

ARTICLE

Assessing optical radiation exposure to opaque incandescent materials by picture analysis – Part 1: from pixel color to radiance

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Abstract – In industrial processes, working on incandescent materials exposes workers to optical radiations that can lead to cataract. In the case where risk cannot be appraised using software simulation, it is necessary to measure visible and near infrared irradiance at the eye of the worker. Since radiometers and spectroradiometers are too expensive for most people in charge of safety at work, a novel method is proposed that assesses irradiance using a photograph taken by smartphone, for example. It consists in summing the irradiance corresponding to each pixel representing the opaque incandescent materials in the picture. Pixel irradiance is assessed from the radiance of the colored body whose temperature and emissivity correspond to the pixel color, weighted by the geometric configuration associated with the pixel in the camera perspective. This virtually free method is accurate enough to assess cataract risk, thereby helping employers to choose an efficient means of protecting workers. In this paper, we present the first principle of the method proposed: temperature and emissivity estimation of incandescent materials.

Keywords: Infrared radiation / imaging / occupational exposure

Résumé – Certains procédés industriels exposent les salariés au risque de cataracte due aux radiations optiques reçues de matériaux portés à incandescence. Si ce risque ne peut être évalué par simulation informatique, l'éclairage dans le visible et le proche infrarouge doit être mesuré au niveau de l'œil du travailleur. Radiomètres et spectroradiomètres étant trop onéreux pour la plupart des préventeurs, une méthode nouvelle est proposée pour évaluer cet éclairage sur la base d'une image du poste de travail, telle que peuvent en fournir les smartphones. La méthode additionne pour tous les pixels associés à une matière incandescente opaque dans l'image, le produit de la luminance d'un corps coloré dont la température et l'émissivité le font correspondre à la couleur du pixel, par le facteur de forme associé au pixel selon la perspective de la caméra. Cette méthode virtuellement gratuite se révèle assez précise pour évaluer le risque et aider l'employeur à prendre les mesures de sécurité adéquates. Cet article présente le premier principe de la méthode: comment estimer la température et l'émissivité des matériaux incandescents.

Mots clés : rayonnements infrarouges / imagerie / exposition professionnelle

1 Introduction

Working on incandescent materials, typically in the 800 to 1300 °C range, exposes workers to visible and infrared optical radiations (Lydahl *et al.*, 1984; Lydahl *et al.*, 1984). It can lead to skin burn and thermal damage to the retina and to the cornea (cataract) (Barlier, 1994; Barlier *et al.*, 1995). Although aversion to skin and eyes pain and exposure levels may prevent retinal injury and skin burns, it is necessary to keep chronic exposure below daily exposure limits (ICNIRP, 2013) to avoid cataract (Whillock *et al.*, 1990). The EU has established such occupational limits (European Union, 2006;

Union Européenne, 2006) that have been transposed in each EU country (e.g., République française, 2010) in France). *In situ* measurements (Barlier, 1994; Barlier *et al.*, 1995) show that occupational exposure can exceed these thresholds tens folds or even hundreds folds.

European regulation limits daily mean occupational irradiance E_{IR} from infrared radiations (IR) as expressed in Eq. (1) where $E(\lambda)$ stands for spectral irradiance at the eye.

$$E_{IR} = \int_{\lambda=780}^{3000\text{ nm}} E(\lambda) d\lambda, \quad (1)$$

Daily E_{IR} limits depend on exposure time

$$t : 1.8E4 * T^{-3/4} \text{ W/m}^2$$

if $t < 10^3$ s, 100 W/m² otherwise.

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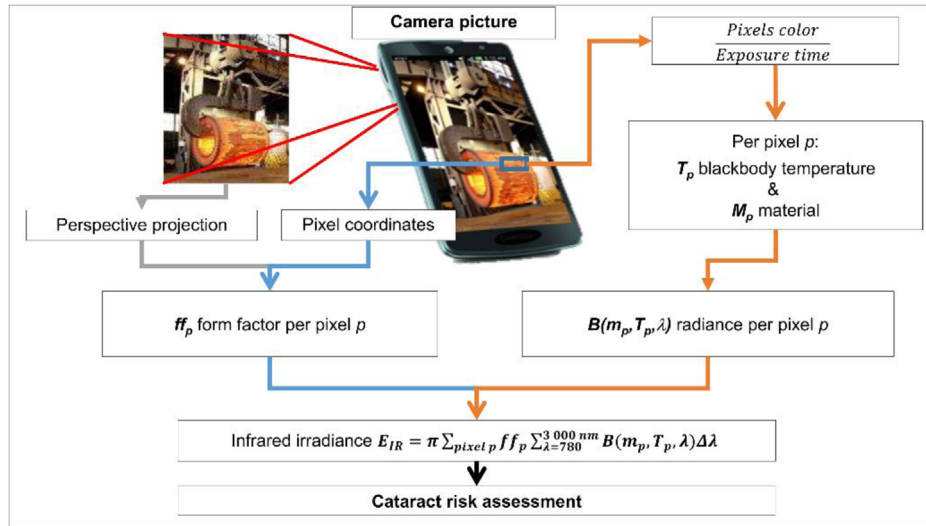


Fig. 1. Scheme of cataract risk assessment from an image with incandescent opaque materials.

