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Importance of radiative heat transfer for infrared thermography measurements

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Abstract

The basics of heat transfer by radiation will be shortly outlined: Planck's law, Stefan Boltzmann's law, emissivity, construction of a black body, effective emissivity, reflection. Several applications for infrared thermography, basic physical principles of microbolometer detector, non uniformity correction without shutter and blocking the image and some original experiments will be discussed afterwards. The main conclusion of this work is that calibration of metrological cameras has to be performed for different temperature of their housing.

Keywords: heat transfer by radiation, thermography, infrared radiation.

Znaczenie radiacyjnej wymiany ciepła w pomiarach termowizyjnych

Streszczenie

W artykule przedstawiono podstawy wymiany ciepła przez radiację: prawo Plancka, Stefana Boltzmanna, emisyjność materiałów, budowę ciała doskonale czarnego, efektywną emisyjność oraz prawo odbicia. Omówiono również niektóre aplikacje w termografii w podczerwieni, w których wykorzystuje się efekty radiacyjne. Omówiono fizyczne podstawy działania detektora mikrobolometrycznego, korekcję niejednorodności matrycy bolometrycznej bez migawki i blokowania obrazu oraz wybrane oryginalne eksperymenty. Przedstawiono wpływ promieniowania obudowy na działanie detektora i kamery termowizyjnej oraz zastosowanie pierścieni pośrednich w badaniach termowizyjnych. Niestety obudowa i pierścienie emitują pasożytnicze promieniowanie, które musi być uwzględnione w pomiarach termowizyjnych. Wnioskiem z pracy jest stwierdzenie, że w metrologicznej kamerze termowizyjnej, kalibracja powinna być przeprowadzona dla różnych wartości temperatury obudowy. Mówimy wówczas o korekcji RNU (*ang. Residual Nonuniformity Correction*). The work is an effect of design and building a prototype of the new infrared camera.

Słowa kluczowe: radiacyjna wymiana ciepła, termografia, promieniowanie podczerwone.

1. Introduction

Thermographic cameras are used to investigate heat transfer processes in all kind of applications: buildings, electronics, mechanics, medicine, hence a good understanding of the basic laws of heat transfer is necessary to interpret the thermographic images correctly. A thermographic camera does not measure the temperature of a solid body or, more precisely, the surface temperature. The camera measures the amount of incoming infrared radiation. The object temperature is then calculated from this amount.

In this paper we will consider only microbolometer type cameras. Their working principles are entirely based on heat transfer processes as will be outlined further on in this paper.

2. Basic laws

The Planck's law, discovered in 1900 is well known. A graphical representation is shown in Fig.1. It gives the amount of emitted power (W) per unit area (m^2) and per unit wavelength (μm), so the dimension is then $W/m^2μm$.

Integrating the Planck's law over all possible wavelengths gives us the well known Stefan Boltzmann's law:

$$q = \sigma \cdot T^4 \tag{1}$$

where $\sigma = 5.6\ 10^{-8}$ W/m^2K^4 and T the absolute temperature.

A square meter of a body surface emits continuously the amount of σT^4 Watts. The only parameter one can change is the absolute temperature T.

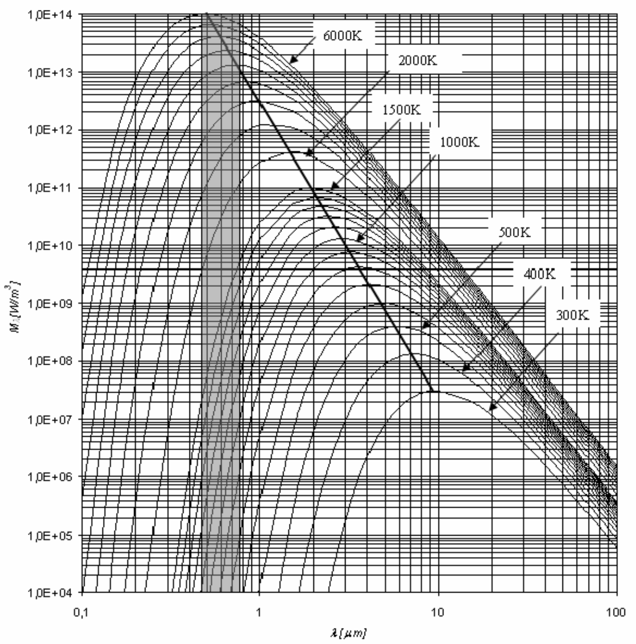

Fig. 1. Graphical representation of the Planck's law [1]
Rys. 1. Graficzna reprezentacja prawa Plancka [1]

For T = 300 K or 27 °C, (1) turns out to be q = 400 W/m^2, which is quite high. Fortunately, all other bodies around us are at similar temperatures and they also emit power towards us, so that the net heat losses are much less than (1).

