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Diagnostics of electric equipments by means of thermovision

***Abstract**. This paper analyses problems of thermovision diagnostics measurement. It examines basic principles and application of non-contact temperature measurement. Knowledge of problems of measurement in the infrared radiation allows us to use the thermovision diagnostic methods more effectively and to localise the disturbance which determines the quality of electric equipments in the inside distribution of electric energy.*

***Abstract**. Przedstawiono zasady diagnostyki termowizyjnej. Znajomość problemów pomiaru promieniowania podczerwonego pozwala na stosowanie termoizji w sposób bardziej efektywny I bardziej dokładnie lokalizować wady. (**Diagnostyka urządzeń elektrycznych przy wykorzystaniu termowizji**)*

Keywords: thermovision, emissivity, radiation, temperature, diagnostics, calculation
Słowa kluczowe: termowizja, promieniowanie podcvzerwone.

Introduction

Fundamental for a non-destructive diagnostics of electrical equipments using thermovision, is the ability to record and to work infrared radiation (heating) to the form of real thermal images of objects, and on the basis of overheating of certain surround, for a detection of a failure (defect).

With non-contact measurement it is able to detect the temperature distribution on the surface of objects using sensitivity measuring of a few Kelvin (or ˚C) decimal. Fig.1. [1]

Infrared radiation is generated as a result of physical processes that take place in the object of radiation; moving atoms, molecules, vibration in crystal lattice, and transition of electrons from one energy level to another. The basic source of infrared radiation is elevated temperature of the source of radiation.

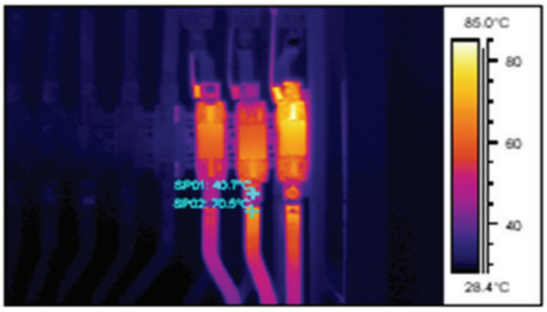

Fig.1 Thermogram of electric wiring breaker

Radiation of hot sources acts like (in respect of surrounding conditions), like visible light. To display temperature fields we can use visualization techniques used in optics. The only differences are materials used for elements of visualization systems, size of values which are derived from the wavelength of radiation, and also sensitivity of sensors for recording the signal.

The surface of the measured object in a state of thermodynamic equilibrium emits electromagnetic radiation and the radiated power depends on the thermodynamic temperature and properties of the surface object.

For thermovision diagnostics of infrared radiation in the inside distribution of electric energy, we need to take into account many important factors affecting the accuracy of measurement.

Results of the measured values of specific electric contact are often biased by measurement defects. In determining the classification of degrees to correct the defects, it is necessary to correct measured values due to disruptive effects of other objects.

Accuracy of warming measurement for thermovision diagnostics is influenced by following factors:

- incorrect determination of radiation coefficient of measured object *ε* (*λ*, *T*) - emissivity,
- current load of electric wiring has a relevant role for assessment of measuring warming,
- effect of hot objects close to measured objects and inaccurate determination of surrounding temperature can cause both changes of emission coefficient and wrong interpretation of measured values of warming,
- various surfaces (the surface can be chromatic, peeled paint on materials and oxidized surfaces) can cause incorrect evaluation of results.

The theory of infrared radiation

Radiation power (intensity) $H(\lambda,T)$ is the only parameter that is measured by infrared receiver and is a function emission coefficient $\varepsilon(\lambda,T)$ and temperature T of radiation source.

(1) $$H(\lambda,T)=\varepsilon\sigma T^4$$

This uncertainty (the value of one parameter is subject of another parameter) is one of the problems of measuring the infrared radiation. Emission coefficient depends on the direction from which is the radiation recorded, on the temperature and also on the surface of material.

If the absorption coefficient of incident radiation on the body is equal to α then the temperature of body will grow as quickly as will coefficient α grow.

