——————— **337**

Tadeusz KRUCZEK, Wojciech ADAMCZYK, Grzegorz KRUCZEK
INSTITUTE OF THERMAL TECHNOLOGY, SILESIAN UNIVERSITY OF TECHNOLOGY,
22 Konarskiego St., 44-100 Gliwice, Poland

Use of Matlab Package for External Local Calibration of IR Camera with Microbolometric FPA Detector

Abstract

This work presents the method of improving the accuracy of temperature measurement results obtained by means of long-wave infrared camera equipped with focal plane array (FPA) detector. The typical accuracy of infrared cameras specified by their manufacturers amounts to ±2 K or ±2% of the measured value of temperature. Very often a better accuracy of the measurements is required, e.g. during the measurements of human body temperature. To improve the measurement accuracy an external local (in terms of temperature range) correction of obtained results on the basis of comparison measurement results of black body temperature and next with use of MATLAB package has been proposed.

Keywords: thermovision infrared measurements, improvement of accuracy of infrared camera measurements.

Nomenclature

a	-	coefficient, constant, 1/K
b	-	coefficient, constant
c_1, c_2	-	first and second radiant constant, respectively, $W \cdot m^2$ or $m \cdot K$
C	-	calibration coefficient
$\dot{e}_\lambda(\lambda, T)$	-	spectral density of black body self-emission for temperature T, resulting from Planck's law, W/m^3
$\dot{e}_{\Delta\lambda}(T)$	-	emissive power of black body in spectral range $\Delta\lambda = \lambda'' - \lambda'$ at a given temperature T, [1,2], W/m^2
$\dot{h}$	-	radiosity of considered surface, W/m^2
I, J	-	total number of pixel rows and columns of FPA detector, respectively
L	-	total number of black body temperature levels during the IR camera calibration
M	-	total number of IR camera thermograms recorded for one temperature level of black body
r	-	reflectivity of the considered surface ($r=1-\varepsilon$)
T_{am}	-	ambient radiation temperature of considered objects, K
T_{bb}	-	temperature of black body indicated by its system, K
T_c	-	temperature measured and indicated by IR camera, K
T_{bc}	-	temperature of demonstration object which value is indicated by IR camera, K
T_{br}	-	real (true) temperature of demonstration object, K
T_{obc}	-	generally, temperature of examined object which is indicated by IR camera, K
T_{obr}	-	generally, real (true) temperature of examined object, K
ε_{bb}	-	emissivity of black body model
ε_b	-	emissivity of demonstration object
ε_{ob}	-	emissivity of examined object, generally
λ	-	wavelength of IR radiation, m or μm
λ', λ''	-	operation spectral range of IR camera, 7,5 μm and 13 μm, respectively.

Indexes and abbreviations

i, j	-	consecutive number of row and column of FPA detector, respectively
l	-	consecutive number of black body temperature levels during the IR camera calibration, $l = 1, \dots, L$
m	-	consecutive number of IR camera thermogram recorded for one temperature level of black body model, $m = 1, \dots, M$

BB, IR - black body model or infrared, respectively.

1. Introduction

The given typical values of measurement accuracy amounting to ±2 K or ±2% of the measured value are valid for the whole temperature measurement range of considered camera [3, 4]. The specified accuracy deals with the measurement results displayed directly by the camera. Simultaneously with the relentless passage of time the material of camera detector goes off and arises the problem of detector temperature drift which is of non-uniform character over the detector surface [5]. Therefore, to keep high accuracy of infrared camera measurements, the camera detector should be periodically calibrated [6].

In the case of measuring the temperature occurring within a narrow range of its values it is possible to improve the accuracy of obtained measurement results by means of external correction of raw measurement results obtained directly from the infrared camera. This correction can be done locally for aforementioned measurement range which should be determined at the beginning of this procedure.

In this methodology the using of a model of black body is necessary. The first step in this procedure is the measuring of the temperature of black body by means of the examined infrared camera. These measurements are repeated several times for different values of black body. These temperature values should cover the whole temperature range which is interested for us. Next, for each pixel of FPA (Focal Plane Array) detector the discrepancy between the real value of the black body temperature and value indicated by the infrared camera is determined. As the result, the matrixes of the discrepancies between the temperatures indicated by the camera and the temperature values reached by the black body model are obtained.

