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Proposition of a method of determining the thermovision measurement extended uncertainty of the surface temperature of an object close to a camera lens

Abstract

In the article the influence of selected factors occurring during thermal measurements on the uncertainty of thermovision temperature measurement is discussed. A situation in which the observed surface was close to the camera lens was measured (distance less than one meter). Based on the type B determination methodology described in the literature on the subject, a method of calculating the measurement extended uncertainty is proposed. A division of factors influencing the thermovision temperature measurement uncertainty into external factors and internal factors is also proposed. Factors associated with the conditions prevailing during the measurement, the geometry of the measurement system and the properties of the observed surface were considered external factors. Factors related to the calibration of the thermal imaging camera, the sensor matrix used and the properties of its measuring path were qualified as internal factors. The method of determining the value of the camera display at the highest and lowest value of a particular factor is discussed. The probability distribution for each of the external factors was determined. The measuring system constructed is presented. It is explained how the uncertainty shares and expanded uncertainty were determined in accordance with the method proposed.

Keywords: uncertainty, thermography, metrology.

1. Introduction

The measurement made with the use of a thermal imaging camera, just like a measurement made with each measuring instrument, is subjected to uncertainty. The value of uncertainty depends on the occurrence of factors affecting the indication of the measuring instrument and the values they meet. In the case of thermovision measurements, the factors can be divided into internal factors and external factors. Internal factors related to the calibration of the thermal imaging camera, the properties of the detector matrix used and the properties of the measuring track were considered internal factors. The NUC correction of the detector array (correction of heterogeneity) should be taken into account. The more precisely the static characteristics of individual detectors have been converted into one common characteristic, the smaller the measurement error. This group of factors can also include the accuracy of the equation used by the manufacturer during the calibration process of the camera and the course of the calibration process itself. For the needs of the calculations necessary to convert the signal measured at the detector terminals into thermogram reflecting the temperature distribution on the observed surface, some of the numbers that are part of the processing equation are rounded. The parameters of the static characteristics of the processing path whose value is also subjected to an error are not without significance. Factors associated with the conditions prevailing during the measurement, the geometry of the measurement system and the properties of the observed surface were considered external factors. External factors shall include:

- value of the emissivity coefficient,
- reflected radiation,
- distance separating the lens from the observed object,
- viewing angle,
- humidity,
- ambient temperature.

The uncertainty shares related to the occurrence of the same factors differ depending on the occurrence of a given factor and its value. They depend on the conditions in which the measurement is made and on the specifics of the measurement. For example, when a black, rough surface of small size near the camera lens is observed, and the space of the lens and object is limited by a black tube, the effect of the factor associated with the reflected radiation and distance is small. In a situation where a smooth metallic surface is observed far from the lens and the space around this surface and the lens is not limited, the impact of the factors related to reflected radiation and distance will be greater, as compared to the first example. Very often, the camera user does not have access to camera processing equations and information about the calibration process. Details of the measuring path of the camera are also reluctantly made available by producers. For this reason, the author of this publication decided to propose a way to determine the extended uncertainty of thermovision temperature measurement. Due to the author's interest and the type of research carried out, it was decided that a situation in which the observed object is located near the camera lens (at a distance of less than one meter) will be analyzed. The publication focuses on the analysis of external factors.

2. Measuring system

The problem associated with determining the thermovision temperature measurement uncertainty has been discussed in many papers [1, 2]. However, it has not been fully resolved. The authors who tried to deal with this problem presented solutions specific to their field. In this work, the publication of the Polish Accreditation Center [3] and definitions from the international metrology dictionary [4] were used as model. A thermovision measurement is an indirect measurement. It is based on the theory of emitting its own electromagnetic radiation of bodies whose temperature is higher than 0 K. The relationship between the radiation recorded by the camera detector array and the actual temperature is described using the processing equation. Unfortunately, the author of the publication does not have access to the processing equation. The lack of it was the main reason for looking for another way to determine the expanded uncertainty of the measurement. On the basis of analyzed publications [5, 6] and the observation of possible settings of the thermal imaging camera [7], it was found that the indication of the thermal imaging camera ϑ_w used during the experiment depends on seven parameters: emissivity coefficient of the observed surface ε, ambient temperature ϑ_a, reflected temperature (parasitic radiation) ϑ_r, temperature of the external optical system ϑ_o, external transmission of the optical system τ_o, relative humidity h and distance between the lens and the observed surface d (Equation 1).