Equation (1) only holds for the so called black bodies. Black means that all the incoming radiation will be absorbed and not reflected. When we talk about a black body we have to look at Fig.1 and we observe that the Planck's law is only significant between 2 and 20 μm wavelength, i.e. the so called thermal or mid infrared. A black body has to be black for $2 < \lambda < 20$ μm. For other wavelengths the "blackness" is not important any more as far as the heat transfer is concerned. Hence, it happens that green, red, white ... paints are all black for the mid infrared. Silicon is transparent for the thermal infrared but for visible light ($0.4 < \lambda < 0.8$ μm) it is a black body. Clear water is a black body in the infrared but transparent for visible light.

In practical situations a correction to (1) is often required:

$$q = \varepsilon \cdot \sigma \cdot T^4 \tag{2}$$

where ε is the emissivity of the body ($0 < \varepsilon < 1$). Coefficient $\varepsilon = 1$ for a perfect black body. For grey bodies ε is between 0 and 1. A better understanding of heat transfer between grey bodies can be gained if one should pay more attention to the reflection coefficient r:

$$r = 1 - \varepsilon \tag{3}$$

Every grey body performs two jobs: it emits radiation according to (2) but it also reflects the infrared radiation from all other bodies in the neighbourhood. All these bodies can have different temperatures, so it is often cumbersome to evaluate the reflected amount of radiation.

3. Basic physics of the microbolometer

A microbolometer is made on a silicon substrate, the same material used in microelectronics. Using special etching techniques, very small and thin bridges can be made (micromachining). A picture of such a pixel is shown in Fig. 2.

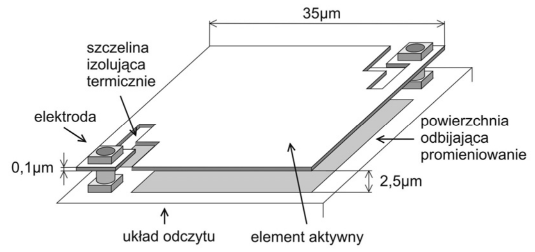

Fig. 2. Image of a few pixels of a microbolometer matrix [2]
Rys. 2. Widok kilku pikseli na matrycy mikrobolmetrycznej [2]

These pixels are arranged in rows and columns to form a matrix. Every pixel generates a signal corresponding to the incident heat radiation. All signals from all the pixels constitute a thermographic image. Note that each pixel has typical dimensions of 35x35 μm with a thickness of only 100 nm.

The microbolometer array is packed in vacuum, to eliminate any convective heat transfer. Just above the matrix there is a window transparent for thermal infrared light.

How does it work? An object at a temperature T_0 is monitored by the thermal camera. The object emits infrared radiation in all possible directions as shown in Fig. 3.

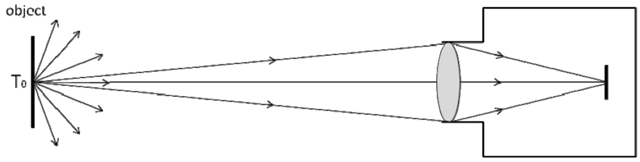

Fig. 3. Schematic view of the working principle of a thermographic camera
Rys. 3. Schemat zasady działania kamery termowizyjnej

A small fraction falls on the lens and is focused on the microbolometer matrix. Hence, every pixel will be heated a little bit. This small temperature change increases the electric resistance of the pixels which is electronically measured. Do not overestimate this "heating". If the object has a temperature of 100 °C above ambient, the pixels will be heated only by 0.3 °C (typical value). If one looks at an object of 1°C above ambient, the pixels are "warmed" up 0.003 °C. If a camera has a resolution of 1 °C, its internal thermal stability must be better than 0.003 °C.

Is it possible to thermally stabilize the substrate, on which the microbolometer matrix is integrated, and the packaging better than 0.003 °C? The answer is simply NO. Due to the variations of the room temperature, the heat produced by the electronics inside the camera, the "reference" temperature is continuously varying. If for example the substrate of the detector matrix is changing only by 0.3°C, the camera will interpret this as an object temperature of 100°C even when the object was at room temperature.

How is this problem solved in practice? First of all, the detectors package is rear cooled (typical 5°C) just to provide a stable (+/- 0.1 °C) reference temperature. But this is still not enough for thermographic recording. Secondly, a shutter is put at regular times in front of the lens. The shutter (when closed) is at a uniform temperature, so all pixels must provide the same signal. If not, corrections are electronically made. Actually, the shutter has to be closed at least once per minute for a short period of 1-2 seconds. It also means that during these periods no images can be recorded. The operation of a shutter was blocked intentionally, while the camera was focused on a stable heat source. Some results are displayed in Fig.4 (Δ-curve).

