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Errors of thermographic measurements – exercises

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Abstract

In paper, the practical exercises of error calculation in infrared thermography measurements were presented. The calculations were performed for two practical cases. In the first case, an object with a high temperature and high emissivity was examined. In the second one, the temperature as well as the emissivity of the investigated object was relatively low. In paper the results of calculations for abovementioned cases were discussed and concluded.

1. Introduction

During our business contacts with users of thermographic systems, we were often asked a question - how to calculate an error of temperature evaluated by infrared thermographic camera for the specific circumstances? Below, some examples for two cases are presented: relatively high temperature (T_{ob} = 363 K) and high emissivity (ε_{ob} = 0.8) – Fig. 1 and relatively low temperature (T_{ob} = 263 K) and low emissivity (ε_{ob} = 0.4) – Fig. 4. These examples illustrate the practical usefulness of simulations results given in authors' monograph [1].

2. Exercises

2.1 Exercise 1

The measurement was performed in the following conditions:
- object is characterized by relatively high temperature (T_{ob} = 363 K) and high emissivity (ε_{ob} = 0.8),
- distance d from camera to an object is 100 m,
- humidity of atmosphere is ω = 50%,
- atmospheric temperature is the same as an ambient temperature $T_o = T_{atm}$ = 293 K.

It was assumed that errors of input quantities ε_{ob}, T_o, T_{atm}, d, ω of model of thermographic camera are [1 – p.51]: $\delta_{\varepsilon ob}$= -30%, δ_{To}= +3%, δ_{Tatm}= +3%, δ_d= -30%, δ_ω= +30%. What is a total error of measurement of the object temperature δ_{Tobt} and value of temperature evaluated by thermographic camera T_{obv}? The solution can be found using the graphs presented in Fig. 1-5 [1 - § 4.3].

In Fig. 1-5, the values of error δ_{Tob} for appropriately input quantities ε_{ob}, T_o, T_{atm}, d, ω of model of thermographic camera are marked by black dots. They are suitable for ThermaCAM PM 595 LW made by FLIR Company. It should be emphasized that due to high complexity of formulae of atmospheric transmission TT_{atm} [1 – pp. 54] we have got the case of the very complex intermediate measurement. The classical definition of relative error can be useful for further error analysis. For hypothetical quantity X we have got:

$$\delta_{X\%} = \left(\frac{X_w - X}{X} \right) \cdot 100\% , \quad (1)$$

where:
$\delta_{x\%}$ - relative error of X,
X_v - value of X evaluated by camera built-in software,
X - true value of X, a'priori assumed for simulation purpose (i.e: T_{ob}, ε_{ob}, T_o, T_{atm}, d and ω).
For example:

$$\delta_{Tob\%} = \frac{T_{obv} - T_{ob}}{T_{ob}} \cdot 100\% = \frac{\Delta T_{ob}}{T_{ob}} \cdot 100\% , \quad (2)$$

where:
T_{obv} – object temperature evaluated by camera built-in software,
T_{ob} – true value of object temperature, a'priori assumed for simulation purpose.

An Eq. (2) is right because T_{ob} is directly given in simulations. When absolute error ΔT_{ob} is needed then it can be calculated from transformed version of Eq. 2, i.e.:

$$\Delta T_{ob} = \frac{\delta_{Tob\%} \cdot T_{ob}}{100\%}. \tag{3}$$

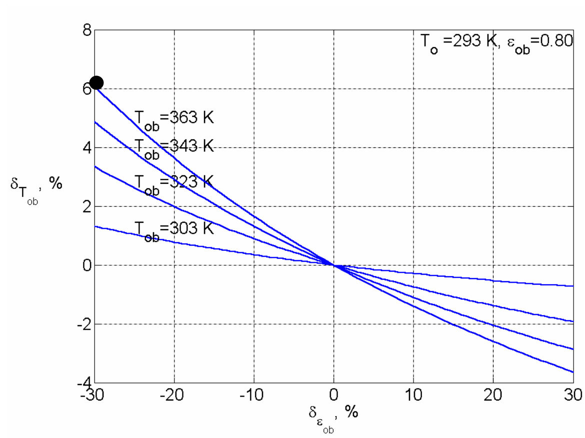

Fig. 1. Influence of object emissivity ε_{ob} setting error on object temperature T_{ob} measurement error (we assume that: ε_{ob} = 0.8, $T_o = T_{atm}$ = 293 K, d = 100 m and ω = 50%)

