be effectively caused by any undesired surrounding appearances such as smoke that is assumed to act like a neutral density filter, i.e. reducing the power density and thus the apparent emittance of the material by a single factor also independently of the considered wavelength.

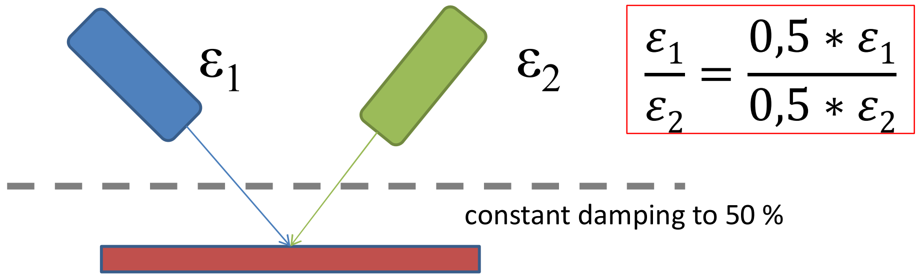

Fig. 1. Working principle of any ratio pyrometer for background-corrected temperature measurement of a hot object (shown in red) if the background meant constant damping illustrated as a dashed line. The two channels of a ratio pyrometer are represented by the green and blue bodies respectively. The damping affects both channels equally and is thus cancelled out of the quotient.

If two detectors 1 and 2 are applied to measure at the same position on the object's surface, but at different spectral regimes, and the corresponding emissivities ε_1 and ε_2 do not change during the measurement then their ratio remains unaffected by a constant damping as it is visualized in **Fig. 1**. The damping factor can be cancelled out from the emissivity ratio thus allowing for emissivity-independent temperature measurement. [3, 4]

Soon this idea had been applied to grey bodies which for a detector behave in the exact same way, namely reducing the emittance at all spectral positions by a constant factor which finally also leads to emissivity-corrected temperature measurement. Theoretically, it works for coloured bodies similarily well if the two detecting wavelengths are as close to each other as possible. In theoretically infinitely close vicinity any change in emissivity as a function of wavelength approaches *zero* which means that for an infinitely small spectral range any coloured body is also grey. However, this places high demands on measurement technology which these days cannot be met, yet, at justifiable costs. Current solutions include assumptions on the relationship between both temperature and emissivity variations [5, 6] or wavelength. The latter includes – primarily for multi-wavelength-pyrometry – a linear and log-linear emissivity model, which refer to the respective relationship between emissivity and wavelength [7, 8].

Finally, ratio pyrometers may be used if a hot sample is smaller than the detection spot of the pyrometer. Assuming a "cold" background, i.e. a surrounding temperature that is much smaller than the object's temperature, then temperature measurement will only be marginally affected by the spot size mismatch as it corresponds effectively to a constant damping. Please note, that the temperature reading would significantly change if a single-wavelength pyrometer was used.

1.3 Status Quo

There have been a few approaches to determine the true sample temperature using pyrometry without possessing any knowledge on the emissivity. A review may be found here [9]. However, at present additional information is required. This may be accomplished through reflectometry which yields a measure for the material's emissivity using Kirchhoff's Law and conservation of radiation if transmission can be excluded [10, 11, 12]. Other approaches use a combination of ratio pyrometry for grey bodies as described above and some knowledge on the material properties [13, 14]. In particular, ratio pyrometry is helpful if one can use literature data on the properties of the material assuming that the emissivity ratio does not change with modified process conditions. Moreover, it may be successfully applied to surfaces that are or become grey during thermal treatment, namely oxidizing steel surfaces [15]. Although the time slot during oxide growth affects the measurement significantly while the true surface temperature may stay the same, but the changing readings can be vice versa interpreted in terms of increasing oxide thickness as a function of time [16]. Multi-wavelength pyrometry uses more than two detecting wavelengths to replicate the course of the thermal radiation spectrum as the full spectrum unambiguously determines the object's temperature regardless of its emissivity [17, 18].

However, considering widely commercially available ratio pyrometers all of the approaches that do not utilize additional measurements (e.g. reflectometry) rely on further information to give a true temperature. Indeed, it is possible to determine any object's temperature within the limits to be discussed if despite the ratio channel the two underlying single channels are simultaneously measured. An iterative algorithm that will be presented then gives the only possible combination of ε_1 and ε_2 and yields a true temperature reading.