Employers must assess workers' exposure to IR, for example, by using the INRS freeware CatRayon (CR^1) (INRS, 2018). For all optical radiation domains covered by the regulation (European Union, 2006), this freeware indicates *risk indices* that are the ratio of the worker's exposure over the daily limit.

When incandescent materials are heated (*e.g.*, absorbing forge hammer kinetic energy) or cooled down, when they move and change form (*e.g.*, forged and rolled iron), irradiance varies over time (Lydahl *et al.*, 1984). As CatRayon does not cover these cases, *in situ* irradiance measurements are necessary. Radiometers and spectroradiometers capable of measuring E_{IR} cost thousands and tens of thousands euros, respectively, making them unaffordable for most people in charge of safety at work.

We assert that incandescent opaque materials worked in industry (*e.g.*, metals, firebricks) can be represented as *colored bodies*. They differ from *black bodies* and *grey bodies* in that their radiance accounts for the spectral variation in the emissivity of the material. We note $B(m, T, \lambda)$ the spectral radiance at wavelength λ of a colored body made of an m material at temperature T (in K). Eq. (2) shows that $B(m, T, \lambda)$ follows Planck's law weighted by m spectral emissivity $m(\lambda)$. For ease of reading, λ is expressed in meter in this equation:

$$B(m, T, \lambda) = \frac{2hc^2}{\lambda^5} * \frac{1}{\exp\left(\frac{hc}{k\lambda T}\right) - 1} * m(\lambda), \quad (2)$$

where h is the Planck constant, c is the speed of light in the vacuum, k is the Boltzmann constant.

From equation (2), it appears that the hue of the incandescent opaque materials radiance (*i.e.*, $B(m, T, \lambda)$ relative distribution) depends on emissivity and temperature.

As depicted in the flow chart in Figure 1, this paper shows how to exploit this relationship in order to estimate E_{IR} from

camera pictures, which can be a cheap way to help preventing workers from risks of cataract.

A color camera picture is a matrix of (r_p, g_p, b_p) pixel colors, each pixel p corresponding to a direction in space from the point of view of the camera. Assessing IR exposure from such a camera consists in summing irradiances at the optical centre of the camera, from incoming directions limited by the camera's field of view.

This assessment relies on two principles. The first is the subject of this paper. It is to associate a p pixel hue with a material m_p and temperature T_p , hence radiance $B(m_p, T_p, \lambda)$ according to Eq. (2). This is illustrated in the right part of Figure 1.

The second principle is exposed in the left part of Figure 1 and will be covered in a next paper: it considers that every p pixel in the picture corresponds to a ff_p solid angle. It is illustrated in Figure 2.

Incoming IR irradiance through the solid angle corresponding to pixel p is simply π times the product of ff_p and $B(m_p, T_p, \lambda)$. Then, E_{IR} is the sum of irradiance from all the *relevant* pixels p (that correspond to incandescent materials and are not too dark), as indicated in the lower part of Figure 1 and expressed in equation (3):

$$E_{IR} = \pi \sum_{\text{pixel } p} ff_p \int_{\lambda=780 \text{ nm}}^{3000 \text{ nm}} B(m_p, T_p, \lambda) d\lambda, \quad (3)$$

2 Materials and method

First, we present the devices used in this paper and their conditions of use. Then we give details about the first of the principles presented above.

2.1 Spectro radiometric measurements

Spectral irradiance in the [380; 1040 nm] range was measured using an Avantes AvaSpec2048-14 single grating CCD array spectroradiometer (now discontinued and replaced

¹ CatRayon is a free software created, distributed and maintained by INRS, to assess risk from optical radiation sources and workers description and positioning in 3D, and propose effective protective equipment.