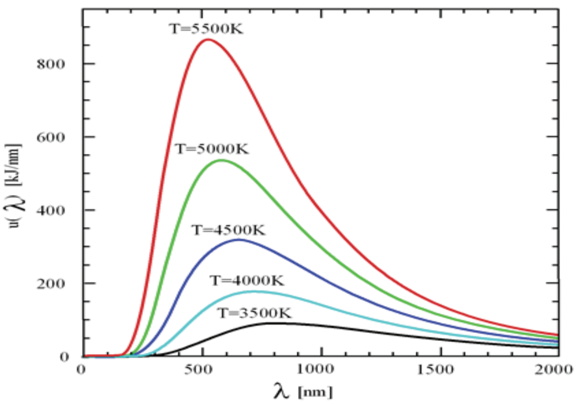

Fig.2 Dependence of spectral density - intensity of radiation to wavelength

The body with temperature T which is slightly above the ambient temperature, will provide energy to the surroundings in the form of radiation whose spectral allocation according to Win's law, is moved to the side of long waves comparing to spectrum radiation of incident energy (Fig.2).

Heating is defined by the relationship α/ε, where α is the absorption coefficient of energy and ε is the emission coefficient (emissivity) of the measured points. [2]

Ratio of intensity radiation of actual body and ideal black body at the same temperature is defined by spectral coefficient of emissivity:

(2) $$\varepsilon_\lambda(\lambda,T)=\frac{H_\lambda(\lambda,T)}{H_{0\lambda}(\lambda,T)}$$

It is clear that the coefficient of spectral emissivity is equal to the spectral absorption coefficient.

The research on issues of radiation of solid bodies is based on knowledge of absolute black body; an object which is able to fully absorb the full spectrum of radiated energy.

By Kirchhoff's law the black body is an ideal emitter. Plank defines the spectrum of black body radiation.

(3) $$\frac{dH(\lambda,T)}{d\lambda}=\frac{2\pi hc^2\lambda^{-5}}{e^{\frac{hc}{\lambda kT}}-1}$$

where: $dH(\lambda,T)$ - spectral radiant flux density surface, i.e. radiated power, which is emitted by a unit surface of the black body in an interval of wave length, h = 6.625.10^{-34} J.s - Planck constant, k = 1,38054.10^{-23} - Boltzmann constant, c - speed of light, T - absolute temperature of black body in ºK.

Spectral radiant flux density of black body surface depends on the length of the wave and temperature.

Plank's law is a function of spectral distribution of values

(4) $$\frac{dH(\lambda,T)}{d\lambda}=f_T(\lambda)$$

Spectral distribution curves $dH(\lambda,T)/d\lambda$ entering at temperature T (Fig.3) go through the maxima. Shift of the maxima at different temperatures is described by Win's law, which is the derivation of Planck's law, where λ = 2898/T [μm] and $dH(\lambda_{max},T)/d\lambda$ = 1,286. 10^{-15}T^5 [W/m^3],

The object with a temperature around 290 ºK has a maximum spectral density of radiation at $\lambda_{max}\approx$ 10μm. (The Sun, whose effective temperature is 6000 ºK has a maximum λ_{max} = 0.5μm what is the actual wavelength, which is central in visible spectrum).

Win law clearly defines the shift of visible and invisible body radiation (when it is heated) to the side of the shorter waves. [3]

Stefan-Boltzmann's law, as an integration of Planck's law to λ, defines an integral radiant flux density of black body at the temperature T:

(5) $$H_T=\int_0^\infty[dH(\lambda,T)/d\lambda]d\lambda=\sigma T^4$$

σ = 5,67.10^{-8} W/m^{2}K^4 – Boltzmann constant. It is actually the area under the curve $dH(\lambda,T)/d\lambda=f_T(\lambda)$.

If the body temperature is T = 300ºK then H_T =5,7 10^{-12}.(300)^4 = 0,05W/cm^2 and power radiated from the body surface (skin area - 2m^2) is P = 1 kW.

Flux density of blackbody radiation (Fig. 4) on the range of wavelengths λ_a, λ_b we receive by integrating Planck equation for λ.