Then the gathered data were applied for the development of mathematical relationships used for the correction of measurement results produced by the examined camera.

2. Description of correction algorithm

The infrared thermography technique is based on the measurement of radiative heat flux emitted from the surface taken into consideration. In the situation when the emissivity of the investigated object is less than 100%, the total radiative heat flux from the tested surface consists of two parts. The first part presents the self-emission heat flux whereas the second part is the radiation flux which comes from surroundings and is reflected by the considered surface. Thus, in a mathematical model during an infrared camera temperature measurement the following radiation heat fluxes arriving at an infrared detector should be regarded:
a) radiation flux emitted by the examined object,
b) radiation flux emitted by the ambient and reflected from the object under examination,
c) radiation flux emitted by the atmospheric air which is to be found between the object and the infrared camera.

During the calibration procedure, due to a very small distance between the source of thermal radiation (a black body model) and the IR camera, the radiation flux specified in point (c) can be omitted. In this case a scheme of radiative heat transfer between considered object, its ambient elements and the IR camera can be shown as in Fig. 1.

The quantity denoted by $\dot{e}_{\Delta\lambda}(T)$ presents a self-emission radiation heat flux emitted within the operation spectral range of the IR camera and is expressed by the relation:
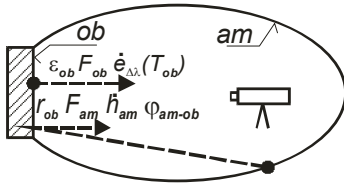
Fig. 1. Scheme of heat transfer in measurement space; *ob*-surface of object under investigation, *am*- isothermal ambient

$$\dot{e}_{\Delta\lambda}(T) = \int_{\lambda'}^{\lambda''} \dot{e}_\lambda(\lambda, T)\ \mathbf{d}\,\lambda \tag{1}$$

where $\dot{e}_\lambda(\lambda, T)$ is spectral density of black body self-emission resulting from Planck's law [1, 2], expressed by the equation (2):

$$\dot{e}_\lambda(\lambda, T) = \frac{c_1 \lambda^{-5}}{\exp(c_2 / \lambda T) - 1} \tag{2}$$

The sum of self-emission heat flux and radiation heat fluxes coming from other surfaces and reflected by the surface under consideration is called the radiosity (denoted by $\dot{h}$) of the considered surface [1, 2].

After applying the closure principle $\varphi_{am-ob} + \varphi_{am-am} = 1$ and reciprocity principle $F_{ob}\varphi_{ob-am} = F_{am}\varphi_{am-ob}$, [1, 2], and after making obvious assumptions that $\varepsilon_{am} = 1$, $\varphi_{ob-am} = 1$, after some manipulations an accurate relation expressing the unit flux of radiation energy $\dot{h}_{ob}$ coming from surface "*ob*" and arriving at an IR camera is obtained [7, 8, 9]:

$$\dot{h}_{ob} = \varepsilon_{ob}\ \dot{e}_{\Delta\lambda}(T_{ob}) + (1 - \varepsilon_{ob})\ \dot{e}_{\Delta\lambda}(T_{am}) \tag{3}$$

The output signal *s* from the camera detector is closely coupled with the aforementioned energy flux and can be described by the formula [3, 7]:

$$s \approx \psi\ \dot{h}_{ob} = \psi\left[\varepsilon_{ob}\ \dot{e}_{\Delta\lambda}(T_{ob}) + (1 - \varepsilon_{ob})\ \dot{e}_{\Delta\lambda}(T_{am})\right] \tag{4}$$