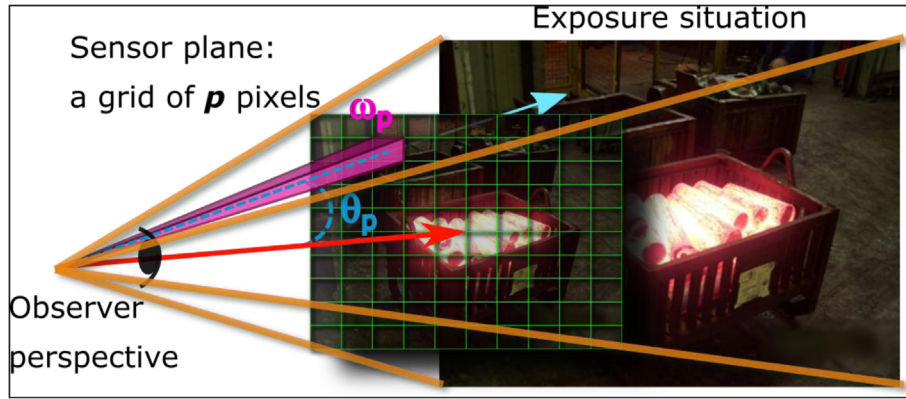


Fig. 2. Principle of associating each pixel p in an image with a form factor ff_p . In green: each p pixel in the picture corresponds to a rectangle in the focal plane of the camera. In purple: from the observer point of view (*i.e.*, the camera optical center), this rectangle corresponds to a solid angle ω_p making a θ_p angle (in blue) with the viewing direction (in red). Then the form factor associated with pixel p is $ff_p = \frac{1}{\pi} \omega_p \cos(\theta_p)$.

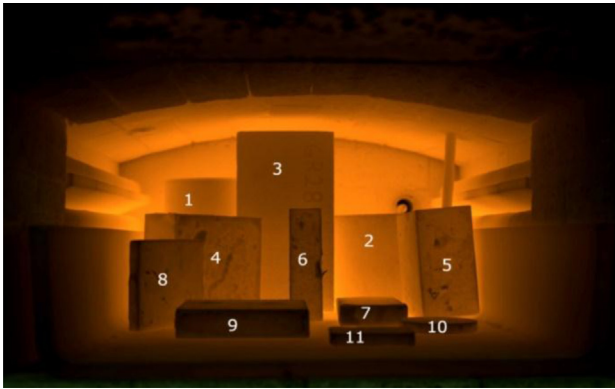


Fig. 3. INRS metal furnace with air temperature probe in the rear wall (just above samples #2 and #5). Incandescent samples as described in Figures 5 and 6: 1 = graphite melting pot, 2 = silica firebrick, 3 = GR 28 firebrick, 4 = ADC3W, 5 = SMV3O, 6 = LA234ESR, 7 = XC, 8 = E24, 9 = LA2714, 10 = GS400diam65, 11 = CF 25 60 × 40.

by ULS2048XL-EVO (Avantes, 2020b)). It was calibrated in our laboratory and its stray light is corrected using the Barlier method (Barlier-Salsi, 2014).

We measured [1000;2500 nm] spectral irradiance with an Avantes AvaSpec NIR256-2.5TEC InGas array spectroradiometer (now discontinued and replaced by the EVO version (Avantes, 2020a)).

2.2 Radiant sources

To characterize the spectral sensitivity of the red, green and blue channels of the Olympus E-M5 mkII camera used in this paper, we used a tunable monochromatic light source in the [380;2500 nm] range. It is composed of a halogen projector and the double grating OL750 monochromator (Optronic laboratories, 2014).

A calibrated GHG RCN 1350 N1 blackbody (HGH, 2020) serves as reference incandescent source. It operates up to 1350 °C and emits energy following Plank's law through a 23 mm diameter opening.

A metal furnace at the INRS workshop was filled with samples (see Fig. 3) whose spectral emissivity was measured at the LNE laboratory (LNE, 2023). This furnace is not an item of laboratory but a real furnace used in industry. Its internal sides are made of silica firebricks and its opening is 40 cm wide and 23 cm high. The furnace air temperatures indicated in this paper were measured on its rear inside side. It can be set to about 1140 °C, but we did not have any information about its probe.

The furnace was opened only during each radiometric measurements and picture captures for less than 30 s. This limited heat differences between the rear and front parts in the furnace, as well as equipment and operator burns. The operating mode was the following: the furnace was heated to its maximum for 24 h, to ensure the samples reached a homogeneous temperature of 1140 °C. Then the furnace was cooled to 1100 °C for an hour. The temperature was then reduced to 800 °C by successive 1 h decrements of 100 °C. Each time, the camera had to be removed then placed again in order to obtain a new picture. This prefigured what could be done in workshops and avoided destroying our equipment.

2.3 Camera

Our camera is an Olympus E-M5 mkII and its 12-40PRO optics were set at 25 mm (equivalent to 50 mm 24 × 36 full format perspective). Its 4640 × 3472 pixel μ 43 sensor at ISO 200 allows capturing RAW picture data with 5405 useful levels per pixel channel (12.4 useful bits (DxO, 2015)). These levels are named *counts* and denoted by c in units.