(6) $$H_T=\int_{\lambda_a}^{\lambda_b}[dH(\lambda,T)/d\lambda]d\lambda=\sigma T^4$$

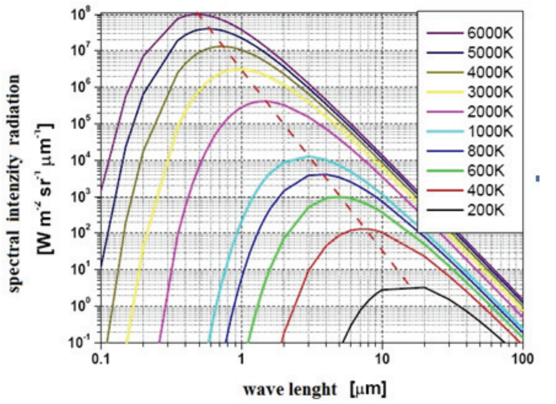

Fig.3 Curves of the spectral distribution

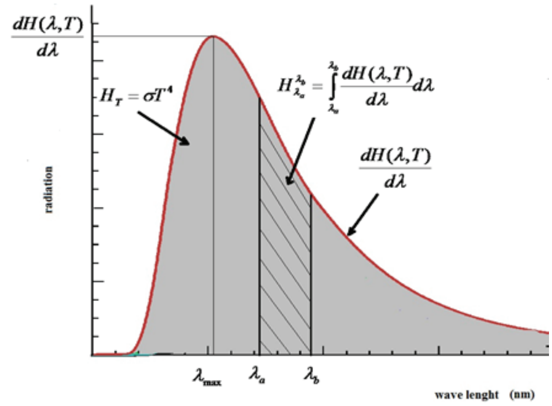

Fig.4 Radiant flux density at temperature T

Derived Planck's equation on temperature dT, we receive change of spectral flux density emitted from black body as a function of temperature:

(7) $$\frac{\partial(dH/d\lambda}{\partial T}=\frac{(hc/k)e^{(hc/\lambda kT)}}{\lambda T^2\left[e^{(hc/\lambda kT)}-1\right]}\cdot\frac{dH}{d\lambda}$$

Measured objects in thermography are mostly with the temperature about T = 300 ºK, where effective measuring is in the spectral range of λ = 10μm and when object temperature is about 750 ºK in a spectral range λ = 4μm, so in both cases $\lambda.T$ = 3000μm and $h.c/k$ = 14388, so if e$^{hc/\lambda kt}$ is much greater than 1 we could use Win's equation in this form:

(8) $$\frac{\partial(dH/d\lambda)}{\partial T}=(hc/\lambda kT^2).\frac{dH}{d\lambda}$$

If we see an object with temperature T_0, which we see on background with a temperature T_f,, then thermal contrast in spectral interval $\Delta\lambda$ we can express with equation: [4]

(9) $$C=\frac{\int_{\Delta\lambda}[dH(\lambda,T_0)/d\lambda]d\lambda-\int_{\Delta\lambda}[dH(\lambda,T_f)/d\lambda]d\lambda}{\int_{\Delta\lambda}[dH(\lambda,T_0)/d\lambda]d\lambda+\int_{\Delta\lambda}[dH(\lambda,T_f)/d\lambda]d\lambda}$$

Types of sources radiation

Real objects generally do not behave as black bodies. No-black bodies absorb only a part of $\alpha(\lambda)\Phi$ (incident radiation), part of the reflected radiation $\varepsilon(\lambda)\Phi$ and part $\tau(\lambda)\Phi$ is transient radiation. Coefficients α (λ), ε (λ), τ (λ) are selective and depend on the wavelength.

If the system is in thermodynamic equilibrium (Fig. 6), under the law of conservation of energy reflected and transient energy is equal to the energy absorbed.