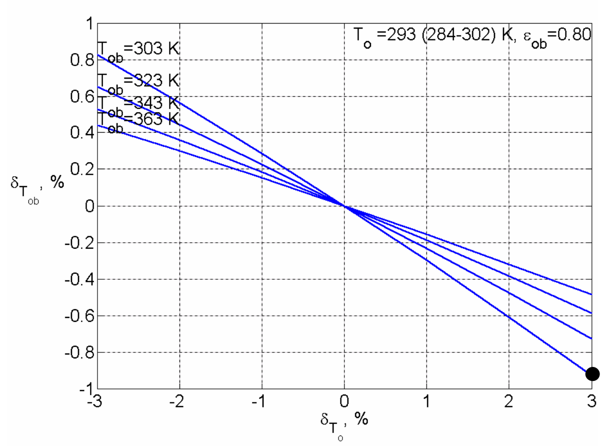

Fig. 2. Influence of ambient temperature T_o setting error on object temperature T_{ob} measurement error (we assume that: ε_{ob} = 0.8, $T_o = T_{atm}$ = 293 K, d = 100 m and ω = 50%)

Similar transformation can be performed for other quantities denoted as X. The calculations were proceeded for temperature in K (Kelvin) complying with arrangements of the International Temperature Scale of 1990. Sometimes the Celsius scale was used to assure the better legibility of results.

Assuming that errors of the input quantities are: $\delta_{\varepsilon ob}$ = -30%, δ_{To} = +3%, δ_{Tatm} = +3%, δ_d = -30%, δ_ω= +30% and according to the Fig. 1-5 is as follows $\delta_{Tob}(\varepsilon_{ob})$ = 6%, $\delta_{Tob}(T_o)$ = -0,9%, $\delta_{Tob}(T_{atm})$ = 0,3%, $\delta_{Tob}(d)$= -0,16%, $\delta_{Tob}(\omega)$= 0,14%. Based on the propagation law of relative errors the error of object temperature δ_{Tobt} is:

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$$\delta_{Tobt} = \delta_{Tob}(\varepsilon_{ob}) + \delta_{Tob}(T_o) + \delta_{Tob}(T_{atm}) + \delta_{Tob}(d) + \delta_{Tob}(\omega) = \\ = 6.00 - 0.90 + 0.30 - 0.16 + 0.14 \approx 5.30\% \quad (4)$$

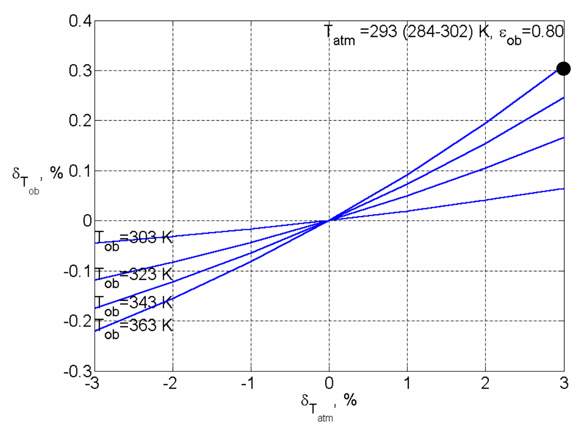

Fig. 3. Influence of atmospheric temperature T_{atm} setting error on object temperature T_{ob} measurement error (we assume that: ε_{ob} = 0.8, $T_o = T_{atm}$ = 293 K, d = 100 m and ω = 50%)