2 Algorithm

If the detection spot is fully filled by the hot object whose temperature is to be measured and no damping needs to be considered then both the single-wavelength signals as well as the ratio measurement from a two-colour pyrometer may be used to determine the material emissivity and thus the object's true temperature without any additional information. Further, this iterative algorithm assumes an exact overlap of the detection spot for all involved wavelength regimes. If these basic requirements are met, than all three (single-wavelength and ratio) channels of a two-colour pyrometer should "see" the same temperature, i.e. all three readings should match. This is mathematically described by the following equation system:

$$\varepsilon_1 M_{bb}^{\lambda_1}(T) = M_1(T) \tag{3}$$

$$\varepsilon_2 M_{bb}^{\lambda_2}(T) = M_2(T) \tag{4}$$

$$\varepsilon_2/\varepsilon_1 \, F_{Ratio}^{1,2}(T) = M_{bb}^{\lambda_1}(T) / M_{bb}^{\lambda_2}(T) \tag{5}$$

This threefold equation system – consisting of the emissivities ε_1 and ε_2 which correspond to the two single-wavelength-channels at λ_1 and λ_2, of the respective real spectral radiances $M_1(T)$ and $M_2(T)$, of their ratio $F_{Ratio}^{1,2}(T)$ as well as of their black body equivalents $M_{bb}^{\lambda_1}(T)$ and $M_{bb}^{\lambda_2}(T)$ – can be solved by an iterative algorithm. It is straightforward to show that for the right combination of ε_1 and ε_2 equation (5) results in a true statement.