$$\vartheta_w = f(\varepsilon, \vartheta_a, \vartheta_r, \vartheta_o, \tau_o, h, d) \qquad (1)$$

When analyzing literature reports, it was found that in order to reliably assess the measurement uncertainty, one should also take into account the observation angle in the horizontal plane α, observation angle in the vertical plane β, change in the air composition and other factors resulting from the specifics of the conducted works. Research work, within which the thermal measurement uncertainty was determined, consisted in registering the temperature distribution on a selected side surface of a steel plate measuring 20 × 3 × 1 cm at a constant temperature of 20°C. For this reason, the plate was placed in a climate chamber with internal dimensions of 455 mm × 450 mm × 540 mm. In order to minimize the influence of radiation reflected in the interior of the chamber, it was lined with black cardboard. The plate was placed in such a way that it was visible in the lateral part of the recorded thermogram. The surface of the plate was also observed at an angle of 30°. This placement of the observed surface in relation to the camera lens allowed to avoid the visible influence of the parasitic radiation from the camera lens. Placing the observed surface at such an angle does not cause a significant increase in the measurement error [8]. Where the chamber door is, a thermoplastic with an opening for thermal imaging was placed. The camera lens were placed less than one meter from the observed surface. It was as close to the styrofoam as possible. This forced the placement of the observed plate in the back of the chamber. The space between the lens and the styrofoam was limited by a black tube. The whole was tightly sealed Taking into account the observed camera settings, literature data and the specificity of the conducted works, it was found that the temperature measurement uncertainty with a thermal imaging camera ϑ_x depends on the following factors (input values) – Table 1.

Tab. 1. Estimated input values, correction symbols and uncertainty

Estimated input value	Value symbol	Correct ion p_i	Uncertainty $u(p_i)$ corrections p_i
Thermovision camera measurement result	ϑ_{kam}	0	0
thermovision camera measurement error	*kam*	p_{kam}	$u(p_{kam})$
instability of the temperature of the climate chamber	ϑ_i	$p\vartheta_i$	$u(p\vartheta_i)$
changes in the value of the emissivity coefficient	ϑ_ε	$p\vartheta_\varepsilon$	$u(p\vartheta_\varepsilon)$
Reflected temperature	ϑ_r	$p\vartheta_r$	$u(p\vartheta_r)$
Change in the composition of the air	ϑ_{air}	$p\vartheta_{\mathrm{air}}$	$u(p\vartheta_{air})$
Ambient temperature	ϑ_a	$p\vartheta_a$	$u(p\vartheta_a)$
Temperature of the external optical system	ϑ_{o}	$p\vartheta_o$	$u(p\vartheta_o)$
deviation of the observed surface in the horizontal axis	ϑ_α	$p\vartheta_\alpha$	$u(p\vartheta_\alpha)$
deviation of the observed surface in the vertical axis,	ϑ_β	$p\vartheta_\beta$	$u(p\vartheta_\beta)$
humidity	ϑ_h	$p\vartheta_h$	$u(p\vartheta_h)$
distance between the lens and the observed surface.	ϑ_d	$p\vartheta_d$	$u(p\vartheta_d)$

When formulating the equation (2), enabling the determination of the improved temperature of the observed object, the following factors mentioned above were taken into account (input values).

$$\vartheta_x = \vartheta_{kam} + p_{kam} + p\vartheta_i + p\vartheta_\varepsilon + p\vartheta_r + p\vartheta_{air} + p\vartheta_a + p\vartheta_o + p\vartheta_\alpha + p\vartheta_\beta + p\vartheta_h + p\vartheta_d \tag{2}$$

It was assumed that the occurrence of the worst situation would be reflected in this way. The occurrence of internal factors (e.g. the influence of optical system transmittance τ_o) is included in the difference between the indication of the thermal imaging camera and the indication of a reference thermometer. For the adopted procedure, it was only possible to determine the p_{kam} correction value based on a comparison of the results of measurements obtained with a thermovision camera and a reference thermometer. For other factors (input values), it was not possible to determine the value of corrections and therefore their values were set to 0. It should be noted that each of these corrections can be burdened with non-zero uncertainty.