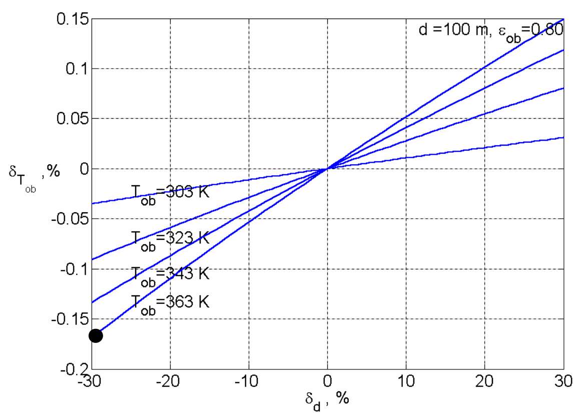

Fig. 4. Influence of camera-to-object distance d setting error on object temperature T_{ob} measurement error (we assume that: ε_{ob} = 0.8, $T_o = T_{atm}$ = 293 K, d = 100 m and ω = 50%)

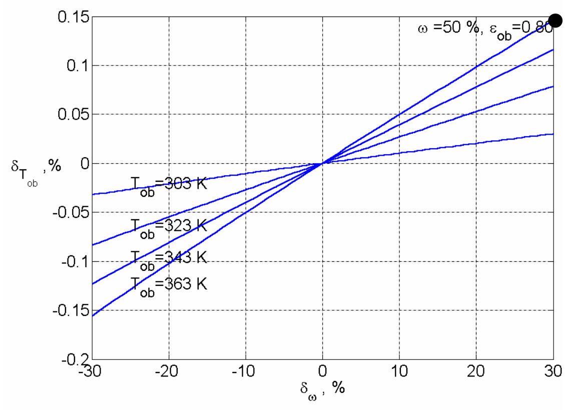

Fig. 5. Influence of atmospheric relative humidity ω setting error on object temperature T_{ob} measurement error (we assume that: ε_{ob} = 0.8, $T_o = T_{atm}$ = 293 K, d = 100 m and ω = 50%)

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It means that an infrared camera should indicate temperature:

$$T_{obv} = \frac{T_{ob} \cdot \delta_{Tobt\%}}{100\%} + T_{ob} = \frac{363 \cdot 5.30}{100} + 363 \approx 382\ \mathrm{K}, \qquad (5)$$

with absolute error:

$$\Delta T_{obc} = T_{obw} - T_{ob} = 382 - 363 = 19\ \mathrm{K}. \qquad (6)$$

Taking into considerations the above mentioned errors the values of input quantities are: $\varepsilon_{ob} = 0.56$, $T_o = T_{atm} = 301.8$ K, $d = 70$ m, $\omega = 65\%$. For Celsius scale of temperature they will be as follows: $T_{ob} = 90$ °C, $T_{obv} = 109$ °C and $\delta_{Tobt} = 21$ %.

Above analysis is illustrated in Fig. 6 and 7. The thermograms have been got from firmware ThermaCAM Reporter also made be FLIR company. Temperature shown by camera visible in Fig. 7 is 380.9 K. Its expected value according to presented calculations is 382 K. The difference which is about 1 K was caused by inaccuracy of calculations and burdened readings from Fig. 1-5.