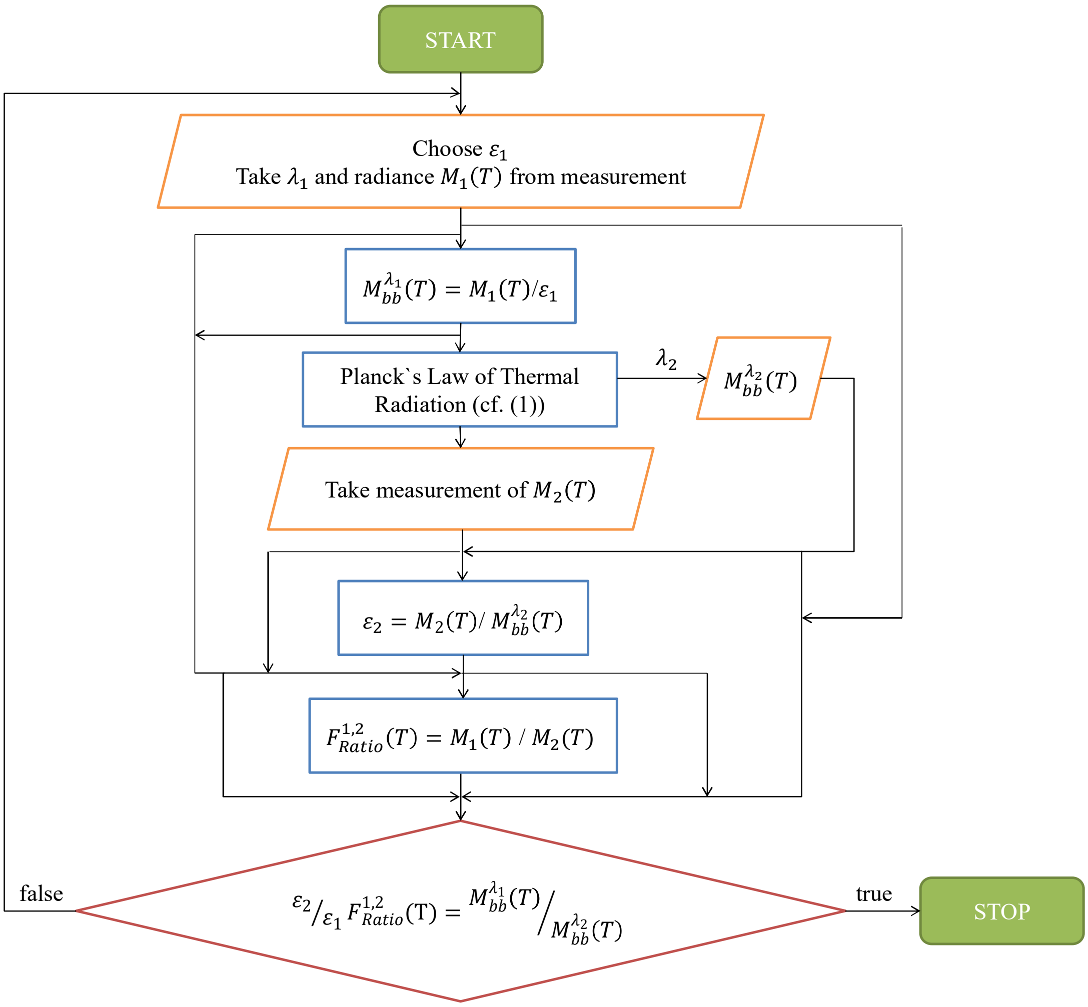

Fig. 2. Visualization of an algorithm determining the true emissivity of an object by evaluating all three attainable channels from a two-colour pyrometer.

Even if no information is given on the material properties the true temperature can be gained by assuming a starting value for ε_1. An iterative approach (cf. **Fig. 2**) follows which may be shortened by an educated guess on ε_1. Consequently, $M_{bb}^{\lambda_1}(T)$ may be calculated taking the measured data from $M_1(T)$ and knowing the detecting wavelength of the first channel. As it must be safe to assume T is equal for all channels $M_{bb}^{\lambda_2}(T)$ can be easily gained and using the measured data of $M_2(T)$ ε_2 is readily obtained. Finally, the ratio of $\varepsilon_1/\varepsilon_2$ and $F_{Ratio}^{1,2}(T)$ are compared to $M_1(T) \,/\, M_2(T)$. If this comparison does not satisfy equation (5) the iteration is repeated with a different starting emissivity ε_1 until a true statement is achieved.

3 Results and Discussion

The above described iteration process was run for nine different hypothetically real emissivity ratios at a wavelength of (1.0 +/- 0.1) µm for temperatures of (1100 +/- 100) K and a measurement uncertainty of 25 K.