To exploit picture capture precision, we converted the RAW data into lossless TIFF 16-bit pictures, while ensuring a linear response of the sensor when observing radiance, and no colour space conversion with DCRAW64 (Dave Coffin, 1997) software and the following command:

```
dcraw64 -v -4 -H 1 -W -r 1 1 1 1 -q 3 -T -o 0 -h .ORF
```

Using our monochromatic light source and the AvaSpec2048-14 spectroradiometer, we determined the relative sensor sensitivity of the three E-M5 color channels. By “relative”, we mean that we determined the ratio between the three channels. In the following we show that an overall

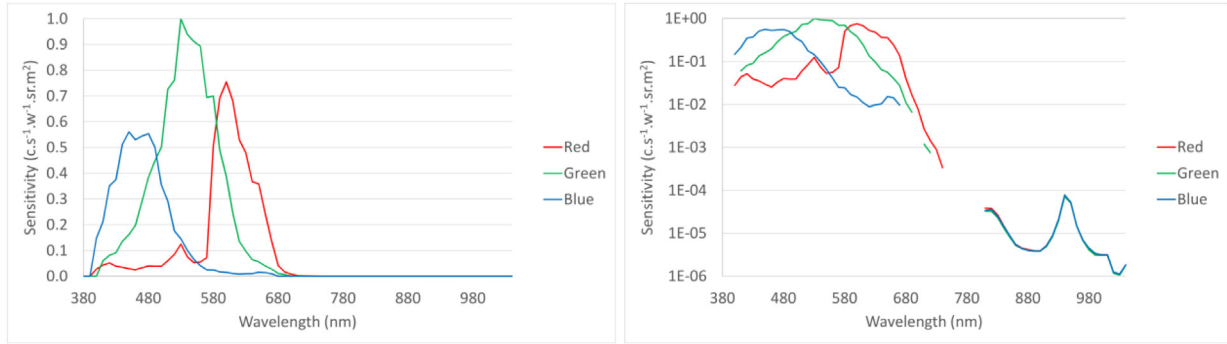


Fig. 4. $Red(\lambda)$, $Green(\lambda)$ and $Blue(\lambda)$ relative spectral sensitivities for the three E-M5 camera color channels, along linear and log scale.

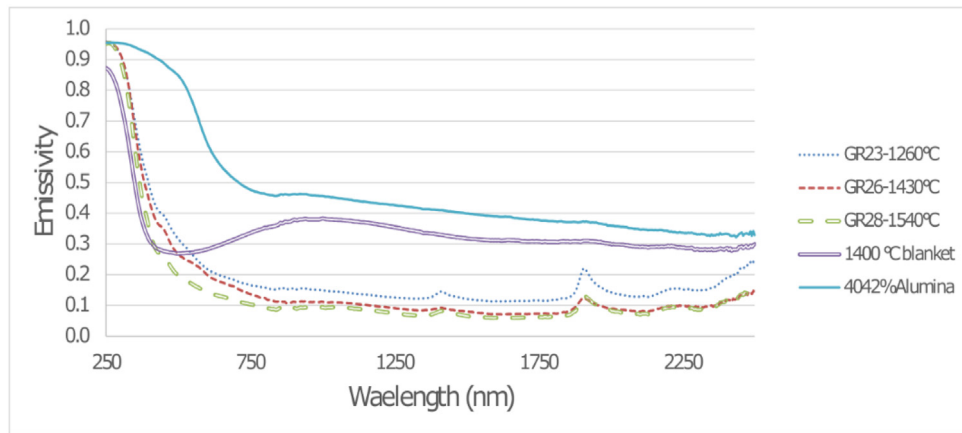


Fig. 5. Emissivity of refractive materials.

scaling factor η to obtain absolute radiance values from pixel $c.s^{-1}$ is not necessary. These $Red(\lambda)$, $Green(\lambda)$ and $Blue(\lambda)$ sensitivities are expressed in $c.s^{-1}W.m^2sr$ and are null outside [380; 1000 nm] wavelength range. They are shown in Figure 4.

2.4 Spectral emissivity of materials

The spectral emissivity of two sets of materials was measured at the LNE laboratory, in the [250; 2500 nm] and [250; 3000 nm] ranges. The first set was composed of refractive materials whose emissivity is shown in Figure 5. The second set was composed of graphite and various cast iron, cast aluminium and steel samples², whose emissivities are shown in Figure 6.

2.5 From pixel color to radiance

The first principle of the method proposed is to relate any p pixel color to material m_p and temperature T_p . This color takes the form of three quantities r_p , g_p and b_p expressed in *counts* (c) accumulated by the camera sensor during a t exposure time

(in s). We ensured that in [380; 1000 nm], the camera response is linear with observed radiances (in $W.m^{-2}.sr^{-1}$) and t exposure time. Then, we can consider that $\frac{r_p}{t}$, $\frac{g_p}{t}$, $\frac{b_p}{t}$ are flows (in $c.s^{-1}$) corresponding to observed radiances pondered by the corresponding $Red(\lambda)$, $Green(\lambda)$ and $Blue(\lambda)$ channels relative sensitivities (in $c.s^{-1}.w^{-1}m^2sr$) and a η scaling factor.

The relationship between observed materials and their temperature, and pixels color is established by integrating the camera response $\left(\frac{r_p}{t}, \frac{g_p}{t}, \frac{b_p}{t}\right)$ to observed radiances $B(m_p, T_p, \lambda)$ over exposure time t and over the whole camera sensitivity wavelength range (typically 380 nm to 1000 nm).

