euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021
www.euspen.eu

# A simple method for estimating the effective emissivity at high temperatures, utilizing a black body radiator

Kenneth Ælkær Meinert[1], Francesco Biondani[1], Venkata K. Nadimpalli[1], Mohamad Bayat[1], David B. Pedersen[1]

[1]*Department of Mechanical Engineering, Technical University of Denmark*

*Kemei@mek.dtu.dk*

**Abstract**
Optical sensors, especially in the Infrared range (**IR**), allow the measurement of the absolute surface temperature, recorded for each layer during fabrication. In order to record the true temperatures, the effective emissivity is of great importance, as it is utilized as input parameter for the IR camera. Many existing methodologies for estimating the emissivity, has formerly been reported [1]. However no viable solutions have been proven for the high temperature regime upward of 500 °C. The motivation for the research, is to acquire the surface temperatures of a heated black body radiator, and compare it to different topographies of AISI 316 stainless steel, which is commonly used as an AM material. The article furthermore seeks to compares to dynamic methods. The first method uses the black body cavity to estimate the emissivity of other regions of the surface, where the other method uses the more traditional by the use of thermocouplers to get the absolute surface temerpature. The simple method examines the possibility of using a more simple approach in the estimation of the emissivity of a surface in general which is much faster and requires less equipment, such as an oven with transparent IR glass. Furthermore a numerical model is created in ABAQUS, in order to examine the heat transfer mechanism, parameter sensitivity and further verify the numerical model by the experimental data. The model investigates the variation of temperature through the thickness and the viewfactor variation over the surface. The results of this study pave the way for better temperature measurement, using in-process IR cameras during Laser-based Additive Manufacturing, by proposing a simple geometric method for estimating the emisivcity by black body radiators at the high temperature regime.

Keywords: True emissivity, Blackbody, Calibration of IR-camera

## 1. Introduction

Infrared (**IR**) Thermography, has formerly been shown to be a well suited method, for measuring the temperatures during manufacturing processes, in order to achive better process control. Challenges however arise, utilizing IR thermography, as the camera only monitors the radiation emitted from a surface, related to its emissivty. The emissivty will variate with temperatures and morphologies of the surface, and it therefor becomes attractive, to develop a simple method, for a rapid and inexspensive estimation of different materials and morphologies. Former methodologies have successfully computed the emissivity of surfaceses, using a geometrical black body radiator at the lower temperature regime [1-5]. However, no verified method has been investigated at the high temperature regime from 500°$C$ and above . The current paper therefore proposes and scrutinize, a simple method for estimating the emissivty at elevated temperatures. This is suggested accomplished, by the means of a black body (**BB**) radiator with known emissivity, as a reference for computing surface emissivities. A blackbody allows all incident radiation to be absorbed without any reflection or transmission. [6] The paper further compares the pros and cons for the different simple dynamic methods for estimating the emissivity of a surface. This includes the black body cavity method and the thermocouple method. Both methods are based on the same experimental setup utilized in the paper and will be discussed and compared. From former work, it has been shown that conductors such as metals in general shows an increasement in emissivty with increasing temperature [8] and vice versa for non conductors. This raises questions about the effect on emissivity from oxide formations at the surface, when during measurements at elevated temperatures in open atmosphere.

## 2. Experimental Setup

The basic setup, includes a geometrical black body radiator model (Fig 1), an Nabertherm LE 4/11/R6 oven, 4 type k thermocouples recorded using a National instruments thermocouple module (NI 9213, autsin TX) and a labveiw program. The thermal imaging system was recorded by a (FLIR-SC645) with a resolution of 640 x 480 pixels and maximum temperature range up to -20 to 1500 °C. The distance between the camera and the black body surface was ≈ 30mm and the angle was ≈48 °. The radiator was placed within sand, where tempepature were sampled with a frequency of 1 [Hz] during cooling. The material investigated is AISI 316 stainless steel.

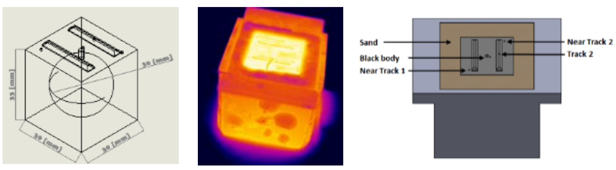

*Figure 1 a) Geometry of BB b) IR image of BB c) Probe locations*

## 3. Methodlogy

The black body radiator was heated in 3 runs, of [200 900 900] °C in the oven until steady state, and then transferred out of the oven for measurements. Absolute and radiation temperatures were then recorded during the cooling. The emissivity was then calculated, based on 2 dynamic methods. **(i)** The black body method, where the emissivity is determined from camera measurements only. **(ii)** The thermocouple method, where it is estimated based on the thermocoupler measurement of the absolute surface temperature. In both methods the emissivity can be calculated from either a known reference emissivity of an ideal surface being $\varepsilon \approx 1$, or by the comparison to a known absolute surface temperature. A numerical model was constructed to investigate the temperature dissipation through the geometry.