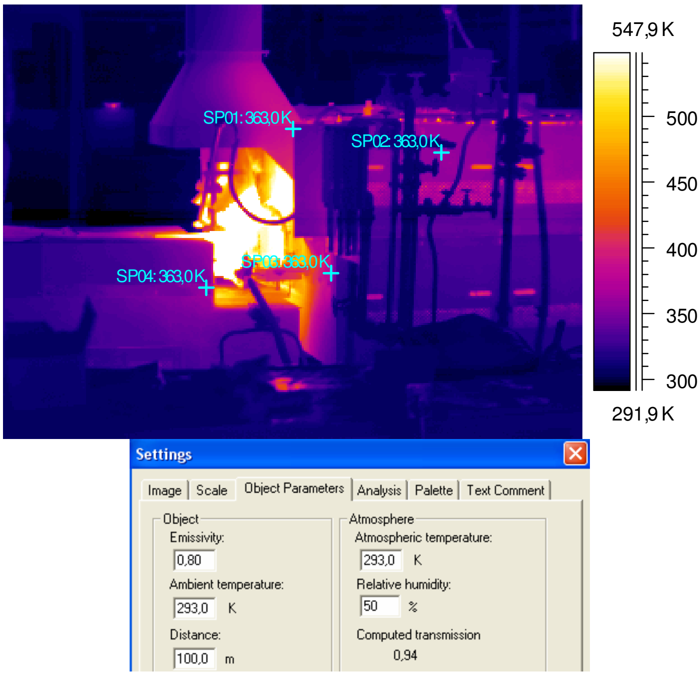

Fig. 6. Thermogram with temperature values for correct values of settings (input quantities)

2.2 Exercise 2

The measurement was performed in the following conditions:
- object is characterized by relatively low temperature ($T_{ob} = 263$ K) and low emissivity ($\varepsilon_{ob} = 0.4$),
- distance d from camera to an object is 100 m,
- humidity of atmosphere is $\omega = 50\%$,
- atmospheric temperature is the same as an ambient temperature, $T_o = T_{atm} = 293$ K.

Similar like in Exercise 1 it was assumed that the errors of the input quantities ε_{ob}, T_o, T_{atm}, d, ω of model of infrared camera are [1 – p.51]: $\delta_{\varepsilon ob} = -30\%$, $\delta_{To} = +3\%$, $\delta_{Tatm} = +3\%$, $\delta_d = -30\%$, $\delta_\omega = +30\%$. What is error of measurement of an object temperature δ_{Tobt} and the value of temperature evaluated by infrared camera T_{obv}? The solution can be found using the graphs presented in Fig. 8-12 [1 - § 4.3].

In Fig. 8-12, the values of error δ_{Tob} for appropriately input quantities ε_{ob}, T_o, T_{atm}, d, ω of model of thermographic camera are marked by black dots. Assuming that the errors of the input quantities are: $\delta_{\varepsilon ob} = -30\%$, $\delta_{To} = +3\%$, $\delta_{Tatm} = +3\%$, $\delta_d = -30\%$, 30%, δ_{ω}= +30% and according to the Fig. 8-12 is as follows $\delta_{Tob}(\varepsilon_{ob})$= -6.80%, $\delta_{Tob}(T_o)$= -10.00%, $\delta_{Tob}(T_{atm})$= -0.28%, $\delta_{Tob}(d)$= 0.15%, $\delta_{Tob}(\omega)$= -0.13%.

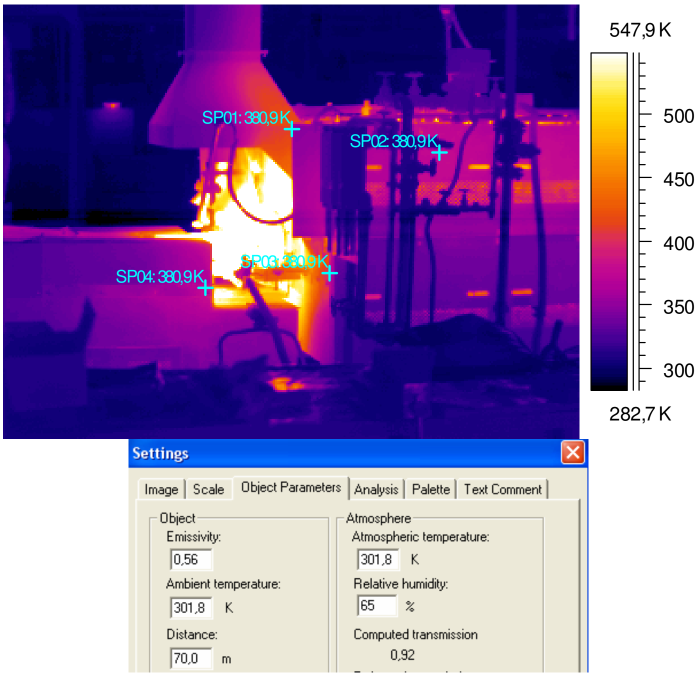

Fig. 7. Thermogram with temperature values for incorrect values of settings (input quantities)