In reality, the optical system is not perfect and several optical phenomena make sensor pixels react differently to a given radiance. A first reason is vignetting (Ray, 2002; Britannica, 2023) also known as “light fall-off”: the farther the pixels are from the center of the sensor, the less amount of light they will receive from a same radiance originating on the camera focal plane, due to several optical phenomena as illustrated in Figure 7. Other reasons can be dirt (e.g., (Deniel, 2002) p. 87) and imperfections in alignment of the optical component in the camera and its lens.

For those reasons, the relationship between observed materials and temperature, and camera response should account for a scaling factor dependent on each pixel. We assume that its dependency on wavelengths is negligible and denote it h_p . Then the complete relationship between

² Contifonte SAS, France, kindly gave us those cast iron and steel samples.

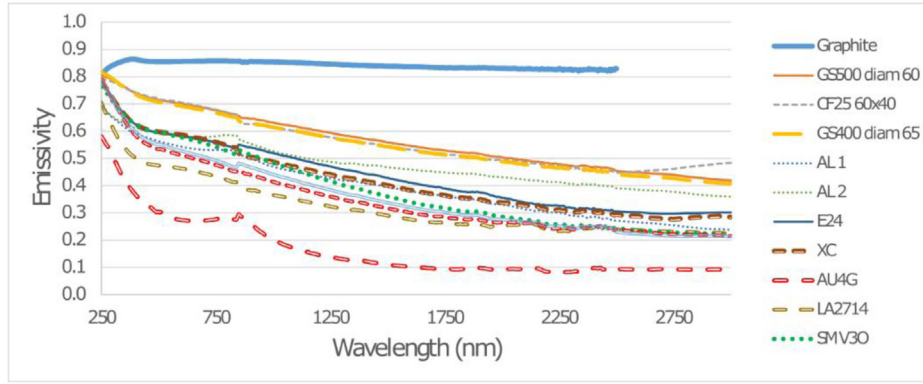


Fig. 6. Non-refractive materials emissivity.

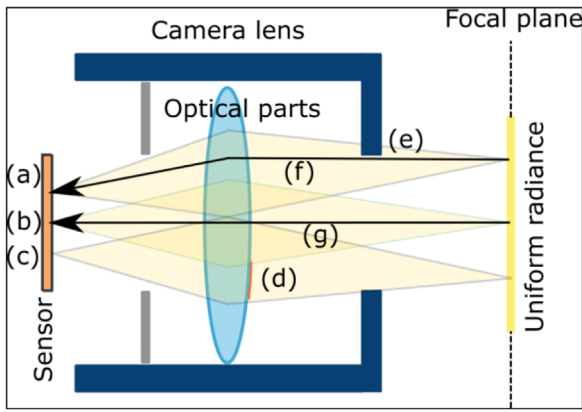


Fig. 7. Schematic examples of non-uniformities in the sensor reaction to a uniform radiance in the focal camera plane. (a) and (c) are pixels in the border of the sensor, while (b) is at its center. In yellow: the optical paths from the observed radiance to the (a), (b) and (c) pixels. Optical vignetting reasons: (a) receives less light than (b) because light is partially occluded at (e); pixel irradiance differ between (a) and (b) because of different optical paths (*e.g.*, (f) and (g)) from observed radiance to pixels. Vignetting due to defects: less light reaches the sensor at (c) than elsewhere due to dirt at (d).

observed radiance and sensor response is expressed in equations (4):

$$\begin{aligned} r_p/t &= \eta * h_p * ff_p * \int_{\lambda=380}^{1000 \text{ nm}} \text{Red}(\lambda) * B(m_p, T_p, \lambda) \partial \lambda \\ g_p/t &= \eta * h_p * ff_p * \int_{\lambda=380}^{1000 \text{ nm}} \text{Green}(\lambda) * B(m_p, T_p, \lambda) \partial \lambda \\ b_p/t &= \eta * h_p * ff_p * \int_{\lambda=380}^{1000 \text{ nm}} \text{Blue}(\lambda) * B(m_p, T_p, \lambda) \partial \lambda \end{aligned} \quad (4)$$

Since incandescent materials in the 800 to 1300 °C range emit more red radiations than green and blue, we normalize pixels color against the red channel, so that $(g_p/r_p; b_p/r_p) \in [0; 1]^2$ represents the p pixel hue independent of ff_p, h_p, t exposure time and η sensitivity scaling factor.

Furthermore, knowing $\text{Red}(\lambda), \text{Green}(\lambda), \text{Blue}(\lambda)$ and collections of emissivities for $m(\lambda)$ every $T \in [800^\circ\text{C}; 1300^\circ\text{C}]$ per 1 °C step, we compute the corresponding

$(g/r; b/r)$ camera color response and IR radiance $B_{IR} = \int_{\lambda=780}^{3000 \text{ nm}} B(m, T, \lambda) \partial \lambda$. Then, B_{IR}, m and T are stored in $(g/r; b/r)$ indexed matrices, keeping the most dangerous cases (*i.e.*, the highest B_{IR}, m).