### *3.1 Emissivty calculation*

The amount of energy emitted from a surface will variate with temperature and surface morphology, and it is therefore of vital importance to estimate the emissivty for ability to acuratly monitor a process. The emissivty was determined using the following equation [7].

$$\varepsilon = \frac{T_r^4 - T_a^4}{T_s^4 - T_a} \quad (1)$$

Here $T_a$ is the ambient temperature, $T_s$ is the absolute surface temperature measured by the thermocupler, and $T_r$ is radiative temperature from the measured surface. In the black body method (i) the abosulte surface temperature is replaced by the temperature reporte by the camera at the black body temperature.

### *3.2 Numerical model*

The radiation from the blackbody radiator was analysed in the commercial modelling software ABAQUS. This was done in order to investigate the teamperture distribution, through the thickness of the body, to prove that the temperature below the surface does not change significantly. The top surface radiation, was modelled by a free cavity radiation feature with an assumption of static effective emissivity at 0.8. The heat dissipation through the sand, was modelled by a surface film condition, based on a calculation of the thermal resistance of the sand. The sand was assumed to have a thermal conductivity of 0.15 $[\frac{w}{mK}]$. The model was validated by comparing the numerical and experimental temperatures at the probe location, which showed a good fit for the model. A plate was further modelled to replicated the cameras position and the viewfactor was investigated from the spatial data of the experimental setup.

The model was used to investigate the temperature variation through the thickness, where the temperature probe had been placed. The viewfactor variation over the surface between the plate and the black body was examined.

## 4. Results and discussion

The proposed method contains several advantages and disadvantages, when compared to the tradiational methods. Here the emissivity is measured from steady state of the sample within a vacuum chamber that is being heated [1]. The emissivity is then measured through transparent Infared glas. This method ensures no thermal gradient in the body and further removes the risc of oxidation and radiative reflection by the air molecules.

The current method utilized for this particular study, estimated the emissivity by measurements taken in a normal atmosphere, and therefore had potential risc of being inaccurate. It might have potential issues, such as thermal gradients and rapid cooling times on the sample. Oxidation of the surface layer will also have an effect. This is minimized in the current case by using stainless steel 316L. The method however showed great advantages in a fast experimental procedure without the need specialized oven. The measurements can also be conducted on a wide temperature range. The method however has several disadvantages compared to the common methods.

### *4.1 Numerical results*

From the analysis of temperature variation through the thickness it was indicated by the numerical model, that the probe was only reading ≈ 0.5°C lower than the actual surface temperature. The location of the measurements is shown in figure 5, where the a temperature profile of the model replicating a run at 900 °C is shown after 207 seconds of cooling. Form the viewfactor analysis the model only showed a slight deviation in the viewfactor. But might not completely replicated the precise optical properties between the camera and the black body surface.

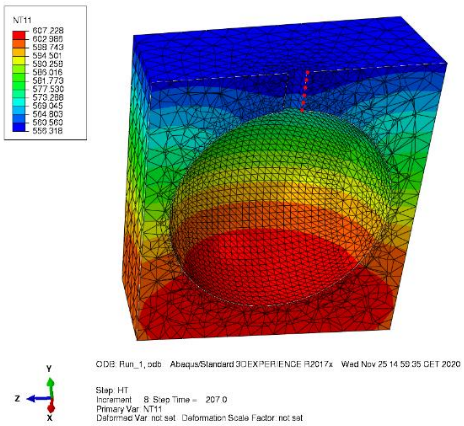


*Figure 2 Numerical model showing the location of the thickness measurement and the inside of the black body cavity.*

### *4.2 The black body method (No thermocouples)*

**(i)** The Blackbody method removes the need for a thermocouple, and can be conducted using only the black body cavity, infared camera and an oven. Here the emissivities is determined, based on the black body radiator point, which has the known, close to ideal, surface properties due to its geometry.

Figure 2, shows temperatures recorded by the thermocouples during the 3 runs. The black body experience continuous temperature gradient, due to radiation. This however also allows the emissivity, to be calculated over the fully recorded range in a single run. The probe was attached to the geometry, after the heating, which is shown in the initial state of the probe data. One can see a good consistency between the temperatures between the 2 runs at 900 °C.

