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Device for emissivity estimation in LWIR range

Abstract

The paper deals with the influence of emissivity on infrared measurements (Tab. 1; Fig. 1-3) and presents the developed device for emissivity estimation (Fig. 4). There is comparison shown between the reference emissivity values measured with thermal camera (Fig. 5) and estimated with the developed device (Tab. 2). Obtained results are in good agreement for three examined samples with emissivity ranging from 0.1 to 0.95.

Keywords: emissivity, infrared, thermal camera.

1. Introduction

Emissivity factor (ε_{obj}) plays the key role during contactless object surface temperature measurement with pyrometer or thermal camera. In general case it is impossible to tell the object surface temperature (T_{obj}) just by measuring the infrared radiation exitance (M_{obj}) that reaches the infrared detector [1]. This is due to Stefan-Boltzmann law for gray bodies given by (1) [2]. It turns out that this emitted energy may be constant for different combinations of surface temperature and its emissivity, as shown in Tab. 1.

$$M_{obj} = \varepsilon_{obj}\sigma T_{obj}^4, \qquad (1)$$

where σ=5.67051·10^{-8} Wm^{-2}K^{-4} is the Stefan-Boltzmann constant.

Tab. 1. Exemplary influence of emissivity on infrared exitance for different object temperatures

T_{obj}, K	ε_{obj}	M_{obj}, W/m^2
350	1	851
370	0.8	851
398	0.6	851
700	1	13615
740	0.8	13615
795	0.6	13615

Surfaces with high emissivity values (e.g. matte plastic) are easy for contactless temperature measurements, as they emit nearly as much energy, as blackbody with the same temperature (T_{bb}) would do. It means higher signal for the detector than in case of low emissivity samples (e.g. polished metal) having the same temperature. The lower is the sample emissivity, the lower is this signal under constant sample temperature, hence SNR (signal to noise ratio) decreases.

Basing on Kirchhoff's law one may also state that for non-transparent samples the reflectivity increases with emissivity decrease, according to (2). Hence for low emissivity samples there is a problem of reflections that are visible for thermal camera in the surface sample and it influences the temperature measurement.

$$\varepsilon_{obj} + \rho_{obj} = 1 \qquad (2)$$

In practice it is convenient to have this reflection coming from thermally uniform surface with known temperature (T_{bkg}), as shown in Fig. 1. This background temperature should be set into the camera software along with measured emissivity factor to enable its precise temperature measurement. Nevertheless this precision will be lower for low emissivity samples due to lower SNR and uncertainties.

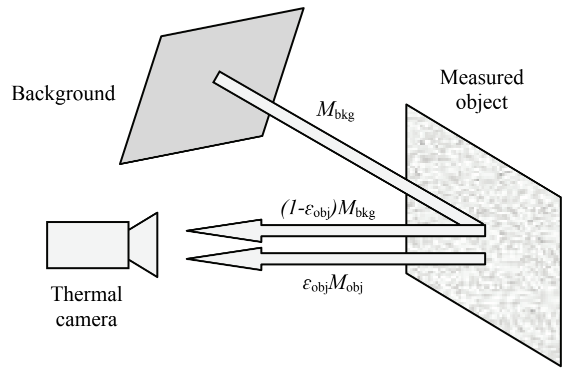

Fig. 1. Typical measurement scenario with thermal camera

2. Correction for emissivity during surface temperature measurements

Considering the information given in introduction, contactless surface temperature measurement requires in general case knowing its emissivity and reflected temperature value. The camera software may apply different models for compensating influence of those factors. In the simplest approach, neglecting the influence of atmosphere transmission, for typical measurement scenario shown in Fig. 1 it may be taken that (3) holds.

$$M_{cam} = \varepsilon_{obj}M_{obj} + \rho_{obj}M_{bkg} \ , \qquad (3)$$

where M_{cam} is the exitance reaching the camera detector and M_{bkg} is the background exitance.

This formula together with (1) enables us to display the influence of object real emissivity on its temperature value measured by the camera - in Fig. 2 there are exemplary plots for different real values of object temperature. The assumption here is the same background (reflected) temperature T_{bkg} = 27ºC and emissivity factor ε_{obj} = 1 set in thermal camera software. It shows that the temperature measured by a thermal camera is correct only for ε_{obj} = 1 and converges to T_{bkg} for $\varepsilon_{obj} \to 0$. It proves the importance of knowing the real emissivity value of a measured object and this value should be set in thermal camera software to enable accurate temperature readout.