Based on the propagation law of relative errors the error of object temperature δ_{Tobt} is:

$$\begin{aligned}\delta_{Tobt} &= \delta_{Tob}(\varepsilon_{ob}) + \delta_{Tob}(T_o) + \delta_{Tob}(T_{atm}) + \delta_{Tob}(d) + \delta_{Tob}(\omega) = \\ &= -6.80 - 10 - 0.28 + 0.15 + 0.13 \approx -17\%\end{aligned} \quad (7)$$

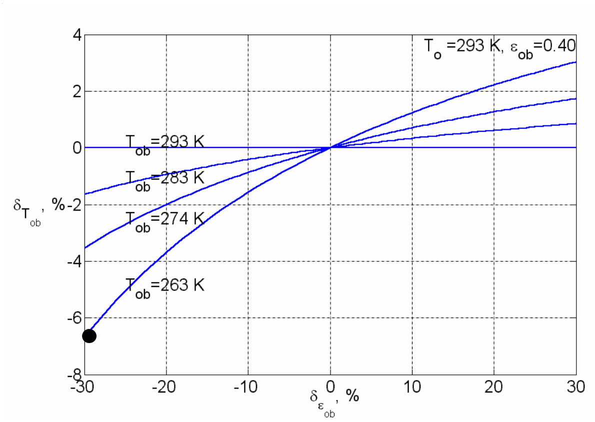

Fig. 8. Influence of object emissivity ε_{ob} setting error on object temperature T_{ob} measurement error (we assume that: ε_{ob} = 0.4, $T_o = T_{atm}$ = 293 K, d = 100 m and ω = 50%)

It means that an infrared camera should indicate temperature:

$$T_{obv} = \frac{T_{ob} \cdot \delta_{Tobt\%}}{100\%} + T_{ob} = \frac{263 \cdot (-17)}{100} + 263 = 218\,\mathrm{K}\,, \tag{8}$$

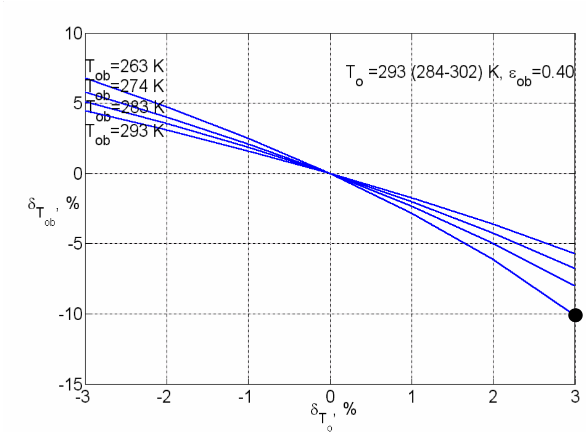

Fig. 9. Influence of ambient temperature T_o *setting error on object temperature* T_{ob} *measurement error (we assume that:* ε_{ob} *= 0.4,* $T_o = T_{atm}$ *= 293 K,* d *= 100 m and* ω *= 50%)*

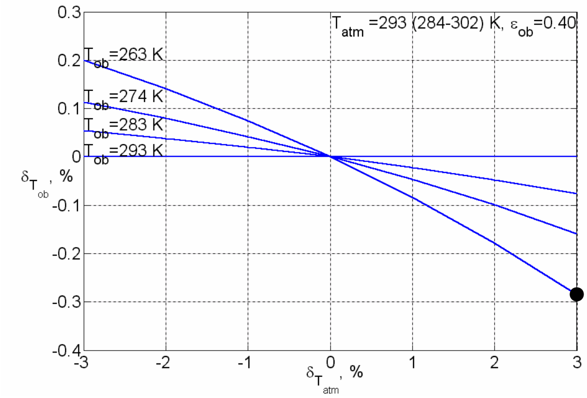

Fig. 10. Influence of atmospheric temperature T_{atm} *setting error on object temperature* T_{ob} *measurement error (we assume that:* ε_{ob} *= 0.4,* $T_o = T_{atm}$ *= 293 K,* d *= 100 m and* ω *= 50%)*