This way, we can associate any $(g_p/r_p; b_p/r_p)$ pixel hue with a $(m_p; T_p)$ worst case and the corresponding $B_{IR,p}$ radiance (or no radiance if the cell in the matrix is empty). To account for camera chromatic noise, our method considers the worst case ± 0.02 around both coordinates. Figure 8 shows the non-null part of the $(g/r; b/r)$ to T E-M5 matrix.

2.6 Estimating temperature of materials inside the metal furnace

As illustrated in Figure 3, the metal furnace was filled with graphite, firebricks and metal samples at 800 °C to 1100 °C every 100 °C, plus 1140 °C. As this is not an item of calibrated equipment, the air temperature from the furnace probe must be considered with caution. In addition, after opening the furnace door even for a few tens of seconds, materials close to the opening become noticeably less hot than those in the back of the cavity. Consequently, only consistency between the estimated temperature of the materials and probe temperature should be considered.

3 Results

We analyzed pictures of the HGH RCN 1350 N1 blackbody and metal furnace, to estimate material m and temperature T . In the first case (blackbody), the emissivity database was reduced to $m(\lambda) = 1$. In the second case (heated materials), it contained all the emissivity data in Figure 5 and 6.

3.1 Blackbody temperature estimation

We analyzed pictures of the HGH RCN 1350 N1 blackbody. This device was set at every 100 °C from 800 °C to 1300 °C. Camera measurement uncertainty takes the form of color noise in pictures, influencing temperature estimates. This is why, each time, we noted the mean, lowest and highest

g/r	b/r	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12	0.13	0.14
0.39		791									
0.4		790									
0.41		813									
0.42		835									
0.43		857									
0.44		878									
0.45		900									
0.46		921									
0.47		941									
0.48		962									
0.49		982	1017								
0.5		993	1002								
0.51		893	1022								
0.52			1042								
0.53			1062								
0.54			1082								
0.55			1102	1143							
0.56			1119	1122							
0.57			1112	1142							
0.58				1161							
0.59				1181							
0.6				1201	1246						
0.61				1217	1220						
0.62				1205	1240						
0.63				1088	1260						
0.64					1279	1329					
0.65					1299	1350					
0.66						1319					
0.67					1161	1338					
0.68						1358					
0.69						1376	1378				
0.7						1364	1398				
0.71						1225	1400				
0.72							1400	1394			
0.73								1258	1400		
0.74								1274	1275		
0.75							1284		1289		
0.76								1305	1306		
0.77								1321	1321		
0.78								1337	1337		
0.79								1339	1353	1353	
0.8									1369	1368	
0.81									1385	1384	
0.82									1390	1400	1400

Fig. 8. Non-null part of the $(g/r;b/r)$ to $T(^{\circ}\text{C})$ matrix.

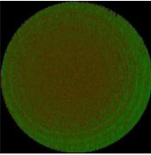
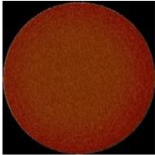
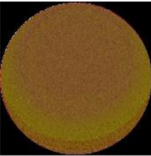
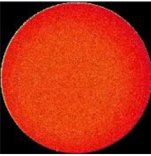
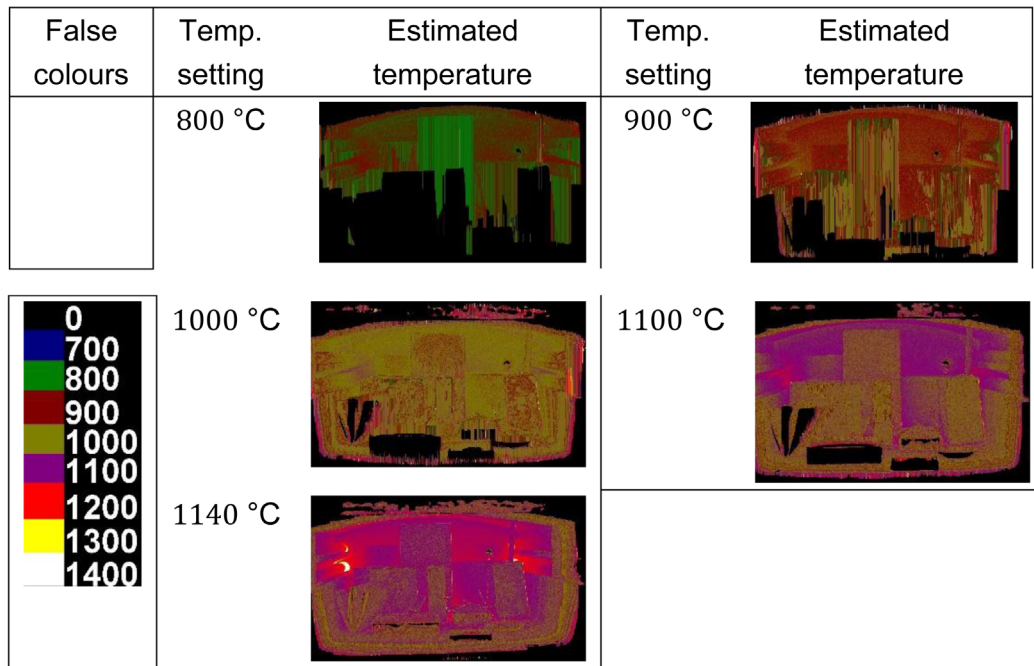
False colors	Temp. setting	Estimated temperature	Temp. setting	Estimated temperature
	800 °C		900 °C	
	1000 °C		1100 °C	
	1200 °C		1300 °C	