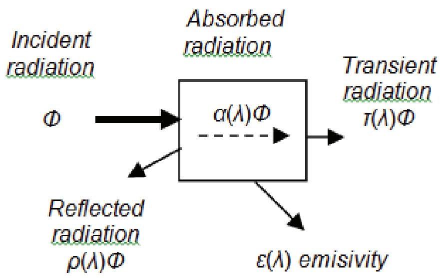

Fig.6 Distribution of the incident radiation

Emissivity $\varepsilon(\lambda)$ (coefficient of radiation), compensates absorption coefficient $\alpha(\lambda)$ then $\varepsilon(\lambda)=\alpha(\lambda)$. It follows that:

(10) $$\varepsilon(\lambda)+\rho(\lambda)+\tau(\lambda)=1$$

where

$\tau(\lambda)=0, \quad \varepsilon(\lambda)+\rho(\lambda)=1$ - non-transparent materials

$\rho(\lambda)\to high \;\; and \;\; \varepsilon(\lambda)\to 0$ - reflective materials

$\varepsilon(\lambda)=1, \quad \tau(\lambda)=0, \quad \rho(\lambda)=0$ - black body

$\varepsilon(\lambda)=const, \quad \rho(\lambda)=const$ - black body

Spectral radiant flux density of any object is bound to spectral radiant flux density of black body, therefore

(11) $$\frac{dH(\lambda,T)}{d\lambda}=\varepsilon(\lambda)\frac{dH_{\check{c}.t.}(\lambda,T)}{d\lambda}$$

Radiated power in the range $\Delta\lambda$ of the body surface with area S at a temperature T is defined as:

(12) $$H=\int_{\Delta\lambda}\varepsilon(\lambda)\frac{dH_{\check{c}.T.}(\lambda,T)}{d\lambda}Sd\lambda$$

Object own radiation is defined by its temperature. Deriving the Planck equation:

(13) $$\frac{\partial(dH(\lambda,T)/d\lambda)}{\partial T}=\frac{hce^{(hc/\lambda kt)}}{\lambda kT^2(e^{\frac{hc}{\lambda kT}}-1)}\cdot\frac{\partial H(\lambda,T)}{d\lambda}$$

The result of object temperature measurement T_0, which is registered in the spectral range of wavelengths $\Delta\lambda$ (surface density of radiant flux), is the registered radiant flux density H_{reg}:

(14)
$$H_{reg}=\int_{\Delta\lambda}\rho_a(\lambda)[dH(\lambda,T_a)/d\lambda]d\lambda+\int_{\Delta\lambda}\tau_f(\lambda)[dH(\lambda,T_f)/d\lambda]d\lambda$$
$$+\int_{\Delta\lambda}\varepsilon_0(\lambda)[dH(\lambda,T_0)d\lambda]d\lambda$$

We need to gather the values of the first two parts of the equation and emissivity $\varepsilon_0(\lambda)$.

When an object is transparent $\tau(\lambda)=0$ and if T_0 is much larger than T_a , the first part of the equation is very small. In this case the task is easier and it is essential to know $\varepsilon_0(\lambda)$.

In measuring, we deal with the problems of reflection of infrared radiation.

Radiation measured at temperature T_0 is only the result of a combination of three phenomena:

- The objects reflect the part of $\rho(\lambda)$ radiation energy which is equivalent to black body radiation temperature T_a.
- If the body is partially transparent, it releases a part of radiation $\tau_f(\lambda)$ which is equivalent to temperature T_f of black body radiation
- Eventually at body temperature T_0 the object has effect of self radiation, so coefficient of absorption $\alpha(\lambda)$ contributes to the increase of temperature T_0.

Difficulties arise when the body is surrounded by other objects, which have high temperature and these temperatures are higher than the examined object.

In this case, its own radiation depends on the T_0 and ε_0 affected by reflected radiation error caused by parasitic (surrounding) objects with a temperature T_e and emissivity ε_e. (Fig.7). If the reflection coefficient is measured as ρ_e - radiation error, then the part characterizing the error is proportional to T_e, ε_e and ρ_e , T_e.

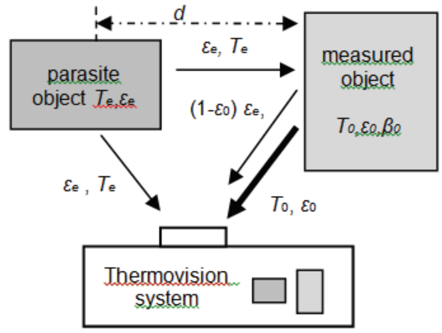

Fig.7 Influence of other radiating objects

For measures of this type it is necessary to know ε_0 and T_0 parameters and the number of equations, which are equal to number of unknowns.