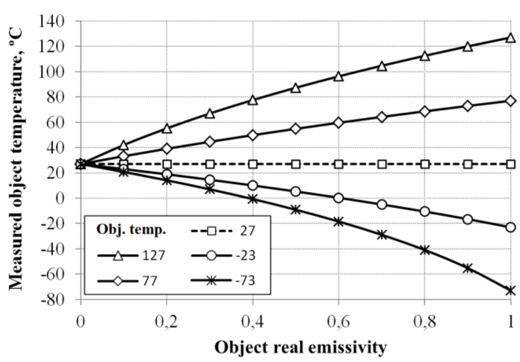

Fig. 2. Influence of object real emissivity on its temperature measured with thermal camera for different exemplary object real temperatures, assuming background temperature 27ºC and emissivity set to 1 in thermal camera

It may be easily noted in Fig. 2 that there is one particular case, in which the emissivity of the surface will not influence its contactless temperature measurement – this is when temperatures of surface and background are equal. Such behavior is easy explained – it is not important in which proportion the radiation emitted from surface and background will be mixed, as both carries the same energy. In other cases emissivity influences the temperature measurement – the more the higher is the difference between T_{obj} and T_{bkg}.

During measurements, thermal camera software recalculates the M_{cam}, T_{bkg} and ε_{obj} to obtain M_{obj} and finally after calibration T_{obj}. This is done with formula (4) [1] which is derived from (3).

$$M_{obj} = \frac{M_{cam} - (1-\varepsilon_{obj})M_{bkg}}{\varepsilon_{obj}} . \qquad (4)$$

Calculated value of M_{obj} is correct only when true value of ε_{obj} is used. When the user sets incorrect emissivity value in camera, it will cause measurement error proportional to the difference between T_{obj} and T_{bkg}, as shown in Fig. 3. Note that in this figure only for $\varepsilon_{obj} = 0.5$ (which is true object emissivity in this example) temperature values are measured correctly (solid marks). Again, there is one particular case ($T_{obj} = T_{bkg}$) in which the emissivity set in camera does not influence the temperature readout. But there is one more important observation from Fig. 3. If the user is uncertain about the true object emissivity value, it is better to overestimate it than to underestimate, in terms of potential temperature measurement error.

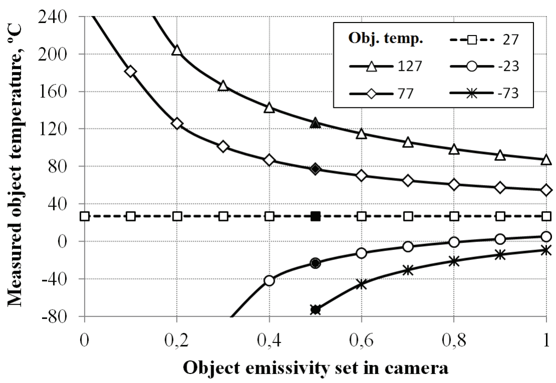

Fig. 3. Influence of emissivity value set in thermal camera software on measured object temperature. In this case $T_{bkg} = 27$ºC and true object emissivity $\varepsilon_{obj} = 0.5$ – only for this value (solid marked) temperature readout is correct

3. Methods of emissivity measurement

There are different methods that enable measurement of emissivity factor value. One must take into account, however, that this value is dependent on many factors, e.g. wavelength of infrared radiation, angle of measurement and surface temperature. Therefore in general case it cannot be assumed that there exist only one emissivity value for any certain surface. Fortunately, in practice it is possible to simplify things, e.g. by assuming that changes of the measurement angle from 0 to 60º exhibit marginal influence on emissivity [3] and it is not necessary to compensate for it. In practice often it is also enough to determine one value of emissivity for certain wavelength range, e.g. LWIR (7.5 – 14 µm), because this is what thermal camera expects from its operator. What is more, if the temperature of measured surface does not change by hundreds of degrees, it may be assumed that the emissivity will not be significantly affected by these changes.

Taking into account above mentioned considerations, it is possible to determine one emissivity value with methods described below [3], and assume it is enough for surface temperature measurements with thermal camera.