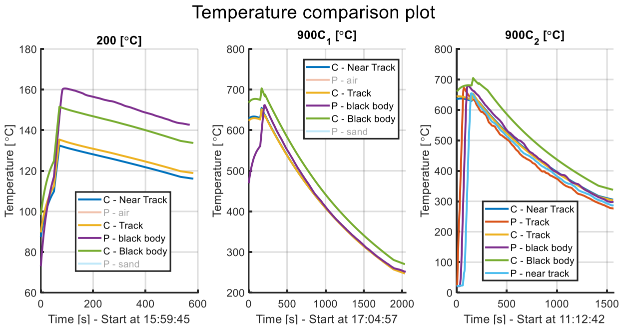


*Figure 3 Temperature comparison between probe and camera measurements*

Based on the infared recorded images, the emissivity of the two tracks, has been been determined by the application of equation 1. The method uses the assumnption of ideal emission properties at the black body radiator point.

Figure 3, shows the determined emissivity with no thermocouple for the 2 tracks on the geometry. Here the emissivity was calculated based on the camera data only.

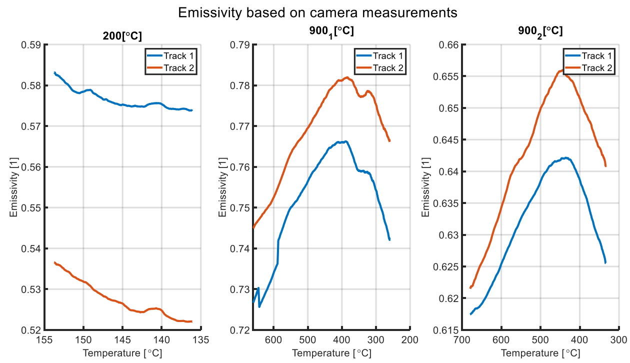


*Figure 4 Emissivity plot based on camera measurements without thermocoupler*

One can observe an inconsistency in the determined emissivity for the 3 runs, as they seem to deviate. The run at 200 °C shows an expected behaviour for a conductor as the emissivity decreases, as the temperature goes down [8] making the excitation of the atoms smaller and reduces the ability to absorb and emit. The difference between the 2 last runs, could be explained by a difference in viewing angle, as the black body cavity was placed with a 90 ° differences relative to the camera. This is potentially the reason for the deviation between the 2 high temperature runs. Another possibly effect could be an increased oxide formation at the surface for the second run at 900 °C due to the sample being cycliced heated.

One can further observe an unexpected behaviour, as the emissivity seems to rise with decreasing temperature. This could be explained by variation in thermal gradiatients and potentially an oxidation of the surface. The oxidation should however have less of an influence due to the use of steel 316 L.

### 4.3 The thermocouple method

This method removed the necesscity for a known surface emissivity as the black body cavity and is the more tradiational method for estimating the property. The particular method in this study, however deviates from former study as it is executed in an open atmosphere and monitored during cooling and not steady state, within the oven. Compared to the dynamic black body method (No thermocoupler) the applied method (Thermocoupler )has several advantages, as there is a reliable temperature measurement of the absolute surface temperature during the experiments. It however also includes other potential issues, such as reliable placement, ensurance of good thermal contact, and the fact that the thermocouple is sinked into the surface. This issue was however indicated by the numerical model, to have a neglectable effect.

Figure 4 shows the emissivity, based on the temperatures reported by the IR camera and the thermocouplers. Here the thermocouple was place at the location of the black body cavity point. The relatively small flucations, could be explained by the different temperature gradients, throughout the black body, as the bottom surface was placed on a table. This further showed a disadvantages in the method, as the bottom surface of the

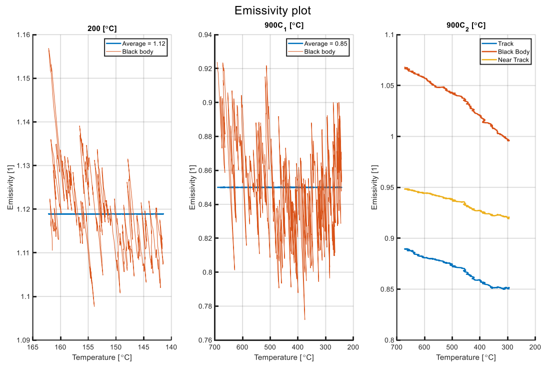


*Figure 5 Emissivty plot using the thermocouple method*

sample, would consist of a different heat transfer condition, than the thermal radiation emitted from the free surfaces at the top.