During the calibration procedure the equation (4) is formulated twice for each i, j-th pixel of FPA detector. The first time for the IR camera with a detector correctly processing the radiation flux generated by black body model at temperature T_{bb} into output signal s_{cor}:

$$s_{cor} \approx \psi\left[\varepsilon_{bb}\ \dot{e}_{\Delta\lambda}(T_{bb}) + (1 - \varepsilon_{bb})\ \dot{e}_{\Delta\lambda}(T_{am})\right], \tag{5}$$

and the second time for the IR camera with a detector which incorrectly converts the radiation flux generated by black body model at temperature T_{bb} into output signal s_{incor} and camera indicates an incorrect temperature value $T_{ci,j}$ for i, j-th detector pixel:

$$s_{incor} \approx \psi\left[\varepsilon_{bb}\ \dot{e}_{\Delta\lambda}(T_{c\,i,j}) + (1 - \varepsilon_{bb})\ \dot{e}_{\Delta\lambda}(T_{am})\right], \tag{6}$$

where ψ denotes an empirical coefficient.

Next, the measurements of the temperature of black body is repeated for *L* temperature levels of this body. On the basis of Eqs (5, 6) and the aforementioned measurement results, a matrix of calibration factors $C_{l,i,j}$ defined by the relation (7) is created:

$$C_{l,i,j} = \frac{s_{cor}}{s_{incor}} = \frac{\varepsilon_{bb}\ \dot{e}_{\Delta\lambda}(T_{bb\,l}) + (1 - \varepsilon_{bb})\ \dot{e}_{\Delta\lambda}(T_{am\,l})}{\varepsilon_{bb}\ \dot{e}_{\Delta\lambda}(\overline{T}_{c\,l,i,j}) + (1 - \varepsilon_{bb})\ \dot{e}_{\Delta\lambda}(T_{am\,l})}, \tag{7}$$

where temperature $\overline{T}_{c\,l,i,j}$ representing the camera measurement result is an average value calculated on the basis of measurements repeated *M* times for each selected *l*-th temperature value of the black body and is determined as follows:

$$\overline{T}_{c\,l,i,j} = \frac{1}{M}\sum_{m=1}^{M} T_{c\,l,i,j,m} \tag{8}$$

Next, after the creation of the matrix of calibration coefficients $C_{l,i,j}$ values, least squares adjustment method was applied to determine the coefficients $a_{i,j}$, $b_{i,j}$ of linear equations describing a dependence of calibration factors on the temperature T_c within the temperature range $T_{cl=1} \div T_{cl=L}$ for each i, j-th pixel of the FPA detector:

$$C_{i,j} = C(T_{c\,i,j}) = a_{i,j}\,T_{c\,i,j} + b_{i,j} \tag{9}$$

3. Experiment description

In the experiment the black body BB-6 with plane testing surface and infrared camera ThermaCAM SC 2000 were used, Fig. 2. The measurements have been carried out for several values of black body temperature taken from the range $15 \div 60°C$. The mentioned range was determined by the technical features of the black body device which we used.

Next, the obtained measurement results from the camera were compared with the preciously measured temperature of black body. On the basis of these data the temperature differences for each pixel of the infrared camera detector were calculated. The gathered temperature differences were used for the determination of mathematical relationships individually for each pixel of the detector array. Then, to improve the quality of measurement results, these relationships can be used for the correction of results produced directly by the camera. Additionally, various statistical quantities were calculated which were useful for the evaluation of camera detector measurement features. To realize this process the MATLAB package was employed.
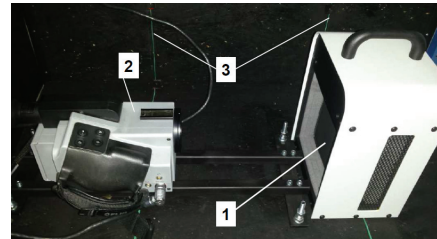

Fig. 2. The infrared camera ThermaCAM SC2000 and the black body in an isothermal chamber, 1-black body, 2- camera, 3-thermocouples for measurement of the chamber walls temperature