Just after the blocking of the shutter the error was about 0.4 °C. After 2 minutes the error reached the value of 2.5 °C, but after 10 minutes the error was raised to 10 °C, which is totally unacceptable.

It proves that a shutter is really necessary for the good operation of a microbolometer camera.

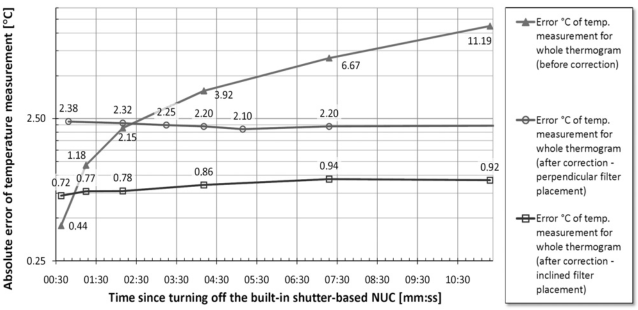

Fig. 4. Measurment errors if the shutter is out of use (Δ). The graphs with o and □ are with the new shutterless operation

Rys. 4. Błędy pomiaru wynikające z braku wykorzystania migawki (Δ). Wykres błędu o i □ przy wykorzystaniu nowej bez migawkowej operacji

Shutterless operations

Strictly speaking, the shutter is just a heat source at the uniform temperature (usually the room temperature). But the major disadvantage is the periodic blocking of the image. In order to avoid this disadvantage another approach will be presented here.

Instead of blocking the image completely, we suggest blocking the image partially by using a semi transparent window as shown in Fig. 5.

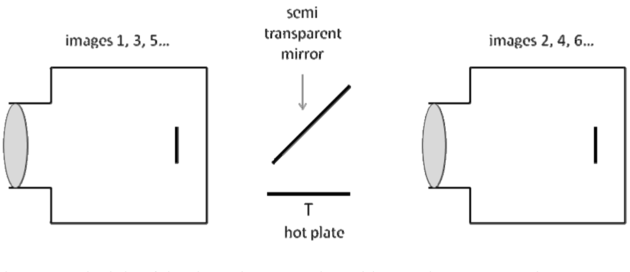

Fig. 5. Principle of the shutterless operation with a semitransparent mirror and a hot plate for the even images. The odd image are obtained without the mirror

Rys. 5. Zasada działania korekcji bez migawki, przy wykorzystaniu półprzeźroczystego lustra oraz gorącej płyty dla obrazów

Assume the transparency of the window being 50%, the camera will observe 50% of the "normal" image but also 50% of the reflection from a "hot" plate at a uniform temperature (can be room temperature). The hot plate and the semi transparent window behave like a partial shutter. If all the odd images are recorded without the semitransparent window and all the even image with it, one can perform a non uniformity correction of every two images. Of course one has to know the exact value of the window transmission.

Some results are also shown in Fig. 4 as well (o and □ curves). The curves indicated with a box are for a window at an inclination of 45°. One observes that the error is quite low but it is also almost constant. It means that the drift was eliminated. The curves indicated with Delta are for a more vertical positioning of the semi transparent window. The error is a bit higher due to reflection originating from the camera itself. The configuration with 45° did only have reflections from the hot plate.

4. Three original experiments

The internal housing of a photographic camera is always painted black. The reason is obvious: light should only come from the scene through the lens towards the CCD detector or the photographic film. Otherwise the images will be corrupted by parasitic light.

The idea of black painting (for infrared) was used for thermographic cameras as well. However, it is completely wrong and does not make any sense. The housing of a thermographic camera is normally at room temperature if we consider the case of a setup in a laboratory. All the walls of the camera emit radiation towards the detector as shown in Fig. 6.

Fig. 6. Internal reflections inside a camera

Rys. 6. Wewnętrzne odbicie w obudowie kamery

It is even possible that this amount of parasitic radiation is greater than the radiation passing through the lens, which is the useful signal we are interested in. The calibration of the camera must take this parasitic radiation into account.

A few experiments were carried out proving that the behavior of a thermographic camera could be sometimes quite different from a photographic one. The top cover plate of a thermographic camera was removed during recording. The thermal image did not change at all (Fig. 7).