3. Determination of the p_{kam} value

The difference between the thermographic camera indication and the indication of the reference thermometer $\Delta\vartheta_{kam}$ was determined according to the following equation (Equation 3):

$$\Delta\vartheta_{kam} = \vartheta_{kam} - \vartheta_s = -p_{kam} \tag{3}$$

ϑ_s - the temperature value indicated by the thermometer considered to be the reference one.

Due to the specificity of the work carried out, the difference between camera and reference thermometer readings was determined for chamber interior temperatures in the range from 16℃ (fixed plate temperature reduced by the assumed margin necessary for the proper determination of the calibration function) to 36℃ (assumed palm temperature). Based on the available data, it was found that the error of the thermometer readings was 0.0 and was affected by an uncertainty of 0.1℃ with the expansion coefficient k = 2. The experiment was carried out by placing the reference plate inside the chamber. The interior temperature of the chamber was controlled by means of a Pt1000 sensor. A thermometer was placed in the middle of the horizontally lying plate. The temperature of the interior of the chamber was changed in the assumed range. After each change, the temperature inside the chamber was to settle. After the time of settling, the camera indication was compared with the thermometer indication (for temperatures higher than 26℃ the camera's display was compared with the sensor's display). For each temperature, a three-fold comparison was made to obtain an average. The difference between the camera and thermometer indications was calculated according to Equation 2. Based on the received data, a calibration curve was created that made it possible to ensure measurement continuity. It was found that the p_{kam} value was –0.2℃.

4. Determination of uncertainty $u(p\vartheta_\varepsilon)$ resulting from improper emissivity coefficient setting

The value of the emissivity coefficient depends on the condition of the observed surface and its texture. In the case of most bodies, this value is also dependent on the temperature of the observed surface. Unfortunately, the function binding the emissivity coefficient value and the temperature of the observed surface is individual for each body. It should be remembered that the value of the emissivity coefficient may change during the course of measurements, e.g. due to any contamination of the observed surface. For this reason, the first value to be determined was the uncertainty value associated with the wrong selection of the emissivity coefficient. A mercury thermometer was placed on the plate, the end of it was placed in a metal block that allows the thermometer to be placed vertically on the surface whose emissivity coefficient was to be determined. According to the information provided by the thermometer manufacturer, the value of the indicated temperature was equal to the temperature of the plate fragment on which the thermometer was placed. After a sufficiently long time allowing the temperature to stabilize in the chamber, the thermometer was removed and the temperature value was read. The measurement was repeated three times to obtain an average. Next, a piece of the plate adhering to the thermometer was observed using a thermovision camera. The value of the emissivity coefficient was chosen so that the temperature indication coincided with the average value read from the thermometer. It was found that the value of the emissivity coefficient at 20°C was 0.65. Then the value of the emissivity coefficient was changed with a 0.01 increment in the range from 0.4 to 0.98. It was assumed that the range would include any incorrect value of the emissivity coefficient resulting from any contamination of the material and the observer error. In this way, it was checked how the value indicated by the infrared camera changes depending on the setting of the emissivity factor ε. It was found that the difference of camera indications between the upper and lower limits of the designated range is 1.8°C. The uncertainty value for this input value was determined in accordance with equation (4)

$$u(p\vartheta_{\varepsilon}) = \frac{\frac{1}{2}(a_{+} - a_{-})}{\sqrt{3}} = \frac{\frac{1}{2}\Delta\vartheta}{\sqrt{3}} = \frac{0.9}{\sqrt{3}} = 0.52°\mathrm{C} \tag{4}$$

$u(p\vartheta_{\varepsilon})$ – resulting uncertainty, $\Delta\vartheta$ – determined temperature range, a_{+} - the upper limit of the range, a_{-} - the lower limit of the range.