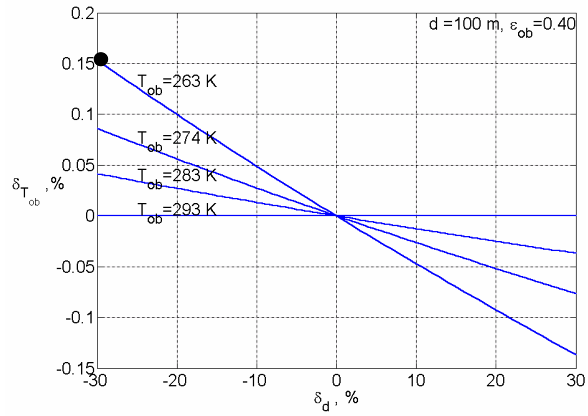

Fig. 11. Influence of camera-to-object distance d *setting error on object temperature* T_{ob} *measurement error (we assume that:* ε_{ob} *= 0.4,* $T_o = T_{atm}$ *= 293 K,* d *= 100 m and* ω *= 50%)*

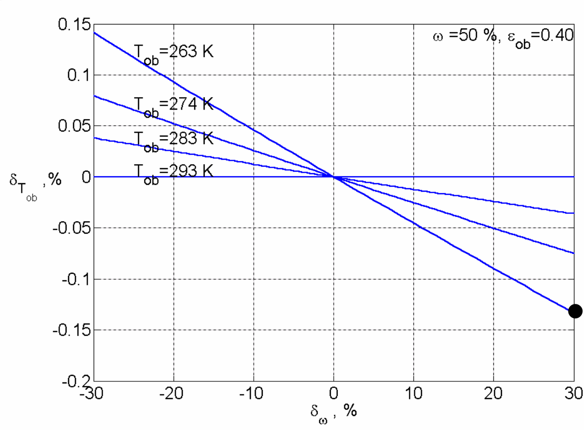

Fig. 12. Influence of atmospheric relative humidity ω *setting error on object temperature* T_{ob} *measurement error (we assume that:* $\varepsilon_{ob} = 0.4$, $T_o = T_{atm} = 293$ *K,* $d = 100$ *m and* $\omega = 50\%$*)*

with absolute error:

$$\Delta T_{obt} = T_{obv} - T_{ob} = 218 - 263 \approx -45\ \mathrm{K}\,. \qquad (9)$$

Taking into considerations the above mentioned errors the values of input quantities are: $\varepsilon_{ob} = 0.28$, $T_o = T_{atm} = 301.8$ K, $d = 70$ m, $\omega = 65\%$. For Celsius scale of temperature they will be as follows: T_{ob}= -10°C, T_{obv}= -55°C and δ_{Tobt}= 450%.

3. Summary

In exercise 1 (high temperature and high emissivity of object) It was shown that the greatest effect on error of temperature measurement has the error associated with the emissivity. In exercise 2 (low temperature and low emissivity of object) the most significant influence is associated with the surrounding temperature and the emissivity. It should be emphasized that the lower emissivity of object the higher influence of surrounding temperature on measured temperature. The problem of evaluation of surrounding temperature was wider discussed in [1- pp. 56].

REFERENCES

[1] Minkina W., Dudzik S.: „Infrared thermography – errors and uncertainties" John Wiley & Sons Ltd, Chichester 2009 r., ISBN 978-0-470-74718-6, OnlineBooks™ ISBN 978-0-470-68223-4.