Fig. 9. Blackbody temperature settings and the corresponding estimated temperature in its cavity, in $^{\circ}\text{C}$, shown as interpolated false colors. For example, blue corresponds to 700 $^{\circ}\text{C}$, violet corresponds to 1100 $^{\circ}\text{C}$.

Table 1. Blackbody temperature estimation, in °C. “Blackbody temperature” refers to the setting of the device. “Estimated temperatures” result from applying our method to the picture colors in a 9×9 pixel region corresponding to the center of the blackbody opening.

Blackbody temperature	Estimated temperature		
	Mean	Min	Max
800 °C	856	812	899
900 °C	943	899	981
1000 °C	1031	981	1062
1100 °C	1131	1082	1160
1200 °C	1227	1180	1278
1300 °C	1326	1298	1357

**Fig. 10.** Wall temperature estimates inside the INRS metal furnace. Temperatures are shown in interpolated false colors: for example, blue corresponds to 700 °C, violet corresponds to 1100 °C.

estimated temperatures from the colors in a 9×9 pixel area at the center of the blackbody opening (see [Tab. 1](#)).

In addition, [Figure 9](#) illustrates the behavior of the method over the entire blackbody opening, which radiance uniformity is not perfect. Values in [Table 1](#) correspond to pixels in the center of pictures in [Figure 9](#).

3.2 Estimated temperature of materials inside the metal furnace

Pictures were taken of the metal furnace set at 800 °C to 100 °C every 100 °C, plus 1140 °C. Note that at 1140 °C, the pixels at the heating coils were saturated. [Figure 10](#) illustrates the application of our method to all these pictures to estimate the temperature of the furnace cavity and samples inside.

To complete these results, we choose to retrieve temperature estimates in 9×9 pixel picture areas in the picture of the furnace set at 1100 °C (see [Fig. 1](#)). We chose this

furnace temperature as the most exposing of the analyzed situations, without any saturated pixels in the picture.

In this picture, four letters correspond to 9×9 pixel areas:

- The GR28 firebrick, that is a cellular material
- A dense silica firebrick in the least cooling part of the cavity, close to the furnace air probe
- A dense silica firebrick next to a heating coil in the back of the cavity
- A heating coil, as these are the hottest parts in the furnace.

For each of these areas, we indicate the mean, min and max estimated temperatures in [Table 2](#).

Lastly, whatever the furnace temperature, almost only graphite (see [Fig. 6](#)) was associated with pixels of interest. A few percent were associated with the 1400 °C blanket (see [Fig. 5](#)). This is because these two materials are among the most emissive and are retained as the worst cases in the $(\frac{b}{r}; \frac{b}{r})$ to m

Table 2. Estimated furnace and samples temperatures, in °C, at areas marked in Figure 11(2). NB: at 1140 °C, the coil (d) pixels red channel is saturated.

Probe temp.	Estimated temp. °C		
	Mean	Min	Max
800 °C			
a	807	790	835
b	868	857	900
c	845	813	878
d	880	857	921
1000 °C			
A	1040	1002	1143
B	1021	982	1062
C	1006	982	1042
D	1043	1022	1082
1140 °C			
a	1107	1022	1143
b	1143	1102	1181
c	1139	1102	1181
d	1390	1139	1400
900 °C			
a	943	899	981
b	916	857	962
c	919	878	962
d	963	941	1002
1100 °C			
a	1042	962	1122
b	1097	1062	1142
c	1097	1062	1161
d	1141	1122	1161

matrix, that we wanted conservative in terms of prevention from occupational exposure.

4 Discussion

4.1 Temperature consistency between sources and our approach

We first tested our method against a blackbody. In this experiment, the source was calibrated and we could verify that its radiance followed Planck's law precisely. Temperature indications could be considered close to reality at $\pm 2^\circ\text{C}$ and emissivity was 1 in the 1000 to 2500 nm wavelength range.

As shown in Table 1 and illustrated in Figure 9, our method is able to estimate the temperature of a blackbody with a precision of $+2\%$ to $+7\%$. In our opinion, this is conservative in the sense that exposure to IR will not be under estimated.