5. Determination of *u*(*p*ϑ_i) uncertainty resulting from the climate chamber instability

In order to determine the error value resulting from temperature instability inside the climate chamber, a Pt1000 sensor was placed in the place of the observed plate. The sensor was connected by a four-wire connection to the Agilent 34401a multimeter. The measured resistance values were sent to the PC via the RS 232 interface and recorded in a spreadsheet. In order to avoid errors related to the induction of interference in the measurement lines, a twisted pair was used as the transmitting medium. The temperature inside the chamber was set at 20°C. The temperature values inside the chamber were measured three times for 3 hours with a 1s increment. The results of the measurements obtained in all three series were converted to temperature values according to the equation from the technical documentation. The maximum and minimum values from all series of measurements were determined. It was found that the difference between the largest and the smallest sensor indication was 0.55°C. By inserting the resulting difference to Equation 4, the uncertainty value sought was calculated.

6. Determination of uncertainty caused by deviation of the observed surface in the *u*($\delta\vartheta_\alpha$) horizontal axis and *u*($\delta\vartheta_\beta$) vertical axis

In order to determine the limits of the range of the thermal imager, depending on the angle of observation, it was decided to repeat the experiment described in [8]. For this purpose, a constructed infrared radiator was used. The design of the radiator allowed the emission of thermal radiation in one direction. The observed surface was covered with a paint with known emissivity coefficient ε of 0.96. The temperature of the observed radiator surface was also measured using a thermocouple. The design of the radiator enabled the change of viewing angle in the vertical and horizontal planes. For both planes, the observation angle was changed from –90° to 90° with a 5° increment. Only the range from –60° to 60° has been considered in further works for both planes. This range selection was caused by the significant increase in the measurement error demonstrated in [8, 9]. It was found that the difference between the highest and the smallest indication of the thermal imaging camera was 0.6°C in the horizontal plane. In the case of the vertical plane, the difference was 0.5°C. The uncertainty values sought were calculated by inserting the obtained differences into Equation 4.

7. Determination of *u*($\delta\vartheta_r$), *u*($\delta\vartheta_a$), *u*($\delta\vartheta_o$), *u*($\delta\vartheta_h$), *u*($\delta\vartheta_d$) and *u*($\delta\vartheta_{air}$) uncertainties

In order to determine the error values associated with the effect of parasitic radiation $\delta\vartheta_r$, incorrect setting of the ambient temperature $\delta\vartheta_a$, incorrect setting of the temperature of the optical system $\delta\vartheta_o$, incorrect humidity setting $\delta\vartheta_h$ and incorrect setting of distance were used from the position described in point. 6. The temperature of the radiator was constant. The values of the function correcting the influence of the mentioned factors were recorded. It was assumed that it would be inversely proportional to the dependence of a particular factor on the value of the thermal imaging camera reading and that it would allow to determine the probability distribution and the limit values of the thermal imaging camera indication. Differences between the largest and the smallest camera indication are presented in Table 2. The uncertainty values sought were obtained by inserting the received differences into the equation (4). The uncertainty value associated with the $u(p\vartheta_{air})$ change in the air composition was determined based on literature data [10].

Tab. 2. Resulting differences between the largest and smallest camera readings for selected input values and the $\delta\vartheta_{air}$ value determined on the basis of literature

No.	Correction p_i	$\Delta\vartheta$	$u(p_i)$
1	$p\vartheta_r$	0.8°C	0.23
2	$p\vartheta_a$	0.2°C	0.06
3	$p\vartheta_o$	0.2°C	0.06
4	$p\vartheta_h$	0.2°C	0.06
5	$p\vartheta_d$	0.2°C	0.06
6	$p\vartheta_{air}$	0.4°C	0.12

8. Development of the final uncertainty budget based on the proposed equation

The determination of measurement uncertainty should start from counting the uncertainty of the estimates of individual values of the input quantity. The input value estimate is the estimated value of the input value used in the calculation of the measurement result. Based on the observations made, it was assumed rectangular probability converge for each of the input value. This made it possible to count the standard uncertainty of the input quantity in accordance with Equation 4. Next, the c_i coefficient of sensitivity value associated with the estimate of the input value should be determined. The sensitivity coefficient describes the influence of the estimate of input values on the estimate of the output values. Its value is obtained on the basis of Equation 5.

$$c_i = \frac{\partial f}{\partial x_i} \tag{5}$$

f - the proposed function (Equation 2), x_i - input value estimate.