If we use a measuring system that works in two different ranges of wavelengths, $\Delta\lambda$ and $\Delta\lambda_1$ (i.e. camera is working in two different spectral of range - spectral filters), then thermal imaging system divides the observed object radiation to the useful signal and parasitical signal (disorder).

Radiation of measured object is formed by the sum of two parts; own H_1 radiation and parasitic H_2 radiation in the infrared spectral range:

(15) $$H_1=S\int_{\Delta\lambda_1}\rho_e(\lambda)\varepsilon_e(\lambda)[dH(\lambda,T_e)/d\lambda]d\lambda + \int_{\Delta\lambda_1}\varepsilon_0(\lambda)[dH(\lambda,T_0)/d\lambda]d\lambda$$

(16) $$H_2=S\int_{\Delta\lambda_2}\rho_e(\lambda)\varepsilon_e(\lambda)[dH(\lambda,T_e)/d\lambda]d\lambda + \int_{\Delta\lambda_2}\varepsilon_0(\lambda)[dH(\lambda,T_0)/d\lambda]d\lambda$$

where S - geometric parameter which depends on the distance of two objects and on their surfaces.

Radiation of parasitic object:

(17) $$H_1^*=\int_{\Delta\lambda_1}\varepsilon_e(\lambda)[dH(\lambda,T_e)/d\lambda]d\lambda$$
$$H_2^*=\int_{\Delta\lambda_2}\varepsilon_e(\lambda)[dH(\lambda,T_e)/d\lambda]d\lambda$$

These equations allow us to find $\varepsilon_e(\lambda)$ and T by direct measurement. If spectral ranges are very near to each other, then measured objects can be considered as gray bodies (solid objects).

Then for a system of equations above (14) applies:

(18) $$H_1 = (1-\varepsilon_0)\varepsilon_e S \int_{\Delta\lambda_1} [dH(\lambda,T_e)/d\lambda]d\lambda + \varepsilon_0 \int_{\Delta\lambda_1} [dH(\lambda,T_0)/d\lambda]d\lambda$$

(19) $$H_2 = (1-\varepsilon_0)\varepsilon_e S \int_{\Delta\lambda_2} [dH(\lambda,T_e)/d\lambda]d\lambda + \varepsilon_0 \int_{\Delta\lambda_2} [dH(\lambda,T_0)/d\lambda]d\lambda$$

modification

(20) $$H_1 - SH_1^* = \varepsilon_0 \int_{\Delta\lambda_1} [dH(\lambda,T_0)/d\lambda]d\lambda - SH_1^*$$
$$H_2 - SH_2^* = \varepsilon_0 \int_{\Delta\lambda_2} [dH(\lambda,T_0)/d\lambda]d\lambda - SH_2^*$$

H_1, H_2, H_1^*, H_2^* are measured values, ε, T are calculated values and S parameter depends on the geometry of the system. [5]

Based on the foregoing, the variables ε and T can be found. The whole process shows that the radiation of objects have very complex structure; therefore it is necessary to take into account temperature of surrounding objects when we want to really evaluate the energy of radiation.

Experimental analysis

In measurement of electrical equipment and wires we deal with warming of contacts, switches, power cables, clamps, contacts of fuses. In electrical substation temperature of each object is measured, focusing on the expansion joints, junctions, bends and coats drivers.

Thermovision is used to measure warming of connections and clamps in electrical machines, as well as to the measurement of electrical equipments in the internal and external electrical distributing of systems. These measurements warn us about the progressive deterioration of transition resistances of connections, about overheating and deterioration of isolation systems condition, machinery and electrical equipment.