On the contrary, our metal furnace was not calibrated and the difference between the air temperature at the probe and that of the samples was unknown. That is why the comparison in Table 2 should be considered with caution. Nevertheless, the estimated temperatures except (d) at 1140°C differed from probe indication by -5% to $+10\%$, which is realistic.

The estimated temperature pictures in Figure 11 show dark areas. Given the camera exposure time, they correspond to

surfaces that do not emit enough light to be considered, whereas their IR emission should not be neglected. To overcome this limitation, picture analysis should rely on bracketing (Debevec *et al.*, 2023) that consists in several successive pictures with different exposure times, exactly like in videophotometers (Safdar *et al.*, 2016). This way, each pixel color should be chosen in the picture where the color channel levels are most exploitable with two-fold benefits: accounting for all the incandescent materials and improving temperature estimation precision.

4.2 Emissivity: limits and dependency on temperature

As it was explained before, our first remark about emissivity is that the picture analysis considers almost only graphite as the incandescent material: in parallel with $(g/r; b/r)$ to T matrix, the method also keeps in memory the corresponding $(g/r; b/r)$ to material index m matrix. Its non-empty cells almost always refer to graphite.

The first reason appears in Figure 5 and 6: this material has the highest emissivity, close to a 85% grey body. In this case, graphite emits the most at a given temperature. This is why the matrices of the method are filled preferentially with graphite.

A second and potential reason could be called “cavity effect”: in the furnace, light is first emitted because of incandescence, then reflected multiple times. We suspect

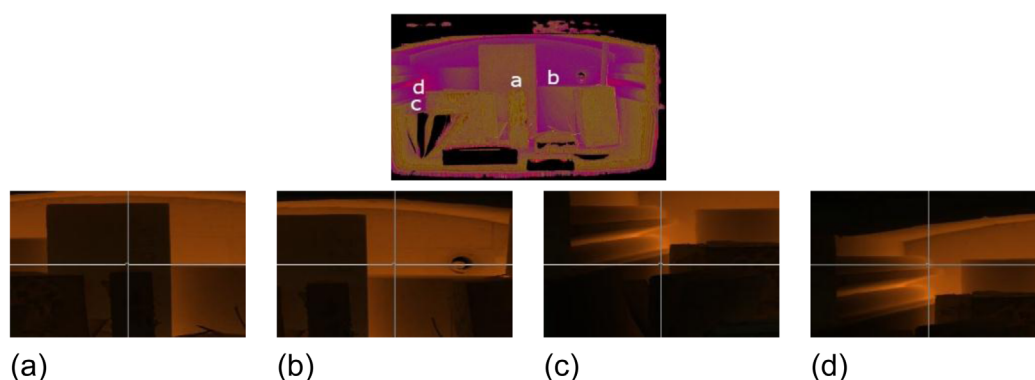


Fig. 11. Zoom on four 9×9 pixel areas denoted (a) to (d) in the 1100°C furnace picture (top). These areas are centered on the cross in the bottom pictures.

inter-reflections tend to make light spectral distribution even over the visible to NIR infrared wavelength range. In pictures, materials may appear as grey bodies, which corresponds the most to graphite. This hypothesis could be tested using the multispectral radiosity method (Cohen *et al.*, 1998).

Our second remark is that irradiance estimated from picture analysis will have to account for

- the increased emissivity of metals with temperature (Watanabe *et al.*, 2003; Touloukian *et al.*, 1970),
- a decrease of emissivity when water leaves porous materials, then an increase with temperature as we could measure it.

To account for these potential changes in the emissivities we measured, it will be reasonable to increase the calculated irradiance by $+20\%$.

5 Conclusion

We propose a method to estimate irradiance from incandescent opaque materials on $[780; 3000 \text{ nm}]$ by analyzing color pictures. The first principle in the method is estimating the temperature and the emissivity of incandescent materials from pixels color. Our results show that temperature estimations are consistent with that of observed sources, a blackbody as well as a furnace.

This method requires a kind of device several to tens of times less expensive than a radiometer or a spectroradiometer. In reality, such a device – a smartphone – is already present in the pocket of every preventer and makes our method virtually free.

To make this method genuinely usable in industry, several perspectives on the principle presented in this paper are planned.

The camera requires an easy and cheap calibration method. This is currently under investigation.

It must be usable with sensors having a low dynamic range, for example through the use of bracketing techniques (Debevec *et al.*, 2023). This will also solve the problem with the method neglecting the darkest areas in the picture although they correspond to incandescent materials.

In a second paper, we will explain how to exploit these temperature and emissivity estimations, to prevent from cataracts in various industrial sectors.

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Conflicts of Interest

The author declares that he has no conflict of interest.

Data availability statement

The data that support the findings of this study are openly available in Open Science Framework (OSF) at <https://osf.io>, under: - reference

DOI [10.17605/OSF.IO/VGFWK](https://doi.org/10.17605/OSF.IO/VGFWK) and - data public link.

Ethics approval

Ethical approval was not required.

Informed consent

This article does not contain any studies involving human subjects.

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