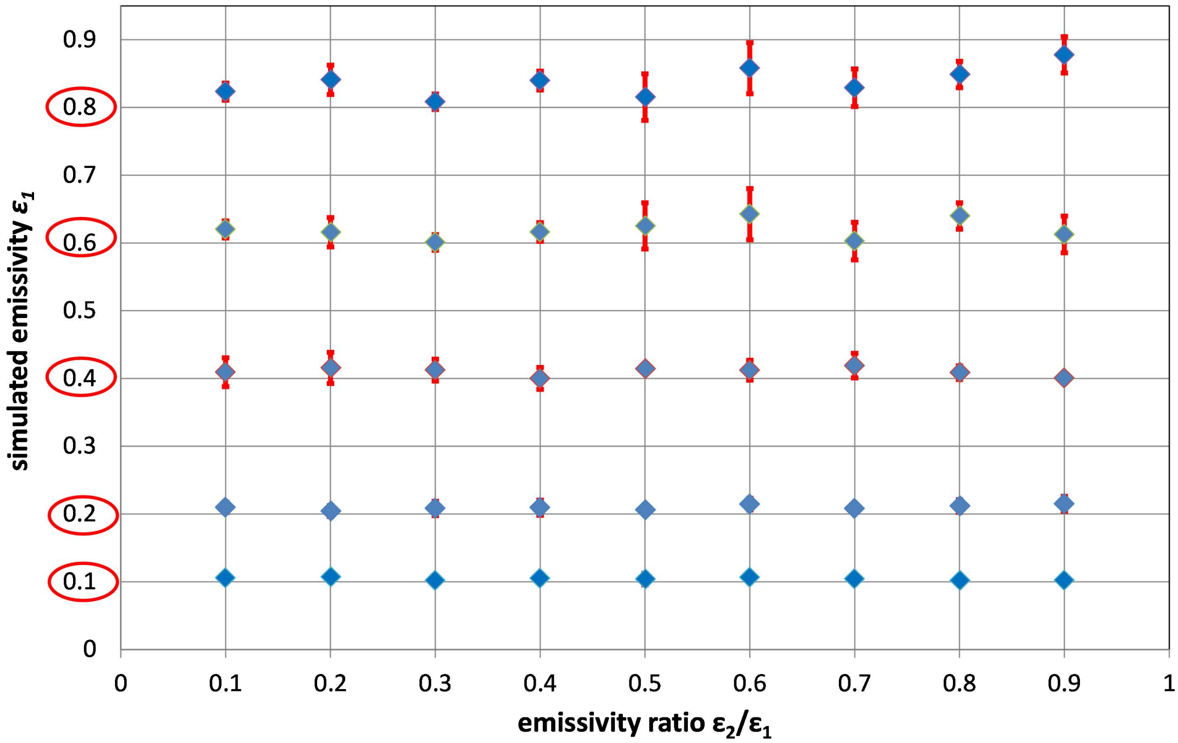

Fig. 3. Simulated emissivity as a function of a true emissivity ratio. The real object's emissivities that were used to obtain measurement data are circled in red. Please note that only the measured results from the two respective single-wavelength channels and from the ratio channel enter the simulation. The stopping condition was set to differences in the calculated and measured ratio factor $F_{Ratio}^{1,2}(T)$ of less than 1E-3. This means that at a temperature of 1100 K a maximum error of 8 K needs to be accepted.

The results presented in **Fig. 3** do not show a significant influence of the emissivity ratio on the simulation results. There seems to be an increased error in temperature due to a rise in the simulation uncertainty for larger nominal emissivities. In fact, this is a consequence of the exponential relationship of thermal radiation and temperature.

Table 1 shows the maximum temperature variation for the maximum deviation of the simulated and true emissivity at a temperature of 1100 K and at a detecting wavelength of 1µm. It can be seen that despite the small standard deviation at a true emissivity of 0.1 the resulting temperature error is indeed larger because the percentage deviation has equally increased which is the decisive contribution. Moreover, the presented errors attribute to less than 1.2 % for an assumed object temperature of 1100 K which is in the order of the set temperature uncertainty of 25 K. However, the stopping condition which accepts a maximum temperature error of 8 K corresponding to 0.7 % at a temperature of 1100 K, needs to be beared in mind although this still does not exceed the afore mentioned uncertainty of 25 K.

Table 1. Maximum temperature error for the considered true emissivites according to **Fig. 3** if the maximally deviated simulation result is used for temperature determination

True Emissivity	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**
	12.71 K	8.94 K	8.79 K	9.44 K	9.53 K

Farther, these results at a wavelength regime of (1.0 +/- 0.1) µm were compared to two further spectral positions at (2.0 +/- 0.1) µm and at (4.0 +/- 0.1) µm (cf. **Fig. 4**).