If we have a thermal camera with sensitivity of 3÷5μm and we have two filters with characteristics:

$\Delta\lambda_1$ = 0,2 μm	$\Delta\lambda_2$ = 0,2 μm
λ_{1a} = 3,5 μm	λ_{2a} = 3,9 μm
λ_{1b} = 3,7 μm	λ_{2b} = 4,1 μm

On the Fig.8 we can see the thermogram of measured object BR1 at a temperature T_0 and emisivity ε_0 which we want to know (radiant breaker BR1 on the left) and from the other side we can see parasitic object with temperature T_e, which is larger than T_0 (radiant breaker BR2 on the right).

Emissivity ε_e of parasitic object is high and the distance from measured object d is small. The temperature value T_e and emissivity ε_e is unknown. The thermal camera distinguishes this different temperature of objects, i.e. temperature, which would have absolutely black body in this spectral range.

Following values were measured:

$\Delta\lambda_1$: T_1 = 346,3ºK T_1' = 357,4ºK
$\Delta\lambda_2$: T_2 = 344,6ºK T_2' = 355,6ºK

From these effective temperatures values we can calculate the radiant flux density, i.e. radiant flux, which would have a black body at the temperature T_1, T_1', T_2, T_2'.

For T_1'=357,4ºK is spectral distribution maximum of radiant flux density by Win:

(21) $$\lambda_{\max} = \frac{2898}{357{,}4} = 8{,}10\mu m$$

Fig.8 Thermogram of breakers in electric switchgear

Physically the radiation flux density H in emission spectrum $\Delta\lambda$ at temperature T is represented by the area under the Planck's curve between the wavelengths λ_{1a} = 3,5μm and λ_{1b} = 3,7μm.

This area is equal to the derivation of spectral radiation flux density for the maximum top of wavelength 3,6 microns in the range of interval $\Delta\lambda_1$ = 0,2μm:

$$H_T = \int_{\lambda_{1a}}^{\lambda_{1b}} [dH(\lambda,T_1')/d\lambda]d\lambda = [dH(\lambda_1 = 3{,}6\mu m, T_1' = 357{,}4^\circ K)/d\lambda]\Delta\lambda_1$$

then

(22) $$H_1' = \frac{2\pi h c^2 \lambda_1^{-5}}{e^{(hc/\lambda k T_1')} - 1}\Delta\lambda_1$$

h = 6,63.10^{-34} Ws^{-2}, k = 1,38.10^{-23} JK^{-1}, c = 3.10^{8} ms^{-1}, λ = 3,6.10^{-6} m, T = 357,4ºK, $\Delta\lambda$ = 0,2.10^{-6}m

(23) $$H_1' = \frac{1{,}240.10^5}{e^{(4{,}004.10^3/T_1')} - 1} = 0{,}096 W/cm^2$$

For others temperatures:

$\Delta\lambda_1 \rightarrow H_1$ = 0,023.10^{-2} , H_1' = 0,096.10^{-2} W/cm^2
$\Delta\lambda_2 \rightarrow H_2$ = 0,025.10^{-2} , H_2' = 0,083.10^{-2} W/cm^2

Calculation T_e and ε_e of parasite object

From measured values of T_1 and T_2 we can calculate the density of radiant flux H_1' a H_2':

(24) $$H_2' = \int_{\Delta\lambda_2} \varepsilon_e(\lambda)[dH(\lambda,T_e)/d\lambda]d\lambda$$

If the parameter ε in this spectral range is constant, then it can be removed by dividing equations

(25) $$\frac{H_1'}{H_2'} = \frac{\int_{\Delta\lambda_1}[dH(\lambda,T_e)/d\lambda]d\lambda}{\int_{\Delta\lambda_2}[dH(\lambda,T_e)/d\lambda]d\lambda} = \frac{0{,}096}{0{,}083} = 1{,}156$$

then

$$1{,}156 = \int_{\Delta\lambda_2}[dH(\lambda,T_e)/d\lambda]d\lambda - \int_{\Delta\lambda_1}[dH(\lambda,T_e)/d\lambda]d\lambda = 0$$

The result of calculated equation is the temperature of parasite object T_e = 361, 5ºK. Value of calculated temperature T_{ce} =361, 5ºK is near to measured temperature T_e = 357.45 ºK.