4. Correction of measurement results

After determination of the matrix of coefficients $C_{l,i,j}$ on the basis of Eq. (9), for each pixel the corrected values $T_{obr\,i,j}$ of the considered object temperature can be calculated. These values can be obtained on the basis of Eq. (10):

$$\dot{e}_{\Delta\lambda}(T_{obr\,i,j}) = C_{i,j}(T_{obc\,i,j})\left\{\dot{e}_{\Delta\lambda}(T_{obc\,i,j}) + \frac{1 - \varepsilon_{ob}}{\varepsilon_{ob}}\ \dot{e}_{\Delta\lambda}(T_{am})\right\} - \frac{1 - \varepsilon_{ob}}{\varepsilon_{ob}}\ \dot{e}_{\Delta\lambda}(T_{am}) \tag{10}$$

where $T_{obc\,i,j}$ is the considered object temperature value shown by the camera for i, j-th pixel of the camera detector. The desired values of the temperature $T_{obr\,i,j}$ occur in the implicit form in

expression $\dot{e}_{\Delta\lambda}\left(T_{ob\;r\,i,j}\right)$. The total value of this expression is known and therefore to calculate the desired temperature from relation (10), the Eqs (1, 2) should be additionally used.

5. Calculated parameters and calculation results

To evaluate the effectiveness of external calibration procedure and the quality of measurement results produced by the IR camera for all pixels of FPA detector the temperature differences defined by the relation (11) were calculated:

$$\delta T_{l,i,j} = \overline{T}_{c\;l,i,j} - T_{bb\;l} \tag{11}$$

The calculation results have been shown for selected black body temperature levels, Fig. 3. These results are useful for the evaluation of measurement results quality obtained by means of the considered camera.

Fig. 3. Histograms of differences between the temperature measured by the IR camera and indicated by the BB before correction, (Eq. 11)

The similar temperature discrepancies can be calculated for the corrected values $T_{brl,i,j}$ of the BB temperature measured by the IR camera:

$$\delta T_{r\,l,i,j} = T_{br\,l,i,j} - T_{bb\;l} \tag{12}$$

In this case the obtained results testify to the quality of calibration method used for the improvement of the quality of measurement results obtained by means of the examined IR camera. The temperature values $T_{brl,i,j}$ are calculated from the relation (13) resulting from Eq. (10):

$$\dot{e}_{\Delta\lambda}(T_{br\,l,i,j}) = C_{i,j}(\overline{T}_{c\;l,i,j})\left\{\dot{e}_{\Delta\lambda}(\overline{T}_{c\;l,i,j}) + \frac{1-\varepsilon_{bb}}{\varepsilon_{bb}}\dot{e}_{\Delta\lambda}(T_{am\,l})\right\} - \\ - \frac{1-\varepsilon_{bb}}{\varepsilon_{bb}}\dot{e}_{\Delta\lambda}(T_{am\,l}) \tag{13}$$

where the values of coefficient $C_{i,j} = C_{i,j}(\overline{T}_{c\;l,i,j})$ are calculated on the basis of known relation (9). The calculation results have been presented in Fig. 4.

In Fig. 5 histograms presenting dispersions of correction coefficient C defined by expression (7) and calculated for all pixels of FPA detector have been shown. These diagrams present the differences in terms of conversion quality of thermal radiation into a measurement signal by the infrared detector for all pixels of the detector matrix.

Additionally, in Fig. 6 the sample of correction line determined for one pixel of FPA detector is presented.

As it is described, for all pixels of IR camera detector the correction lines expressing the changes of correction coefficient according to the measured temperature by means of the least squares adjustment method have been determined. Simultaneously, the values of a correlation coefficient have been calculated. The value of this coefficient expresses the quality of the fitting of the determined line to the considered set of points. The fitting of correction lines was quite satisfactory, because for most pixels of the camera detector the correlation coefficients took values on the average 0.98.
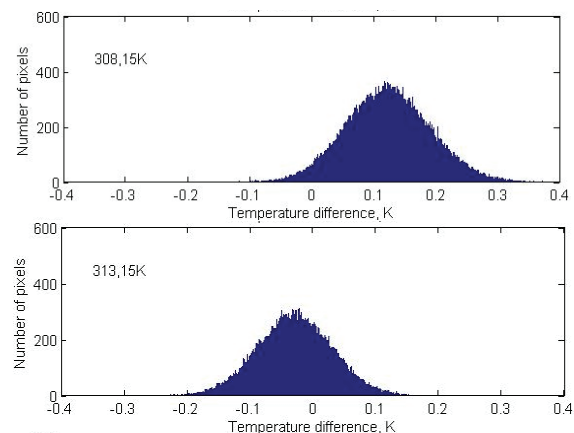