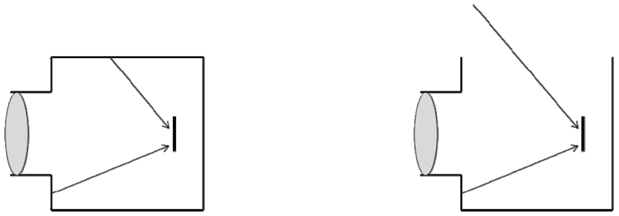

Fig. 7. Removing the top cover of a thermographic camera during operation

Rys. 7. Usunięcie górnej pokrywy kamery podczas jej pracy

The explanation is quite obvious. After the cover plate was removed, the detector received some parasitic radiation from the sealing of the laboratory. But the cover plate and the sealing were at the same temperature. Hence, the amount of parasitic radiation falling on the detector was the same in both cases.

Extension tubes were mounted in front of a thermographic camera (Fig. 8) to make microscopic recordings [3].

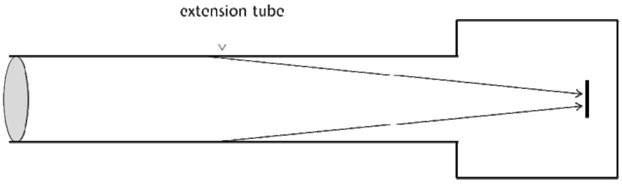

Fig. 8. Parasitic infrared radiation due to use of an extension tube for microscopic imaging

Rys. 8. Pasożytnicze promieniowanie podczerwone powstałe ze względu na zastosowanie podłużnej rurki dla mikroskopowego obrazowania

The temperature of a flat plate at a uniform temperature was recorded and some results are shown in Fig. 9. The results are far from being correct. Not only did the temperature in the middle depend on the extension tube length. The pixels far from the central axis displayed different temperature than the central pixel although the plate was at a uniform temperature. The explanation is quite obvious. The inner side of the extension tube generates a lot of parasitic infrared radiation on the matrix detector. The longer the extension tube, the more parasitic radiation falls on the detector. By cooling or heating the extension tube a bit, different results could be obtained.

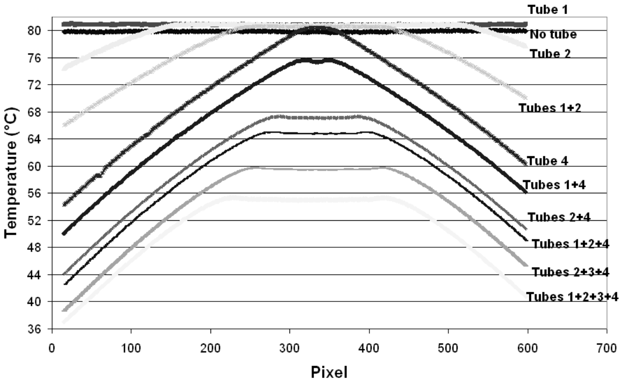

Fig. 9. Influence of the extension tube on the isothermal plate recorded temperature [3]

Rys. 9. Wpływ zastosowania podłużnej rury na rejestrację temperatury izotermicznej płyty [3]

A third experiment is related to the (inevitable) internal radiation inside a camera, i.e. the space between the lens and the detector. The camera housing is normally at the room temperature, but modern cameras are very compact and have a lot of heat dissipating electronics. Hence, the walls of the cavity between the lens and the microbolometer detector can be at a higher temperature. Camera designers must take this phenomenon into account in the calibration procedure. Another problem is the non uniformity of this temperature distribution. Assume that the top wall (Fig. 6) is warmer than the bottom plate. The upper pixels will receive more radiation than the other ones so that a non uniformity problem arises. The origin of these troubles is that cavities are often painted black, a wrong idea copied from photographic cameras. The walls should be made or covered with a material of low emissivity and ,hence, the high reflection coefficient. As a consequence, the parasitic radiation from the walls is reflected many times so that the microbolometer detector receives more uniform (but still parasitic) radiation, reducing the non uniformity problem. Moreover, low emissivity also gives rise to less parasitic radiation. These facts were experimentally verified by covering the inside of the camera with aluminum foil. In this section we described three experiments which would yield totally different results if one would do the same thins with photographic cameras.

5. Conclusions

An overview of the radiation heat transfer processes occurring in thermographic cameras has been given. Especially the modern cameras equipped with a microbolometer matrix detector fundamentally based on heat transfer by radiation have been described. An important feature concerning the non uniformity correction has been discussed and a solution which does no longer require the interruption of the image has been proposed. Also some uncommon experiments have been presented the results of which could only be explained using the basic principles of heat transfer by radiation.

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otrzymano / received: 02.08.2011
przyjęto do druku / accepted: 05.09.2011 *artykuł recenzowany*