3.1. Reference body method

This method assumes that some part of the measured surface is covered with the layer of reference material with known (possibly high) emissivity ε_{ref}. This layer should heat up to the same temperature T_{obj} as the measured surface. Next, by transforming equation (3) one may obtain formula (5) for emissivity measurement

$$\varepsilon_{obj} = \varepsilon_{ref} \frac{M_{cam(obj)} - M_{bkg}}{M_{cam(ref)} - M_{bkg}} , \qquad (5)$$

where $M_{cam(obj)}$ and $M_{cam(ref)}$ stand for exitance of the measured and reference surfaces respectively [3]. In this case M_{bkg} may be measured by temporarily covering the object with another, highly reflective layer of e.g. aluminum foil.

3.2. Calorimetrical method

In case of this method there is a need for the real surface temperature, which should be measured with a contact thermometer. Knowing this value, one can adjust the emissivity in camera software to match the temperature readout with the reference one. In another variant of this method, the object emissivity may be calculated with formula (6), which is very similar to (5).

$$\varepsilon_{obj} = \frac{T_{cam}^4 - T_{bkg}^4}{T_{obj}^4 - T_{bkg}^4} , \qquad (6)$$

where T_{cam} stands for the object temperature displayed by the thermal camera with emissivity set to 1. It would be correct only if the object emissivity was 1, which is not possible in practice. T_{obj} is the reference, contact measured surface temperature. T_{bkg} is the background temperature [3].

4. Developed device for emissivity measurement

The developed device utilizes the method described in paragraph 3.2. It comprises two temperature sensors – one contactless MLX90614 [4] (LWIR) and one that requires direct contact with the surface (thermistor NTC 10k). The principle of operation is to heat up the surface and measure its temperature with the two above mentioned sensors. The assumption is that the contact sensor measures the real surface temperature, while the contactless one is also affected by this emissivity, as shown in Fig. 2. Hence it is possible to estimate the emissivity with formula (6). This value is calculated automatically in real-time by ATmega328 processor and displayed during measurements. The developed device is shown in Fig. 4.

Fig. 4. Developed device for emissivity estimation

To estimate the emissivity with this device one needs to heat up the measured surface and put the device to it so that there is a direct contact with the thermistor. In theory, the thermistor should heat up to the same temperature as the surface. In practice it is often not possible due to surface roughness and low contact area. The thermal resistance between the surface and the thermistor is not 0 nor even close and possibly could be reduced by applying thermal grease. Nevertheless in general case the surface temperature measured with the thermistor T_x is lower than it is in reality. In the developed device the author proposed a simple way of compensating for this effect by using formula (7).

$$T_{th} = T_x + 0.57(T_x - T_{amb}) \,, \tag{7}$$

where T_{th} is the compensated temperature and T_{amb} is the ambient temperature. The coefficient 0.6 was found empirically by comparing T_{th} with measurement performed with thermal camera for surface with known emissivity heated up to about (45 – 60)ºC. This coefficient is valid only for this particular configuration and may be different for other temperature sensors mounted with different methods, for other temperature ranges and even for different force that operator uses to put the device to the measured surface. In the particular case of this device, however, the formula (6) was found adequate and sufficient.

There is one more factor that needs to be determined – this is the background temperature T_{bkg}. In case of the developed device it is possible to read the temperature of MLX90614 itself (T_{case}), however it cannot be taken that $T_{case} = T_{bkg}$. This element heats up during emissivity measurement when it is in proximity with the examined hot surface, therefore it has to be distanced from it with metal cylinder (which also heats up but has low emissivity). Therefore to estimate the value of T_{bkg} the author proposed the empirically determined formula (8) involving both T_{case} and T_{amb}.

$$T_{bkg} = T_{amb} + 0.57(T_{case} - T_{amb}) \tag{8}$$

5. Measurements

There were three samples investigated: dark isolation tape, printed circuit board (PCB) heatbed and lightly oxidized metal. The reference emissivity of the isolation tape was previously known ($\varepsilon_{real} = 0.95$). This fact was used to measure the reference emissivity of the two other surfaces with thermal camera (FLIR® i5 first generation) using reference body method described in paragraph 3.1. The emissivity in camera software was adjusted to match the temperature readout of the measured surface with the readout for isolation tape attached to this surface when emissivity in camera was set to $\varepsilon = 0.95$ (Fig. 5). This way the reference emissivity of PCB heatbed and lightly oxidized metal was found to be 0.84 and about 0.1 respectively.

a) b)