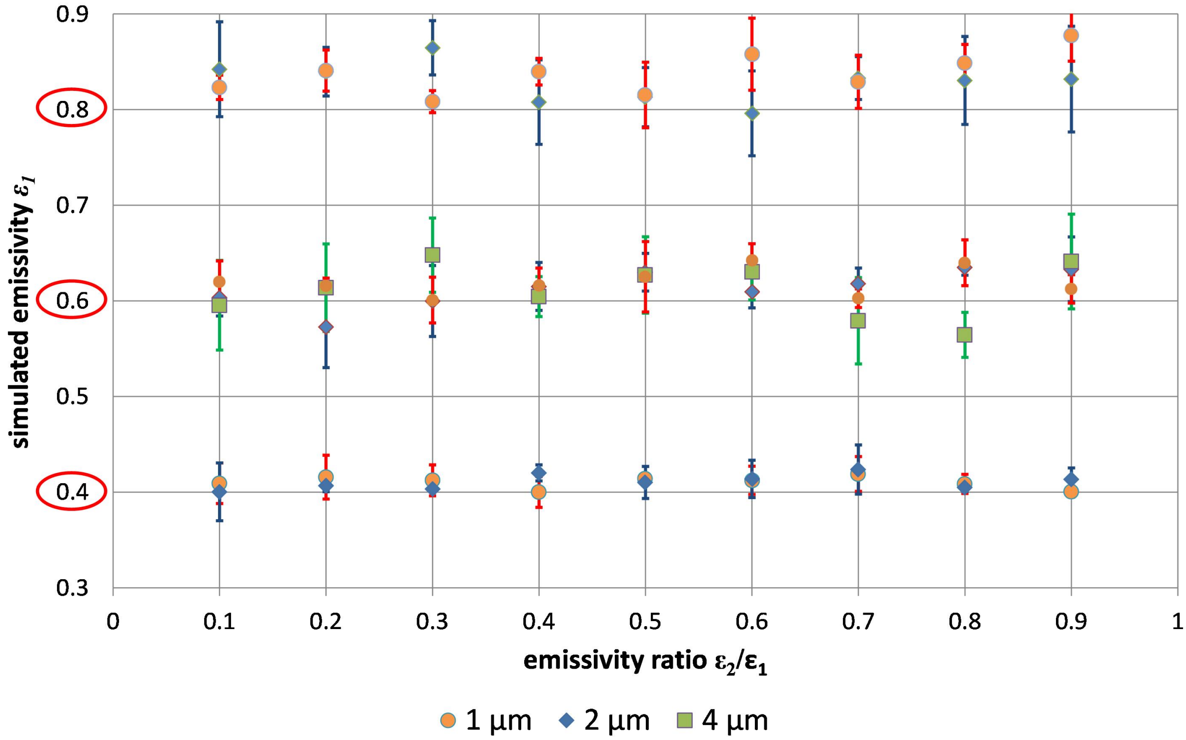

Fig. 4. Simulated emissivity as a function of a true emissivity ratio and the central wavelength. The real object's emissivities that were used to obtain measurement data are circled in red.

An analysis of variances shows that the deviations are insignificant by a probability of more than 99 %. Larger standard deviations may be attributed, however, to the behaviour of Planck's Law of Thermal Radiation for larger wavelengths. Towards larger wavelengths the maximum spectral emittance slowly declines in an asymptotic manner. The distance between different temperatures decreases likewise and even a small error in the assumed emissivity will result in comparatively large errors in temperature reading and vice versa. That means, the given temperature uncertainty of 25 K causes larger deviations in the emissivity simulation for larger wavelengths.

Finally, the measurement uncertainty was increased from 25 K to 100 K. As to be expected this led to a comparatively enormous increase both in the mean values and standard deviations (cf. **Fig. 5**). This is due to an increase in possible solutions to the equation system (3-5) which may be compensated by a stricter stopping condition rising the number of iterations at the same time. Again no significant influence of the emissivity ratio could be found.