The proposed function is the sum of the input values. For this reason, the values of all sensitivity coefficients will be equal 1. Multiplying the uncertainty of the $u(x_i)$ input estimate by the value of the c_i, sensitivity coefficient the $u_i(y)$ share of uncertainty is obtained, where y is the input value. The obtained results are presented in Table 3. Table 3 presents the construction of the uncertainty budget for measurements with a value closest to 20°C. The input value p_{kam} and its uncertainty were determined on the basis of Equation 3. The uncertainty budget for this quantity is presented in Table 4. The estimate uncertainty $u(\vartheta_s)$ was obtained by inserting the double error value of the thermometer into Equation 4.

The value of the total uncertainty of the standard estimate of the initial value $u(y)$ is equal to the element of the sum of the estimate uncertainty squares of individual input values (Equation 6):

$$u(y) = \sum_{i=1}^{n} \sqrt{u_i(y)^2} \tag{6}$$

The standard uncertainty value obtained was 1.23°C. The share of the uncertainty of the p_{kam} input quantity was determined on the basis of Equation 3, constructing a subordinate budget of uncertainty for the value. The uncertainty budget constructed is presented in Table 4. The procedure was identical as in the case of the budget presented in Table 3. The value of the indication of the reference thermometer (ϑ_s) was read from the available source and divided by the value of the expansion coefficient (k = 2) to be inserted in Table 4. The thermovision temperature measurement extended uncertainty was obtained by multiplying the obtained standard uncertainty value (last row of Table 3) by the k = 2 expansion coefficient. Such an assigned extended measurement uncertainty corresponds to the probability of an enlargement of approx. 95%. Finally, the temperature measurement expanded uncertainty of the observed plate was 2.46°C.

Tab. 3. Input value estimate values x_i, uncertainty estimate of input values $u(x_i)$, and the resulting share in the standard uncertainty $u_i(y)$

Input value	**Input value estimate x_i**	**Input value estimate uncertainty $u(x_i)$**	**Share in the standard uncertainty $u_i(y)$**
ϑ_{kam}	20.3°C	-	-
p_{kam}	–0,20°C	0.05°C	0.05°C
$p\vartheta_i$	0.00°C	0.16°C	0.16°C
ϑ_ε	0.00°C	1.16°C	1.16°C
$\Delta\vartheta_r$	0.00°C	0.23°C	0.23°C
$p\vartheta_{air}$	0.00°C	0.12°C	0.12°C
$p\vartheta_a$	0.00°C	0.06°C	0.06°C
$p\vartheta_o$	0.00°C	0.06°C	0.06°C
$p\vartheta_\alpha$	0.00°C	0.17°C	0.17°C
$p\vartheta_\beta$	0.00°C	0.14°C	0.14°C
$p\vartheta_h$	0.00°C	0.06°C	0.06°C
$p\vartheta_d$	0.00°C	0.06°C	0.06°C
$\boldsymbol{\vartheta_x}$	**20.1°C**	-	**1.23°C**

Tab. 4. Determination of the p_{kam} uncertainty

Parameter symbol	x_i	$u(x_i)$	$u_i(y)$
ϑ_{kam}	20.4	-	-
ϑ_S	20.2	0.05	0.05
$\boldsymbol{p_{kam}}$	**-0.2**	-	**0.05**

9. Conclusions

In this paper, a method for determining the uncertainty of extended thermovision temperature measurement is proposed. The resulting uncertainties of extended measurements made with the thermal imaging camera in the same series may differ from each other. It results, among others, from different values of the difference between the camera indication and the indication of the p_{kam} reference thermometer - the influence of internal factors. The remaining components of the uncertainty budget will remain close. The above presented expanded uncertainty of this measurement, which was taken when the chamber interior temperature was set to 20°C. This is the temperature value at which the reference plates are stored and at which the comparison of the length of the reference plates is performed. The obtained value of the expanded uncertainty was greater than the value of uncertainty found in the camera catalog note. It should be remembered that the catalog value is the value obtained for the most common conditions prevailing during measurements and it is mainly related to internal factors. Depending on the occurrence and value of particular external factors, it may take on a value greater than that in the catalog. It should be remembered that the uncertainty values of standard estimates of individual input values may vary depending on the assumed probability distribution and the assumed range of change of the thermal imager's indication caused by the occurrence of a given factor.

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