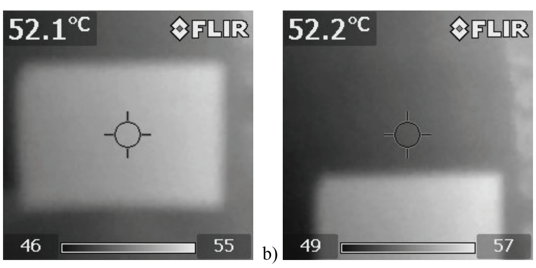

Fig. 5. Thermograms of PCB heatbed with temperature measurement marker pointed to a) isolation tape attached to the surface and in-camera ε set to 0.95, b) heatbed surface with in-camera ε set to 0.84. Note almost equal temperature readouts confirming the heatbed emissivity ε = 0.84

To estimate the emissivity with the developed device one needs to heat up the measured surface (similarly as in case of the reference measurement with thermal camera) and put the developed device to it so that there is a direct contact with the thermistor. There is no need to keep constant, particular temperature value of the measured sample. In case of this paper the measured surfaces were heated with PCB heatbed to temperatures ranging from about (45 to 60)ºC. The emissivity measurement results obtained for $T_{amb} = 26$ºC with the developed device for the three above mentioned samples are shown in Tab. 2. As it may be seen, the emissivity value measured with the developed device (ε_m calculated with (6) for Kelvins) is close to the real value (ε_{real}). In fact, there are two versions of ε_m presented – the first one with ∞ subscript was calculated exactly with (6) for Kelvins, what means that all the wavelengths were taken into account. The second version with subscript 5.5–14 µm was calculated only for this spectral range, which corresponds to the sensitivity band of the applied radiative sensor [4].

Tab. 2. Obtained emissivity measurement results with the developed device

T_{obj}, ºC	T_{bkg}, ºC	T_{th}, ºC	$\varepsilon_{m(\infty)}$	$\varepsilon_{m(5.5–14 \mu m)}$	ε_{real}
sample 1 – dark isolation tape					
54.5	37.9	55.1	0.96	0.963	0.95
55.5	38.8	56.0	0.967	0.968	0.95
sample 2 – printed circuit board heatbed					
48.8	36.7	51.2	0.824	0.824	0.84
55.4	40.6	58.3	0.826	0.853	0.84
sample 3 – lightly oxidized metal					
30.4	28.2	46.4	0.113	0.110	0.1
30.8	28.6	49.3	0.096	0.096	0.1

6. Uncertainty analysis

The calculation of emissivity estimation uncertainty with the developed device is presented for simplified case, where the emissivity value is obtained from (9):

$$\varepsilon_{obj} = \left(\frac{T_{obj}}{T_{th}}\right)^4 , \tag{9}$$

where T_{obj} is measured with the radiative sensor and T_{th} is measured with contact sensor, both in Kelvin. This formula may be used while the measured temperature is significantly higher than the ambient one [5]. A combined standard measurement uncertainty u_ε of the emissivity estimation [5, 6] may be given with (10):

$$u_\varepsilon = \sqrt{\left(\frac{\delta\varepsilon}{\delta T_{obj}}\right)^2 \left(u_{T_{obj}}\right)^2 + \left(\frac{\delta\varepsilon}{\delta T_{th}}\right)^2 \left(u_{T_{th}}\right)^2} , \tag{10}$$

where u_{Tobj} and u_{Tth} stand for the B-type standard uncertainty of the temperature measured with radiative and contact sensor, respectively, as given by (11) and (12):

$$u_{T_{obj}} = \frac{\Delta_{T_{objm}}}{\sqrt{3}} , \tag{11}$$

$$u_{T_{th}} = \frac{\Delta_{T_{thm}}}{\sqrt{3}} , \tag{12}$$

where $\Delta_{T_{objm}}$ and $\Delta_{T_{thm}}$ indicates the maximum errors of radiative and contact temperature measurements, respectively. The partial derivatives of (11) and (12) may be solved as (13) and (14) respectively:

$$\frac{\delta\varepsilon}{\delta T_{obj}} = 4\left(\frac{T_{obj}}{T_{th}}\right)^3 \frac{1}{T_{th}} = \frac{4\varepsilon}{T_{obj}} , \tag{13}$$

$$\frac{\delta\varepsilon}{\delta T_{th}} = -4\left(\frac{T_{obj}}{T_{th}}\right)^3 \frac{T_{obj}}{T_{th}^2} = -\frac{4\varepsilon}{T_{th}}. \quad (14)$$