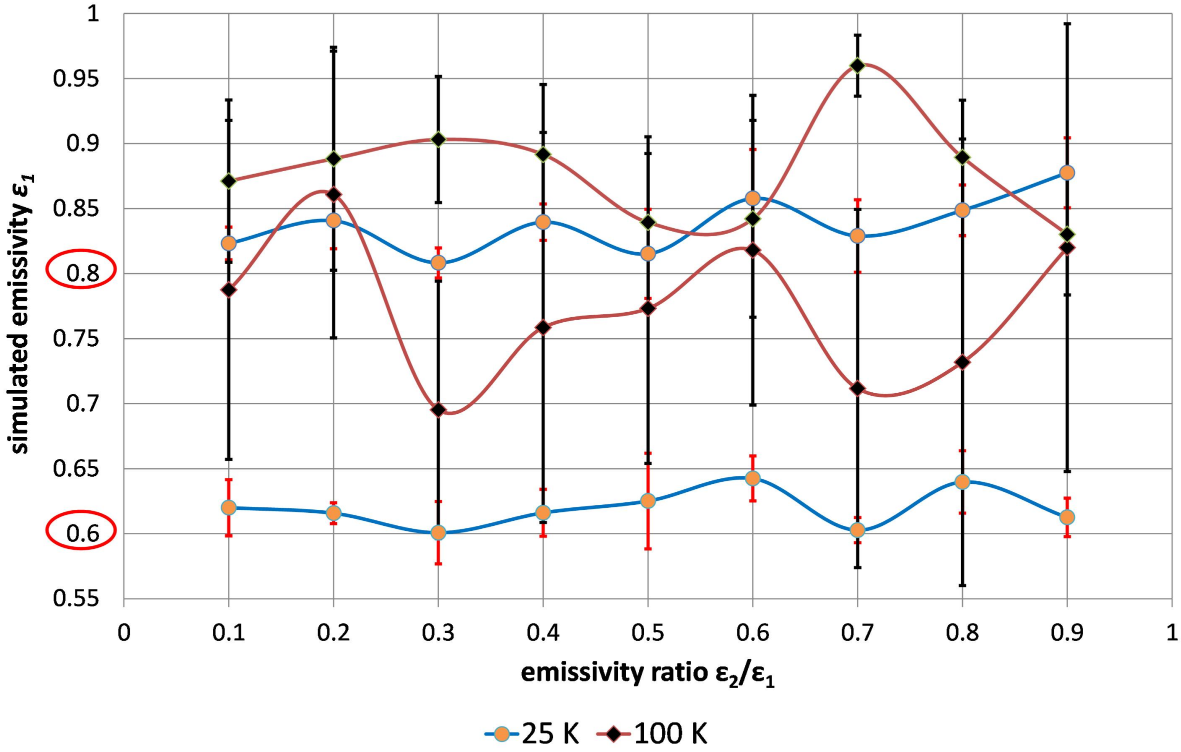

Fig. 5. Simulated emissivity as a function of a true emissivity ratio and an assumed measurement uncertainty of the pyrometer of 25 K and 100 K. The real object's emissivities that were used to obtain measurement data are circled in red.

Ratio pyrometers can be implemented in different ways. One may be the use of two actually individual detectors. They may be either arranged at different positions or stacked one behind the other ("sandwich detector"). The latter may lead to an undesired crosstalk behaviour [19]. Further, there may be only one detector that is filtered at different wavelengths which will automatically lead to a temporal mismatch between the channels. However, due to a finite sampling time a similar mismatch may likewise occur even if different detectors are used. During the simulation such a mismatch has been accounted for by the measurement uncertainty which acts randomly on the temperature measurement of both channels. Moving objects, which are a common application of pyrometry are accounted for by a random change in temperature of a total of 200 K. If larger changes are to be expected such as it would be the case for active heating and cooling the simulation time may exceed a critical change in temperature thus increasing the simulation error.

For practical use, it is important to point out that a real detector cannot operate at a single wavelength. On the other hand, this detector only gives integral values of the thermal radiance within its spectral range. This excludes an analytical determination of the temperature T and asks for a secondary simulation to find an $M(T)'$ which converges towards the measured value $M(T)$. In the end, a balance needs to be found between simulation time and accuracy.

4 Summary

The present work has presented an algorithm to determine an object's emissivity without any knowledge on the material properties. The sole prerequisite is that both "detectors" – may this be physically different devices or one detector with different filters – view the exact same position on the object's surface such that one temperature can be assumed for all channels at a time. In this case the emissivities at both spectral positions ε_1 and ε_2 and the true temperature T form a threefold equation system that – once the correct combination of ε_1 and ε_2 has been found – returns a true statement.

A dependence on the emissivity ratio has not been found and resulting temperature errors have not shown a significant influence of the nominal value of the true temperature although an increase in standard deviation for rising emissivities can be seen. The latter is, however, in good accordance with Planck's Law of Thermal Radiation.

Though it could be seen that larger wavelengths result in a higher uncertainty whether the true emissivity had been found in the simulation as predicted by Planck's Law the means have not shown to differ significantly. However, raising the pyrometer's measurement uncertainty from 25 K to 100 K was found to increase the simulation error by almost an order of magnitude.

Considering real measurement conditions the present paper has proven the concept of evaluating an object's true emissivity by a numerical solution of the equation system that results from the working principle of a ratio pyrometer.

List of Nomenclature

M_{bb}^{λ}	thermal radiance of a black body at a detection wavelength λ
h	Planck constant
c	speed of light
λ	detection wavelength
k_B	Boltzmann constant
T	temperature
α	absorptivity
$\alpha_{s,d}(\lambda,\gamma)_T$	spectral and directional absorptivity as a function of detection wavelength λ and angle γ at a temperature T
ε	emissivity
$\varepsilon_{s,d}(\lambda,\gamma)_T$	spectral and directional absorptivity as a function of detection wavelength λ and angle γ at a temperature T
$F_{Ratio}^{1,2}$	ratio of the real-body spectral radiances $M_1(T)$ and $M_2(T)$