The emissivity results presented in figure 4, shows an expected emissivity behavior for the track and near track locations [8] where the emissivity is decreasing as the temperature goes down. This has formerly been reported for conductors. [8] The emissivity reported at the black body point is above 1, which indicates that the system is not replicating the true temperature of the top surface, but rather the bottom of the geometry. For the track one can orbserve, that it goes towards a meta platuea at 450-300 °C The emissivty here seems to be responding well compared to records for heavyliy oxidized metal surfaces [9]. In general the data recording, seems to be unstable from the approach, due to the transferring of the geometry outside the oven. A more stable reading can be achived by measuring the body at steady state inside an oven. Hower the method seems to provide a rough indication of the variation and magnitude of emissivity which is much faster and less expensive than tradiational methods.

### 4.4 Comparison

The 2 model showed different behaviours during the estimation of the emissivity by the dynamic method. The emissivity by the cameras, showed and emissivty in the range of ≈ 0.73 to 0.78, compared to the emissivity estimated by the more tradiational thermocouple method, was found for the initial run at 900 °C to be ≈ 0.85 and spanding from ≈ 0.85 to 0.89. It is clear to orbserve a variation between the two methods, which could be explained by the many disadvantages of the methods described formerly. The method however shows potential in rough estimation of the emissivity when compared to other emissivity results found in other studies.

## 5. Conclusions

Estimating the emissivty in the high temperature regime, has never been a straightforward task, as there are many properties and condition effecting the radiative flux between objects. The results showed, that the position of the camera among the reflection and arbosoption from ambient environment, has a large effect on the temperature mesasured by the IR imaging system. The method also shows a disadvantage in transferring the geometry outside the oven, as it is subjected to convective cooling, which is also shown in the data. The geometry of the black body has a disadvantage as the bottom will cool slower than the top surface giving rise to thermal gradients, which was orbserved in the temperature comparison plots.

The current paper proposed 2 simple dynamic methods for estimating the emissivity of a surface fast and inexpensive compared to traditional methods.

### *5.1 The black body method*

The first method utilized the geometric black body, to estimate the emissivity of two tracks on the surface of the geometry. The method showed advantages in fast experimental runs, without the necessity of an oven an ideal atmosphere, it however also showed an unexpected behaviour in the emissivity. Here it rised with decreasing temperature, which have been reported not to be common for conductors (metals). It should also be empathized, that comparison to other studies is in general not easy, as many studies finds results with relatively large variation of the emissivity for the same material, further illustrating the many variables effecting the measurements.

### 5.2 *The thermocouple method*

The emissivity was indicated to have a more expected tendency by falling with decreasing temperature, the emissivity was further around the expected ranges when compared to another study found [8-9]. The method further showed a good consistency in the probe data, between the runs but also showed the importance of the viewfactor. The tracks created a deviation that could be observed, between the to runs at 900 °C. This is hypothesized to be effected, by the view angle deviation and a potential formation of oxides, on the surface due to cyclic heating.

## References


*[1] - Approximation of absolute surface temperature measurements of powderbed fusion additive manufacturing technology using in situ infrared.* Emmanuel Rodriguez, Jorge Mireles ∗, Cesar A. Terrazas, David Espalin, Mireya A. Perez, Ryan B. Wicker. Elsevier 11 December 2014 p31-39.

[2] Javier De Lucas A Simple Geometrical Model for Calculation of the Effective Emissivity in Blackbody Cylindrical Cavities. 2013 Springe

[3] T J Quinn 1967 Br. J. Appl. Phys. 18 1105, The calculation of the emissivity of cylindrical cavities giving near black-body radiation

[4] G.H. Mei, J. Zhang, S.M. Zhao, Z. XieEffective emissivity of a blackbody cavity formed by two coaxial tubes Appl. Opt., 53 (2014), pp. 2507-2514

[5] H.P. Chen, T.Q. Li, S.R. Chen, Z.X. ChuCalculation of effective surface emissivity of square cavities Chin. J. Ir. Res., 3 (1984), pp. 166-171

[6] Planck, M. (1914). *The Theory of Heat Radiation*. Masius, M. (transl.) (2nd ed.). P. Blakiston's Son & Co

[7] Coppa P, Consorti A. Normal emissivity ofsamplessurrounded by surfaces at diverse temperatures. Measurement 2005:124–31.

[8] Bergman - (Fundamentals of Heat and Mass Transfer, 7th Edition) pp. 795

[9] HangJin Jo, Jonathan L.King, Kyle Blomstrand, Kumar Sridharan - Spectral emissivity of oxidized and roughened metal surfaces