Considering the above formulas, the combined standard measurement uncertainty u_ε of the emissivity estimation may be expressed as (15):

$$u_\varepsilon = \frac{4\varepsilon}{\sqrt{3}T_{th}}\sqrt{\left(\frac{T_{th}}{T_{obj}}\right)^2 \Delta^2_{T_{objm}} + \Delta^2_{T_{thm}}}. \quad (15)$$

This leads us to the expanded uncertainty (16):

$$U_\varepsilon = 3\sqrt{3}u_\varepsilon = \frac{4\varepsilon}{T_{th}}\sqrt{\left(\frac{T_{th}}{T_{obj}}\right)^2 \Delta^2_{T_{objm}} + \Delta^2_{T_{thm}}}. \quad (16)$$

The error of temperature measurement $\Delta_{T_{objm}}$ is related to the accuracy of the MLX90614 sensor, which is equal to ±0.5ºC for measured object positive temperatures not exceeding 60ºC and the ambient not higher than 50ºC [4]. Otherwise it is higher (from ±1ºC up to even ±4ºC according to [4]). Despite the case of the measurements presented in Tab. 2, where object temperatures do not exceed 60ºC, one should assume more general scenario taking $\Delta_{T_{objm}} = 1$ºC, which allows higher temperatures of measured surfaces (up to 120ºC [4]).

As far as $\Delta_{T_{thm}}$ is concerned, the NTC 10k thermistor used in this device has 5% accuracy. It means that its resistance at 25ºC may vary from 9.5 kΩ to 10.5 kΩ, which may be translated into $\Delta_{T_{thm}}$ value equal to about 1.1ºC. For more precise measurements one should use a 1% thermistor or e.g. MCP9808 with a typical accuracy of ±0.25°C in the range from –40°C to +125°C.

The expanded uncertainty of emissivity measurement may be calculated with (16) as about 0.017 in case of samples with high emissivity ($\varepsilon_{obj} = 0.95$, e.g. dark isolation tape). It may drop to about 0.015 for samples with lower emissivity ($\varepsilon_{obj} = 0.84$, e.g. PCB heatbed). In theory for low emissivity samples ($\varepsilon_{obj} = 0.1$, e.g. lightly oxidized metal) this uncertainty may be as low as about 0.002, but one has to remember that in practice it will be much greater because radiative temperature measurement is very inaccurate for such samples because:

- the exitance is very low compared to sample with the same temperature but high emissivity, according to (1), hence signal to noise ratio is low,
- only small part of the total exitance reaching the detector comes from the measured sample, the majority of exitance comes from the background, according to (3),
- the detector is reflected in the measured surface as the angle of measurement is zero, and there is no compensation of this effect applied in the developed device.

Let us consider the graph shown in Fig. 6, where for each measurement shown in Tab. 2 there are three bars shown. The first two of them represent the absolute value of the difference between the real and measured emissivity value, while the third one stands for the calculated uncertainty. One may notice that the obtained error levels are comparable to the calculated emissivity, except for the last sample with low emissivity. In this case, as previously stated, this low uncertainty value results from taken simplifications during its calculation and in practice should be much greater. Nevertheless, one may assume that the uncertainty of the emissivity measurement with the developed device should not exceed the value of ±0.02, which is acceptable for most applications.

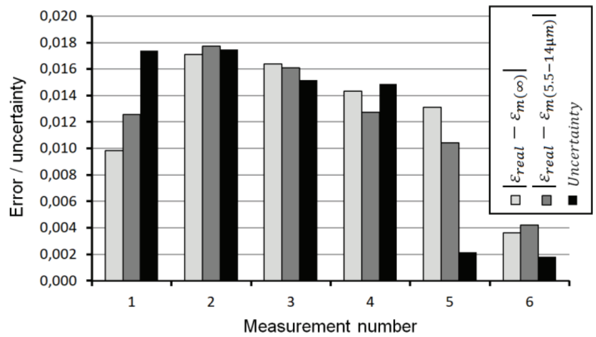

Fig. 6. Absolute error and uncertainty values calculated for each performed emissivity measurement

7. Conclusions

The developed device for emissivity estimation works by comparing the emitted infrared radiation in the LWIR range to the temperature measured with the touch sensor. It is compact and lightweight but requires heating the examined surface. Performed tests for three samples shows good agreement with reference measurements, what is coherent with calculated uncertainty value. No significant improvement was observed when emissivity was calculated in the spectral range covered by the sensor instead of the whole electromagnetic spectrum. Factors in (7) and (8) are valid for this particular device and may differ for other constructions or different sensors.

8. References

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