Fig. 4. Histograms of differences between the temperature measured by the IR camera and indicated by the BB after correction, (Eq. 12)
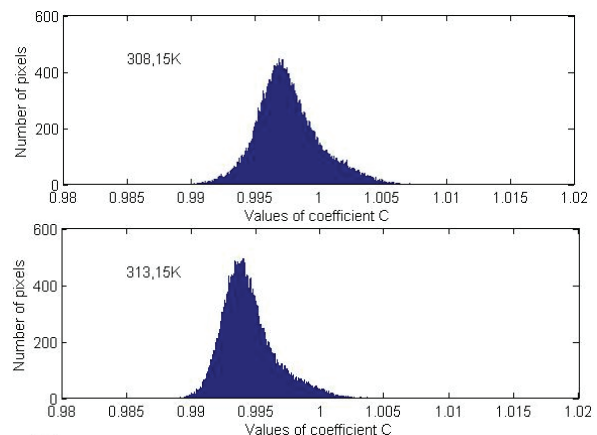

Fig. 5. Histogram presenting the dispersion of value of the correction coefficient C
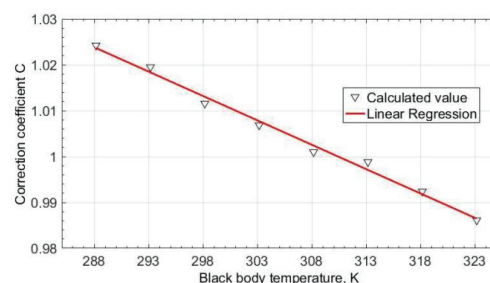

Fig. 6. Correction line of coefficient C for specified coordinates of pixel of FPA detector ($i=20$, $j=50$)

6. Verification of the method

To verify the developed method, an additional measurement series using the examined IR camera and the black body model was made. The experiment was carried out for the temperature of black body amounting to 36.6°C (i.e. 309.75 K). Next, the

obtained measurement results have been corrected with the use of Eq. (13) and for all pixels of IR detector the temperature differences between measurements and the black body temperature have been calculated according to Eq. 14 (before correction) and Eq. 15 (after correction). Next, the obtained results have been presented in a form of histograms (in Fig. 7), and as visual matrix images in Fig. 8.

$$\delta T_{bc,i,j} = T_{bc\ i,j} - T_{bb} \tag{14}$$

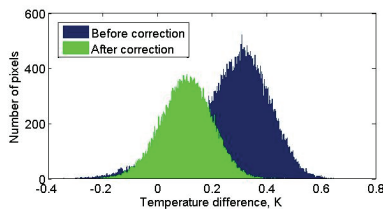$$\delta T_{br,i,j} = T_{br\ i,j} - T_{bb} \tag{15}$$

Fig. 7. Histogram of the temperature differences between the temperature indicated by the camera and the black body before and after applying the correction
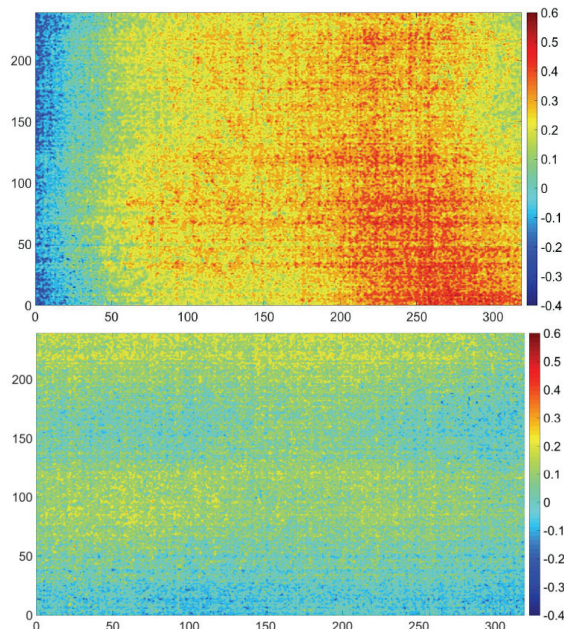