Coefficient ε_e can be calculated with the equation (17)

(26) $$\varepsilon_e = \frac{H_1^{'}}{\int\limits_{\Delta\lambda_1} dH(\lambda_1 = 3{,}6\mu m, T_e = 1070K)/d\lambda} = 0{,}82$$

Calculation ε_0 and T_0 of measured object

The size of radiation flux density of parasite object BR2 (ε_e = 0.96 and temperature T = 357.45 ºK) is:

(27) $$H_e = \varepsilon_e \int\limits_{\Delta\lambda_1} [dH(\lambda, T_e)/d\lambda] d\lambda$$

then the radiant flux density of the measured object is:

(28)
$$H = \varepsilon_0 \int\limits_{\Delta\lambda} [dH(\lambda, T_0)/d\lambda] d\lambda + (1-\varepsilon_e)\varepsilon_e S \int\limits_{\Delta\lambda} [dH(\lambda, T_e)/d\lambda] d\lambda$$

If S = 1 then for a measured value T_1 and T_2 we can use equations (5) and as a result we have the equation:

(29) $$\int\limits_{\Delta\lambda_1} [dH(\lambda, T_0)/d\lambda] d\lambda - 0{,}083$$
$$-1{,}156 \int\limits_{\Delta\lambda_2} [dH(\lambda, T_e)/d\lambda] d\lambda + 0{,}096 = 0$$

where calculated temperature of measured object BR1 is T_0 = 303, 15º*K*.
And for emisivity:

$$\varepsilon_0 = \frac{H_1 - H_1^{'}}{\int\limits_{\Delta\lambda_1} dH(\lambda_1 = 3{,}6\mu m, T_0 = 357{,}4^{\circ}K)/d\lambda} = 0{,}75$$

Following data were calculated:
BR1: T_0 = 303,15ºK =43ºC, ε_0= 0,75
BR2: T_e = 361,5ºK = 84ºC, ε_e= 0,82

Conclusion

Comparing the results of calculated and measured values; we see that real measured temperature values are influenced by parasite object. The differences between the calculated and measured values are illustrated on the graph (Fig. 9).

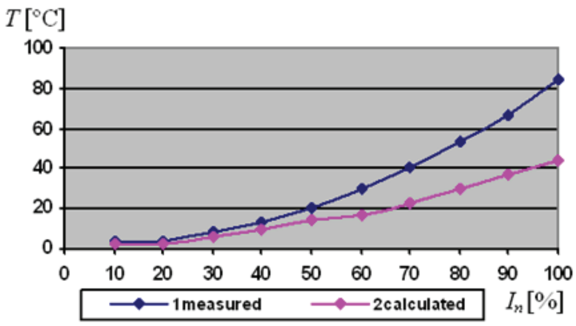

Fig.9 Dependence of measured and recalculated warming T_0 to breaker BR1

On the graph we see measured and calculated temperature differences of breaker BR1 at the current load.

Measured temperature of BR1 is higher than calculated because close parasite object influences its temperature. As we can see on the graph (Fig.9) temperature differences depend on the value of current load (In).

The results of experimental measurements and mathematical calculations of temperature differences for parasitic object we can see on the graph (Fig.10).

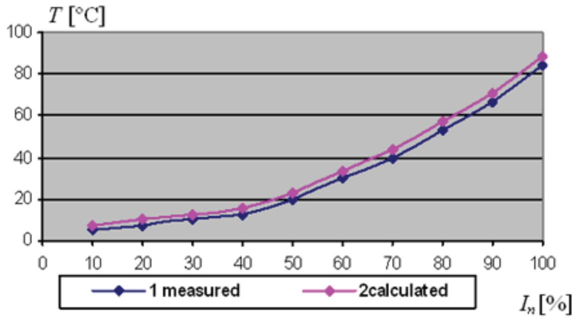

Fig.10 Dependence of measured and calculated values of warming T_e on breaker BR2

In carrying out repeated surveys of professional and technical examinations of selected technical equipments thermovision is an important diagnostic method for determination in energy audits and revisions of power wiring and equipments. Heated objects with higher temperature near measured objects influences values of measured temperature of these examined electrical equipment.

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