References

1. Planck, M.: Über eine Verbesserung der Wien'schen Strahlungsgleichung. Verhandlungen der Deutschen Physikalischen Gesellschaft (1900)
2. Kirchoff, G.: Über den Zusammenhang zwischen Emission und Absorption von Licht und Wärme. Monatsberichte der Königlichen Preußischen Akademie der Wissenschaften zu Berlin, 783 (1859)
3. Gibson, A. F.: A two-colour infra-red radiation pyrometer. Journal of Scientific Instruments 28(5), 153 (1951)
4. Araújo, A.: Multi-spectral pyrometry – a review. Journal of Measurement Science and Technology 28, 082002 (2017) DOI: https://doi.org/10.1088/1361-6501/aa7b4b
5. Sun, X. G.: Processing Method of Multi-Wavelength PyrometerData for Continuous Temperature Measurements. International Journal of Thermophysics 26(4), 1255 (2005) DOI: 0.1007/s10765-005-6724-6
6. Xing, J. et al.: A data processing algorithm for multi-wavelength pyrometry-which does not need to assume the emissivity model in advance. Journal of the International Measurement Confederation 67, 92 (2015) DOI: https://doi.org/10.1016/j.measurement.2014.11.019
7. Wen, C.-D., Chai, T.-Y.: Examination of multispectral radiation thermometry using linear and log-linear emissivity models for aluminum alloys. Journal of Heat and Mass Transfer 47, 847 (2011) DOI: https://doi.org/10.1007/s00231-011-0769-9
8. Araújo, A., Silva, R.: Surface temperature estimation in determined multi-wavelength pyrometry systems. Review of Scientific Instruments 91, 054901 (2020) DOI: https://doi.org/10.1063/5.0005676
9. Reichel, D.: Temperature Measurement in Rapid Thermal Processing with focus on the application to Flash Lamp Annealing. Critical Reviews in Solid State and Material Sciences 36(2), 102-128 (2011) DOI: https://doi.org/10.1080/10408436.2011.572757
10. Nulman, J. et al.: Pyrometric Emissivity Measurements and Compensation in an RTP Chamber. In: MRS Proceedings, pp. 146 – 461. Cambridge University Press, Cambridge (2011) DOI: 10.1557/PROC-146-461
11. Sentenac, T.: Trichromatic thermoreflectometry for an improved accuracy of true temperature field measurement on a multi-material part. International Journal of Thermal Sciences 145, 105980 (2019) DOI: https://doi.org/10.1016/j.ijthermalsci.2019.105980
12. Fu, T.: Measurements of the directional spectral emissivity based on a radiation heating source with alternating spectral distributions. International Journal of Heat and Mass Transfer 90, 1207 (2015) DOI: https://doi.org/10.1016/j.ijheatmasstransfer.2015.07.064
13. Madura, H., Piatkowski, T.: Emissivity compensation algorithms in double-band pyrometry. Journal of Infrared Physics and Technology 46(1-2), 185-189 (2004) DOI: https://doi.org/10.1016/j.infrared.2004.03.024
14. Müller, B., Renz, U.: Development of a fast fiber-optic two-color pyrometer for the temperature measurement of surfaces with varying emissivities. Review of Scientific Instruments 72, 3366 (2001) DOI: https://doi.org/10.1063/1.1384448

15. Muller, M. Fabbro, R.: Temperature measurement of laser heated metals in highly oxidizing environment using 2D single-band and spectral pyrometry. Journal of Laser Applications 24(2), 022006 (2012)
DOI: https://doi.org/10.2351/1.3701400
16. Roebuck, B., Edwards, G., Gee, M. G.: Characterisation of oxidising metal surfaces with a two colour pyrometer. Journal of Materials Science and Technology 21(7), 831 (2013)
DOI: https://doi.org/10.1179/174328405X46169
17. Coates, P.B.: Multi-Wavelength Pyrometry. Metrologia 17(3), 103 (1981)
DOI: https://doi.org/10.1088/0026-1394/17/3/006
18. Madura, H., Kastek, M., Piatkowski, T.: Automatic compensation of emissivity in three-wavelength pyrometers. Journal of Infrared Physics and Technology 51(1), 1-8 (2007)
DOI: https://doi.org/10.1016/j.infrared.2006.11.001
19. Luryi, S., Xu, J., Zaslavsky, A.: Future Trends in Microelectronics: Up the Nano Creek. 1st edn. John Wiley & Sons, Inc., Hoboken New Jersey (2007)