Fig. 8. Visual image of distribution of temperature differences between the temperature indicated by the camera and the black body measuring system before (top) and after (bottom) applying the correction procedure for the examined infrared camera (along the axes - numbers of detector pixels)

7. Final remarks and conclusions

In the paper the method of improving the accuracy of temperature measurement results obtained by means of an infrared camera equipped with FPA detector is presented. The typical accuracy of infrared cameras amounts to ±2 K or even ±2% of the measured value of temperature [3]. Very often a better accuracy of the measurements is required, e.g. during the measurements of human body temperature. To improve the measurement accuracy an external correction of obtained results on the basis of comparison measurement of black body temperature and next with use of MATLAB package has been described.

The developed method allows to improve locally in term of temperature range, the accuracy of measurement results recorded by the IR camera. It is expected that in the case of using the black body model of high accuracy in this calibration procedure, the reaching of measurement accuracy close to detector thermal sensitivity is possible.

In the work different diagrams which are useful for the evaluation of IR camera measurement accuracy and its operation have been worked out and presented. It is expected that the proposed method will be very effective for narrow measurement ranges of temperature.

8. References

[1] Howell J.R., Siegel R., Mengüç M.P.: Thermal radiation heat transfer. CRC Press Taylor&Francis Group, New York 2011.
[2] Modest M.,F.: Radiative heat transfer. McGraw-Hill, Inc., NY, 1993.
[3] Technical Documentation ThermaCAM SC2000, FLIR.
[4] Minkina W., Dudzik S.: Infrared Thermography - Errors and Uncertainties. Wiley & Sons, UK; 2009.
[5] Olbrycht R., Więcek B.: Correction of microbolometer detector temperature drift, MAM, vol. 55, No 11, pp. 890-893, 2009.
[6] Rainieri S., Pagliarini G.: Data processing technique applied to the calibration of a high performance FPA infrared camera, Infrared Physics & Technology, vol. 43, pp.345-351, 2002.
[7] Kruczek T.: Analysis of the influence of external conditions on thermovision measurement results. Proc. of 5-th Conf. TTP 2002, Ustroń (Poland), pp.327-332, 2002, (in Polish).
[8] Kruczek T.: Conditions for the use of infrared camera diagnostics in energy auditing of the objects exposed to open air space at isothermal sky. Archives of Thermodynamics, vol. 36, No. 1, pp.67-82, 2015.
[9] Kruczek T.: Use of infrared camera in energy diagnostics of the objects placed in open air space in particular at non-isothermal sky. Energy, vol. 91, pp.35-47, 2015.

Tadeusz KRUCZEK, PhD

Study and doctor's thesis at Mechanical and Energy Faculty of Silesian University of Technology. Research activity in area of rational use of energy, techniques of thermal and infrared measurements, thermal diagnostics of objects. Author or co-author of more than 170 various scientific papers. Scientific visits in different foreign universities and research institutions. Member of Energy Commission of Polish Acad. of Science, Katowice Dep., Head of Laboratory of Thermal Technology in ITT.

e-mail: tadeusz.kruczek@polsl.pl

Wojciech ADAMCZYK, PhD

Study and PhD thesis at Mechanical and Energy Faculty of Silesian University of Technology (SUT) in Gliwice, Poland. Currently, an assistant professor at Institute of Thermal Technology at SUT. Author of over 15 publications in international journals devoted to modeling fluidization processes, heat transfer, numerical modelling. Over his academic carrier participation in numerous projects devoted to industrial, laboratory and medical applications.

e-mail: wojciech.adamczyk@polsl.pl

Grzegorz KRUCZEK, MSc

PhD student at Mechanical and Energy Faculty of Silesian University of Technology. Study in the same Faculty and one year at Technical University of Stuttgart, Germany. Professional trainings in Istituto Motori, Napoli, Italy (3 months) and in General Electric Engineering Design Center, Warsaw (twice). He deals with numerical modelling of thermal processes, especially in internal-combustion engines. Co-author of 6 papers (2 in international JCR journals).

e-mail: grzegorz.kruczek@polsl.pl